# Freezing in Parkinson's Disease: A Reaching Study

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Abstract

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Freezing of gait is a debilitating symptom affecting individuals with Parkinson's disease. Emerging evidence suggests freezing may represent a global motor control deficit beyond gait. We investigated freezing episodes in the upper limbs using spatially-constrained reaching tasks known to elicit freezing of gait. Fourteen people with Parkinson's disease and 13 controls completed reaching tasks under three spatial conditions with varying backgrounds. The tunnel condition produced the greatest kinematic disruptions. Despite people with Parkinson's disease showing significantly longer movement times and slower speeds, they were less accurate in their movements, suggesting observed differences reflect genuine motor control deficits rather than speed-accuracy trade-offs. The tunnel's narrow spatial constraints challenge the motor system's ability to maintain coordinated movement trajectories, with people with Parkinson's disease exhibiting increased trajectory variability. These findings demonstrate that freezing-like episodes extend beyond gait, supporting the hypothesis that freezing represents a global motor phenomenon in Parkinson's disease.

**Keywords:** Parkinson's disease, freezing of gait, upper limb, reaching, spatial frequency, motor control, kinematics

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## List of Abbreviations

PD: Parkinson's Disease

PwPD: People with Parkinson's Disease

FOG: Freezing of Gait

FOUL: Freezing of Upper Limbs

MDS-UPDRS: Movement Disorders Society-Unified Parkinson Disease Rating Scale

PDQ-39: Parkinson Disease Questionnaire-39

## Introduction

## Freezing in Parkinson's Disease: A Reaching Study

Parkinson's disease (PD) is one of the most prevalent neurodegenerative diseases, second only to Alzheimer's disease (Ou et al., 2021). Recently, PD's prevalence has experienced the fastest growth of all neurological disorders and, globally, is a leading cause of disability. Parkinson's disease is a movement disorder that results from the selective destruction of dopaminergic neurons in the substantia nigra pars compacta (SNc), leading to the positive and negative motor signs and symptoms associated with PD. There are various non-motor symptoms linked to PD, such as cognitive deficits, mood disturbances and visual impairments; however, PD has been primarily associated with motor dysfunction. The cardinal motor signs of PD include bradykinesia, a slowing of movement (a negative sign), rigidity, resting tremor (positive signs), postural instability, and gait dysfunction.

A particularly debilitating manifestation of gait dysfunction in PD is freezing of gait (FOG), defined as a "brief episodic absence or marked reduction of forwarding progression of the feet despite the intention to walk" (Giladi et al., 1997). Patients frequently describe FOG as the feeling that their feet are glued to the floor. Typically lasting one to two seconds, FOG episodes vary individually and can present as rocking, leaning, decreased step length or shuffling. These episodes increase the risk and fear of falling in individuals with PD (Gilat et al., 2021). Common transitions known to trigger FOG are reversals (walking away from and back to a starting position), turning corners, and navigating through narrow spaces like doorways (Rahmen et al., 2008).

Although freezing is not well understood, researchers have observed that visual stimuli can alleviate episodes of FOG (Rahmen et al., 2008; Bryant et al., 2010; Cao et al., 2020). For example, horizontal lines and laser beams placed on walking surfaces can enhance step length or help overcome freezing episodes (Bryant et al., 2010; Cao et al., 2020) through a phenomenon known as 'paradoxical kinesia' (Distler et al., 2016). The connection between vision and freezing is interesting, as there is evidence that PwPD experience changes in their ability to perceive visual patterns (Davidsottir et al., 2012; Ming et al., 2015).

The pattern of FOG triggers being associated with transitions and FOG releases associated with visual patterns suggests that freezing might be linked to central nervous system (CNS) functioning that may influence other motor systems. Indeed, freezing-like episodes have been observed in the upper limbs during finger-tapping, rapid alternation of hand postures, and during writing tasks (Barbe et al., 2014; Delval et al., 2017; Heremans et al., 2015; Nieuwboer et al., 2009; Nutt & Bloem, 2011 & Ziv et al., 1999). It is unknown if FOG is related to freezing of upper limbs (FOUL). Aside from one case study (Nemanich et al., 2017), to our knowledge, no studies have investigated FOUL using tasks that involve transitions known to induce FOG. The present study addresses this critical gap in the literature by investigating whether PwPD experience freezing during upper limb reaching tasks that incorporate established FOG triggers. Specifically, we developed novel reaching paradigms that embody the spatial and cognitive challenges associated with reversals, corners, and narrow passages (tunnels). We also examined whether the frequency and characteristics of FOUL episodes are sensitive to visual-spatial frequency manipulations, given the established role of visual processing in FOG and the documented visual processing deficits in PD.

This research is important for several reasons. It provides the first systematic investigation of upper limb freezing using ecologically valid paradigms based on established FOG triggers. It also examines the role of visual-spatial frequency processing in upper limb motor control, potentially revealing common mechanisms underlying both gait and reaching difficulties in PD. Further, the findings may inform the development of novel assessment tools and therapeutic interventions that could be implemented in clinical and laboratory settings. This work contributes to our theoretical understanding of freezing as a potentially global motor control phenomenon rather than a gait-specific deficit.

**Background and Literature Review**

Parkinson's disease is characterized by the degeneration of nigra-striatal dopaminergic neurons, which results in a diminished amount of dopamine projected to the dorsal striatum of the basal ganglia. When approximately 80% of these neurons are lost, the classic motor signs of PD emerge: resting tremor, rigidity, bradykinesia, and postural instability, including gait dysfunction (Jankovic, 2008). Resting tremor is a rhythmic, involuntary shaking that typically occurs in a limb when it is at rest and disappears with voluntary movement or during sleep. It most commonly affects the hands ("pill-rolling" tremor) but can also involve the legs or face, though not present in all PD patients, resting tremor can be one of the earliest symptoms, and may lead to social embarrassment, functional impairment, and difficulty with fine motor tasks.

Rigidity is characterized by an involuntary increase in muscle tone that leads to resistance during passive movement of a joint. Unlike spasticity, this resistance is typically uniform throughout the entire range of motion and does not vary with the speed of movement (Jankovic, 2008). Clinically, rigidity may present as either "lead-pipe" rigidity, which involves smooth and constant resistance, or "cogwheel" rigidity, in which the resistance is interrupted by rhythmic jerks due to coexisting tremor. Rigidity can affect the limbs, neck, and trunk, contributing to stiffness, reduced mobility, discomfort, and functional impairment in individuals with PD (Berardelli et al., 2013).

Bradykinesia involves both reduced movement speed and decreased amplitude of voluntary and automatic movements (Jankovic, 2008). People with PD may have difficulty initiating movement, experience a progressive reduction in movement size (e.g., micrographia, a progressive shrinking of handwriting, or reduced facial expression), and perform tasks such as dressing, walking, or speaking more slowly. Bradykinesia contributes significantly to motor disability and is often used as a diagnostic criterion for PD.

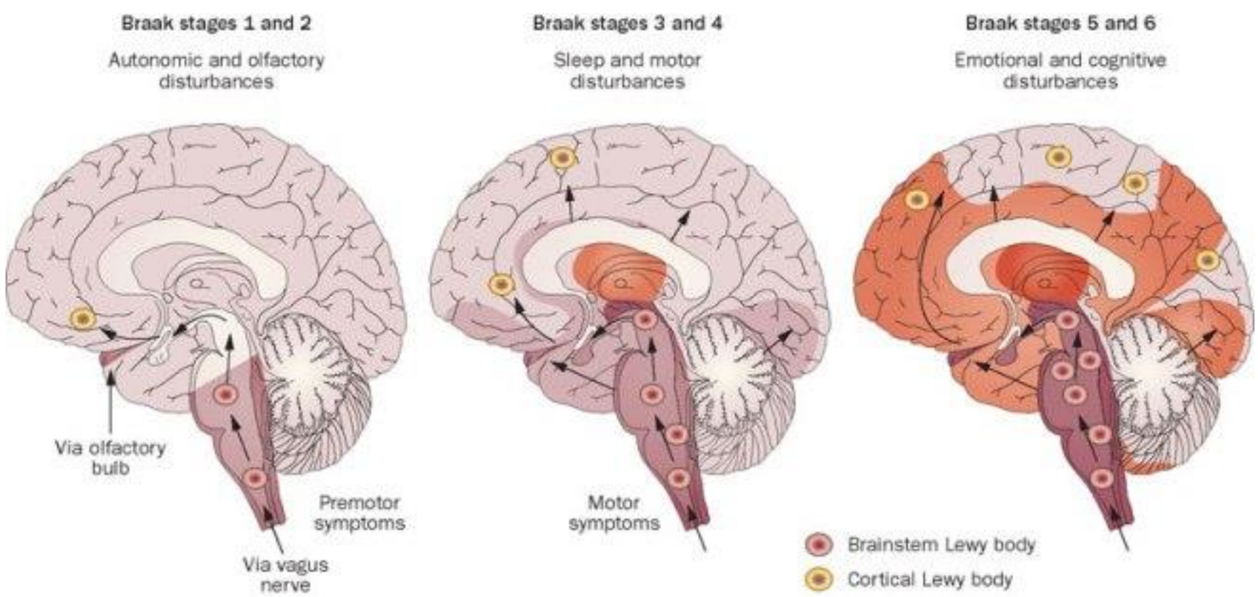
Postural instability refers to impaired balance and difficulty maintaining upright posture, particularly during movement transitions such as turning, standing, or walking (Jankovic, 2008). This symptom usually emerges in the later stages of PD and is a significant risk factor for falls. It is due to dysfunction in postural reflexes and is poorly responsive to dopaminergic therapy. It also affects confidence and increases fear of movement, contributing to reduced mobility and quality of life.

Gait dysfunction in PD refers to abnormalities in walking, including shortened stride length, reduced arm swing, shuffling steps, and FOG (Jankovic, 2008). Gait disturbances contribute significantly to functional impairment in PD. Patients often have difficulty initiating walking, turning, or navigating tight spaces. Gait dysfunction increases the risk of falls and affects independence, particularly as the disease progresses.

The non-motor manifestations of PD include mood disruptions (depression, anxiety), visual impairments, cognitive deficits, sleep disturbances, and olfactory impairments, often appearing long before the motor signs in PD (Braak et al., 2003; Kalia & Lang, 2015; Schapira et al., 2017). The Braak Hypothesis (Braak et al., 2003) suggests that PD progresses in stages, possibly beginning in the enteric nervous system and progressing rostrally via the vagus nerve. The earliest stages result in olfactory and autonomic disruptions, with motor signs not emerging until stage three, once nigral-striatal degeneration has occurred (Figure 1).

**Figure 1**

*The Braak Hypothesis of PD*




*Note:* The Braak Hypothesis (Braak et al., 2003). The figure shows the hypothesized stages of the disease progression beginning with autonomic and olfactory disturbances.

***Causes of Parkinson's Disease***

The cause of PD is unknown. Environmental risk factors such as exposure to pesticides, rural living and drinking well water have been identified as risks (Priyadarshi et al., 2001). Mutations in 20 genes (e.g., PRKN, LRRK2, alpha-synuclein) have been associated with PD (Blauwendraat et al., 2020). First identified by Polymeropoulos et al. (1997), a gene mutation resulting in familial PD was found in the SNCA gene, which encodes a protein called alpha-synuclein (α-synuclein). This mutation causes the protein to misfold, which leads to the development of fibrils, followed by abnormal aggregation into larger structures known as Lewy bodies. The build-up of α-synuclein leads to widespread neuronal damage and death. Lewy bodies are commonly found in the brains of PwPD upon autopsy, a pathological hallmark allowing for diagnosis. Incidental Lewy body disease (iLBD) may be found in a small percentage of older adults, but it usually lacks clinical symptoms and the widespread pathology of PD (Markesbery et al., 2009). Immunohistochemistry has identified α-synuclein aggregates throughout the enteric, autonomic and central nervous systems, offering support for the Braak Hypothesis (Blauwendraat et al., 2020; Dauer et al., 2003). Importantly, mutations in the SNCA gene are now thought to be one of the major genes associated not just with familial but also with idiopathic PD (Stefanis, 2012).

***Diagnosis***

Once motor symptoms emerge, a clinical diagnosis of PD can be made. No lab or imaging tests can definitively diagnose PD; however, imaging like magnetic resonance (MRI) or dopamine transporter scan (DaT scan) can be used to support the diagnosis or rule out other disorders with similar signs and symptoms. A neurologist will obtain a detailed family history, plus an account of the patient's symptoms. To obtain a diagnosis of PD, the International Parkinson and Movement Disorder Society's guidelines reflect that the individual must have bradykinesia and at least one of the following: resting tremor, rigidity and/or difficulty with balance or a history of falls. The Movement Disorder Society's Unified Parkinson's Disease Rating Scale (MDS-UPDRS) is a four-part clinical assessment tool consisting of questions and motor evaluations that can determine the severity of the disease. The MDS-UPDRS is not only used to rate the impact of PD on an individual's daily life, but it also yields a Hoehn & Yahr stage of disease categorization, which ranges from 1, unilateral involvement only, to 5, wheelchair-bound or bedridden unless aided.

***Treatment***

Pharmaceutical treatments for PD, such as dopamine agonists and precursors (L-dopa, for example), aim to augment dopamine levels in the brain, which improves motor dysfunction in PD, but is only efficacious for a while, usually five to eight years (Poewe et al., 2010). Other therapies, such as deep brain stimulation (DBS), might be considered if the patient is a good candidate (Hartmann et al., 2019) DBS is a neurosurgical procedure that uses electrical stimulation via implanted electrodes in the brain. DBS is suitable for patients if their PD symptoms significantly impact daily living and they experience mobility changes during their ON-OFF medication states (i.e., worsening of motor symptoms when their medication wears off). Those who are not ideal candidates for DBS have speech difficulty as one of the main symptoms, those with memory problems or cognitive dysfunction, and those who experience one of the most debilitating gait issues associated with PD, freezing.

***Motor Control and Speed-Accuracy Trade-offs in Parkinson's Disease***

A fundamental principle of motor control is the speed-accuracy trade-off, first formally described by Fitts (1954), which demonstrates that faster movements are typically associated with reduced accuracy, while more accurate movements require longer movement times. This relationship reflects the competing demands placed on the motor system when executing goal-directed movements, requiring the nervous system to balance the desire for rapid movement completion against the need for precise endpoint control.

The basal ganglia, which operate through three primary circuits (direct, indirect and hyper-direct), play a critical role in managing these competing demands between movement speed and accuracy (Mazzoni et al., 2007; Shadmehr & Krakauer, 2008). The direct pathway projects directly from the striatum to the globus pallidus (GPi) and substantia nigra pars reticulata (SNr), providing disinhibition of thalamic nuclei and facilitating voluntary movements. The indirect pathway, in contrast, projects through the external globus pallidus (GPe) and subthalamic nucleus (STN) before the projections reach the GPi and STN, which results in the inhibition of thalamic activity and suppression of unwanted movements. The hyper-direct pathway provides rapid excitation from the cortex directly to the STN, acting as a brake by enabling immediate inhibition of movement, allowing additional time for evidence accumulation and thus enhancing accuracy. Together, these pathways provide a neurobiological mechanism for balancing the trade-off between rapid action selection and precise response control (Bogacz & Gurney, 2007; Herz et al., 2017).

In PD, the depletion of dopamine disrupts the pathways by reducing the activity in the direct pathway and enhancing the indirect pathway transmission, therefore, the compromised basal ganglia circuits become less capable of effectively managing the speed-accuracy trade-off, often resulting in movements that are both slower and less accurate than those of healthy individuals (Desmurget & Turner, 2010). This disruption also contributes to the characteristic motor signs of bradykinesia, rigidity and difficulty initiating movement as well as difficulties in adapting movement parameters to changing task demands (Albin et al., 1989; Wichmann & DeLong, 2006). When PwPD exhibit prolonged movement times without corresponding improvements in accuracy, this suggests that the slower movements represent genuine motor control deficits rather than strategic compensations. The need to trade even more speed for accuracy indicates that the underlying neural mechanisms responsible for optimizing movement parameters have become compromised, supporting the conceptualization of PD as a disorder of motor control optimization rather than simply movement slowing.

This theoretical framework has important implications for understanding freezing phenomena in PD. Situations that place high demands on the speed-accuracy trade-off system, such as navigating through narrow spaces or making precise movements under time pressure, may overwhelm the compromised basal ganglia circuits and contribute to the emergence of freezing episodes. The increased cognitive load of prioritizing accuracy over speed, potentially exceeding the available processing capacity and leading to movement breakdown or cessation. This vulnerability becomes evident during movement transitions, including gait initiation, turning corners, navigating through doorways, and other situations that require quick recalibration of movement parameters between different spatial or directional demands, all of which are common inducers of freezing in PD (Giladi & Niuebower, 2008; Nutt et al., 2011; Schaafsma et al., 2003).

**Freezing of Gait in Parkinson's Disease**

Approximately 50% of individuals with PD will experience FOG, which is characterized by trembling in place without motion, shuffling, hastening or akinesia (a complete lack of movement) during which time patients describe their feet as being glued to the floor (Giladi et al., 1997). Preceding a FOG episode, gait asymmetry or a decrease in step amplitude may be present along with a reduction of the length of consecutive footsteps, known as the sequence effect (Danoudis et al., 2012). Freezing episodes often last between a few seconds and ten seconds, although some episodes can be longer (Nutt et al., 2011; Giladi et al., 2001). Despite episodes usually being short, their unpredictability and recurrence contribute significantly to anxiety, falls and loss of mobility in PD (Macht et al., 2007).

Electromyography (EMG) studies have identified two primary muscle activation patterns associated with FOG in Parkinson's disease: a "trembling in place" subtype, characterized by rhythmic bursts of leg muscle activity at 2–6 Hz, and an "akinetic" subtype marked by minimal or absent muscle activation (Jacobs et al., 2009; Nutt et al., 2011; Okuma, 2006). These subtypes were formally distinguished in a seminal study by Jacobs and colleagues (2009), who examined PwPD using a platform translation paradigm designed to provoke protective stepping. In this protocol, participants stood on a movable force platform that suddenly translated backward, simulating a forward loss of balance. The expected motor response was a rapid, compensatory forward step. In people with FOG, however, this perturbation often elicited freezing episodes, particularly of the trembling subtype, characterized by repetitive anticipatory postural adjustments (APAs) without actual step execution. EMG recordings revealed rhythmic, low-frequency muscle bursts in the tibialis anterior and gastrocnemius muscles during these episodes, consistent with multiple failed motor planning attempts. In contrast, the akinetic subtype was marked by an absence of preparatory muscle activity, suggesting a complete block in motor output despite the intention to move.

Some individuals with PD will develop FOG earlier than others; risk factors for early-onset FOG include individuals who first present with left-sided motor signs, cognitive and sleep disturbances, poorer balance, early presence of falls, high daily dose of L-dopa, visual hallucinations, along with depression and anxiety (Banks et al., 2019; Ehgoetz Martens et al., 2018d; Forsaa et al., 2015; Herman et al., 2019; Ou et al., 2018; & Zhang et al., 2016). In addition to these risk factors, there are various situational and environmental scenarios that are known to elicit instances of FOG (Giladi et al., 2003).

**Factors that Influence Freezing of Gait**

Giladi et al. (2003) identified five subtypes of FOG: (i) hesitation and freezing were detected in patient-initiated walking. (ii) turn hesitation, when the patient's feet appeared stuck to the floor while turning; (iii) hesitation in tight quarters, when the patient passed through a narrow space; (iv) destination-hesitation, when FOG occurred as the patient approached a target, and (v) open-space hesitation, when the patient appeared to freeze while walking in an open space in the absence of a provoking stimulus. Environmental and cognitive factors such as dual tasking or feeling stressed produce FOG, as does being in complete darkness, which highlights the importance of sensory processing deficits in FOG (Ehgoetz Martens et al., 2013; Nutt & Bloem, 2011).

A survey of 130 PwPD found that 72% of respondents experienced FOG, and 46% experienced a daily episode (Rahman et al., 2008). FOG was assessed using the gait and falls questionnaire (GFQ), which includes questions about the frequency and severity of freezing, falling, and festination. Respondents also reported stimuli that induced and alleviated their FOG. The most common inducers reported were turning around and fatigue (58.5%), followed by confined spaces (53.1%), stressful situations such as approaching a crowd (53.1%), walking in a narrow corridor or between objects (49.2%), being in a crowd (49.2%), and going through doorways (43.8%). When assessed by PD stage (H&Y, self-reported), those with mild PD (H&Y stage 1 – 1.5) indicated turning, fatigue, confined spaces, and doorways as the most common inducers. Patients with moderate PD (H &Y stage 2 – 3) reported stressful situations, fatigue, turning, confined spaces and walking in narrow spaces as their most common inducers. Finally, in severe PD (H &Y stages 4 – 5), fatigue, walking in narrow spaces and turning were the most common inducers.

**Sensory Cues and Freezing of Gait**

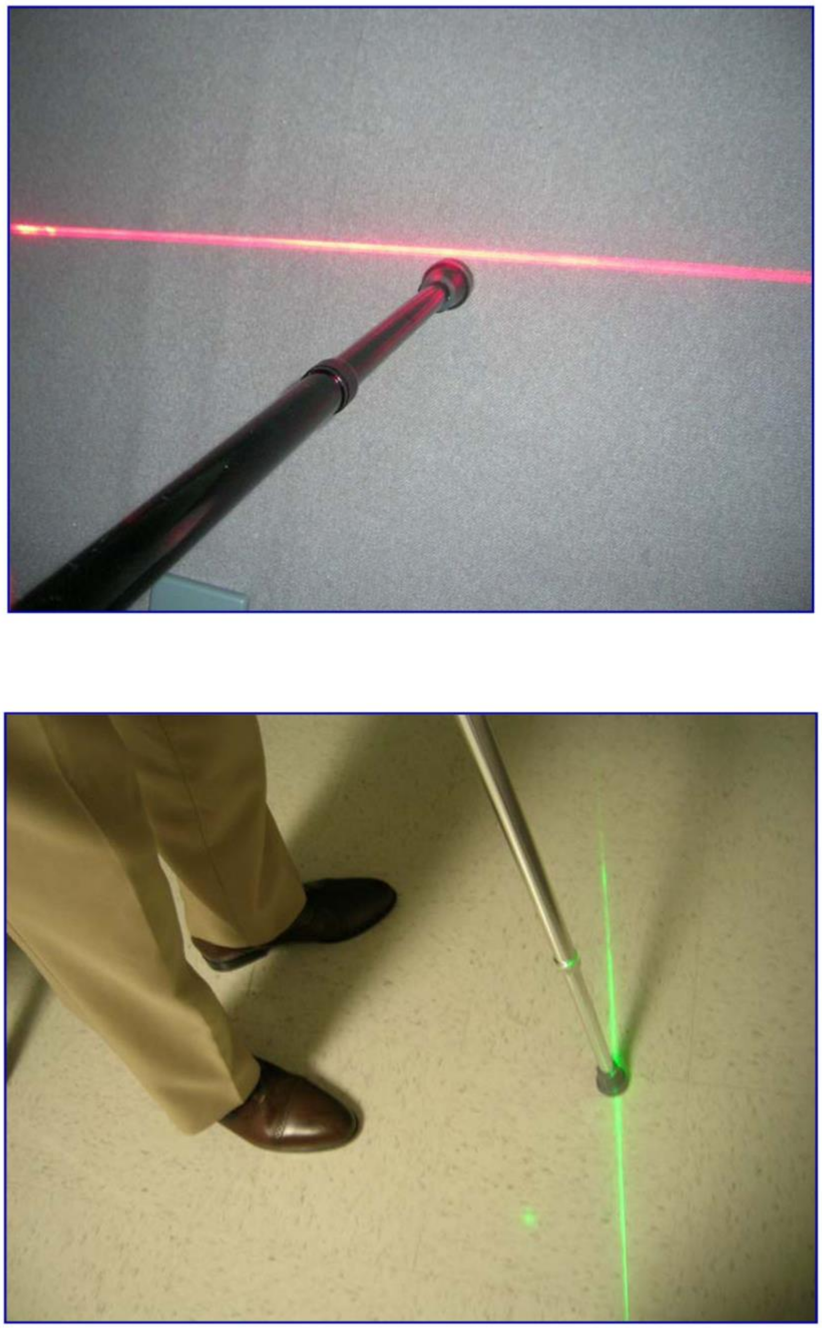
In FOG research, cues are defined as specific stimuli or reference markers designed to facilitate and enhance the execution of motor actions (Ginis et al., 2018). They are typically categorized into three main types: somatosensory, auditory and visual. Cues involved in alleviating FOG or increasing the threshold for its expression include auditory cues: metronomes and startling sounds (Zadeh et al., 2022) and visual cue-like patterns, lines or laser projections on the walking surface (Bryant et al., 2010; Cao et al., 2020; Gal et al., 2019).

There is a history of noting that patterns alleviate FOG. For example, in the 1990 movie Awakenings, based on the memoir of the same name by Oliver Sacks, a neurologist who documented his real-life experiences treating a group of patients with encephalitis lethargica at Beth Abraham Hospital in the 1960s, patterns were shown to play a crucial role in alleviating the patients' episodes of freezing, which, for most patients, was in an advanced stage where they spent most of their time frozen. Dr. Sayer (Sacks), observing the patients' difficulties, discovered that when visual patterns, such as floor tiles or lines, were present, the patients were able to initiate and sustain movement more easily. By stepping over lines or following a patterned path, patients were able to bypass the freezing. This depiction reflects real strategies used when freezing occurs in PD.

Bryant et al. (2010) used laser beams to determine their effectiveness in alleviating FOG in PwPD. Seven individuals (six males and one female) who indicated they experienced at least occasional freezing using the UPDRS completed the study. The Freezing of Gait Questionnaire (FOG-Q) assessed the severity of the participants' FOG. Participants' gait speed, cadence and stride length were measured while walking on an electronic walkway during ON and OFF-medication states using canes with red and green beams of light, not controlled for brightness, attached (Figure 2). There was also a 'no-light' condition. Researchers counted the number of freezing instances during straight walking and turning. In the OFF-state, participants' stride length was improved using the green light, but not in the red or no light conditions. The green light also resulted in fewer instances of freezing while walking on a straight path and turning compared to red or no light.

**Figure 2**

*Bryant et al. (2010) Laser Beam Stimuli*



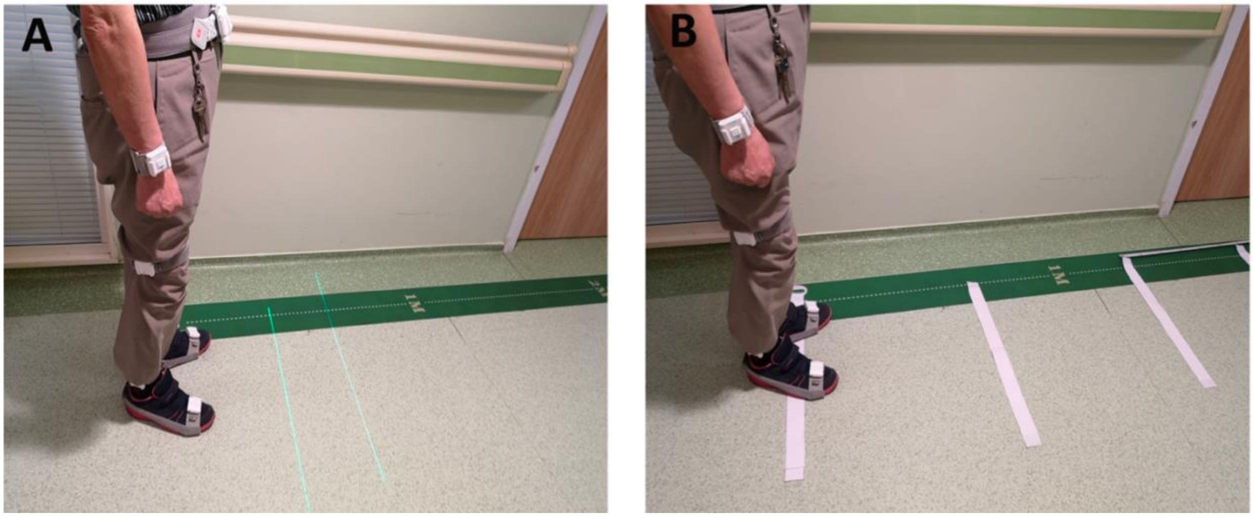
*Note:* Bryant et al. (2010) used green and red laser beams projected from a cane the participant used to determine the light's effect on FOG.

Cao et al. (2020) were also interested in how visual cues, such as laser beams, might assist with symptoms of FOG. Thirty-five individuals with PD (15 with FOG and 20 without) walked 10 m in their ON-medication state. They used inertial sensors to measure gait parameters such as step length and variability and the sequence effect under the following conditions: no visual cue, green laser lights projected on the floor in front of them, and transverse lines on the floor. Fixed to the participant's belt, the laser device was used to provide two parallel transverse laser lines in front of them (Figure 3A). Participants were guided to step over the laser line while walking at a comfortable pace. The transverse lines, which measured 60 cm long and 48 mm wide, were placed on the floor with a distance in between the strips of 40% of the patient's height, rounded to the nearest 5 cm (Figure 3B).

The authors found that both transverse lines on the floor and green lasers assisted with gait parameters such as step length and step length variability, but only transverse lines on the floor alleviated the sequence effect, concluding that visual cues presented on the floor might be effective as a strategy for overcoming FOG in PD.

**Figure 3**

*Cao et al. (2020) Visual Cues*

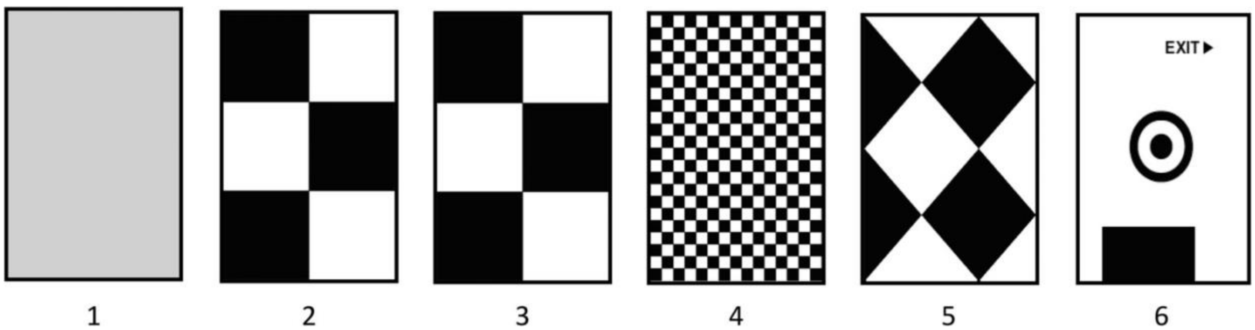



*Note:* Cao et al (2020) used laser beams and transverse lines taped to the floor to determine the cues' effect on FOG.

To explore the effectiveness of visual cues on FOG in PD, Gal et al. (2019) had 32 participants with PD and FOG walk on an eight-metre track under either single or dual-task conditions: no distraction or counting backward by three. Six different floor patterns (Figure 4) served as visual stimuli, designed to assess the influence of various cue characteristics on gait. These included a baseline 'no pattern' (grey carpet), a 'real' (foam floor tiles) 50x50 cm transverse regular black-and-white chessboard, and four virtual patterns projected onto the floor. The virtual patterns varied in size (50x50 cm and 5x5 cm), orientation (transverse and diagonal), and regularity (regular chessboard and irregular geometrical figures). A virtual 50x50 cm transverse regular black-and-white chessboard (Pattern 3) served as the reference pattern. The virtual reality setup utilized three digital light processing projectors controlled by a custom application to ensure consistent light conditions and seamless projection. The outcome measures selected were step length and gait speed.

**Figure 4**

*Gal et al. (2019) Flooring Patterns*




*Note:* 1: No pattern. 2: Real 50 x 50 cm chessboard. 3: Virtual 50 x 50 cm chessboard. 4: Virtual 5 x 5 cm chessboard. 5: Virtual 50 x 50 cm diagonal chessboard. 6: Irregular virtual pattern.

Visual cues improved gait parameters in PD by stabilizing step length, enhancing attentional focus, and shifting gait control from automatic to goal-directed processes. The researchers observed that compared to walking on no pattern, walking on large, transverse virtual floor patterns (pattern 3) significantly improved the participants' overall time, velocity, and step count. Step length was also significantly longer in this condition compared to no pattern or irregular patterns. Participants also showed improved time, step length and velocity when walking on regular patterns compared to irregular (pattern 6). Compared to walking on the real foam tiles, participants' time decreased, and velocity increased when walking in the virtual environment, which the authors surmised was due to its novelty.

**Vision in Parkinson's Disease**

Visual cues may alleviate FOG in PD by providing external spatial references that compensate for specific visual processing deficits commonly experienced by PwPD. Visual impairments are highly prevalent in this population; for example, Hamedani and Willis (2019) surveyed 854 PwPD and found that 82% reported some form of visual change or difficulty. The most frequently reported issues include altered colour vision, slowed eye movements affecting reading ability, and visuospatial dysfunction. While several types of visual stimuli have been shown to influence FOG, the precise nature of this relationship remains incompletely understood.

Evidence suggests that both retinal and cortical pathways are involved in the visual deficits associated with PD (Weil et al., 2016). Dopaminergic dysfunction contributes to impairments beginning at the retinal level, where reduced dopamine levels can affect colour discrimination, particularly along the blue-yellow (tritan), red-green (protan and deutan) axes. PwPD also show impairments in contrast sensitivity (the ability to discern brightness differences between foreground and background) and in spatial frequency sensitivity, which is the ability to perceive visual detail ranging from fine, high-frequency patterns (e.g., tightly spaced lines) to broad, low-frequency patterns (e.g., widely spaced lines). Spatial frequency processing is particularly important for motor control because it provides critical information about object boundaries, surface textures, and spatial relationships that guide movement planning and execution (Asher et al., 2019). Notably, deficits in spatial frequency sensitivity in PD span a range of frequencies (Bulens et al., 1986) and are believed to reflect cortical rather than retinal dysfunction. This is supported by the fact that cortical neurons exhibit greater selectivity for specific spatial frequencies compared to neurons in the retina or thalamus (Campbell & Robson, 1968; De Valois et al., 1982; Regan, 1982). Further evidence points to orientation-specific impairments in PD, with horizontal gratings being particularly affected (Regan & Maxner, 1987; Bulens et al., 1988; Trick et al., 1994). Given that neurons in the primary visual cortex (V1) are tuned to specific orientations (Hubel et al., 1978), these findings implicate V1 and associative areas as key sites of dysfunction rather than earlier visual processing areas.

**Cortical Links Between Vision and FOG**

The human visual system processes information through two primary cortical pathways: the dorsal and ventral streams. The dorsal stream originates in the occipital lobe and projects to the parietal lobe. This pathway is primarily responsible for processing spatial information, including object location, motion perception, and guiding actions in space (Goodale & Milner, 1992). It is crucial for visuomotor control, enabling individuals to interact with their environment by providing real-time spatial awareness and information about self-motion. In contrast, the ventral stream also begins in the occipital lobe but projects to the temporal lobe. This stream is specialized for object recognition, form perception, and identifying visual stimuli (Ungerleider & Haxby, 1994). It allows for the detailed analysis of visual features necessary for recognizing faces, objects, and scenes. While traditionally viewed as distinct, there is increasing evidence of significant interaction and integration between these two pathways, particularly in complex tasks requiring both spatial processing and object identification (Kravitz et al., 2011).

Research has increasingly demonstrated that the dorsal visual stream may be particularly vulnerable in PD, which could explain the relationship between visual processing deficits and motor control difficulties including FOG (Lord et al., 2012; Gan et al., 2022 2012; Weil et al., 2016). The dorsal stream receives substantial input from magnocellular pathways, which are characterized by their sensitivity to low spatial frequencies, high temporal frequencies, and motion detection, properties that make them particularly important for the visual guidance of movement and spatial navigation (Merigan & Maunsell, 1993). However, the dorsal stream also receives input from parvocellular pathways, which are more sensitive to high spatial frequencies and fine spatial detail. This combined input pattern suggests that dysfunction in the dorsal stream would be expected to affect visual processing across the entire spatial frequency spectrum.

The preferential vulnerability of the dorsal stream in FOG has been directly demonstrated by Lord et al. (2012), who conducted the first systematic investigation of visuo-perceptual and visuospatial function specifically in relation to freezing status in PD. Their study assessed visuospatial function using angle discrimination (tapping into dorsal stream function) and overlapping figure tests (ventral stream function), focusing on fixation durations and response times to evaluate the dorsal and ventral visual pathways. Their study revealed that PwPD and FOG showed preferential dysfunction of dorsal occipito-parietal pathways compared to those without FOG, and importantly, this relationship was independent of disease severity, attentional deficits, and basic contrast sensitivity measures. This finding provides compelling evidence that the visual processing deficits associated with FOG are not simply secondary consequences of general disease progression or motor dysfunction but rather reflect specific impairments in the neural systems responsible for visuomotor integration.

**Spatial Frequency Sensitivity in PD**

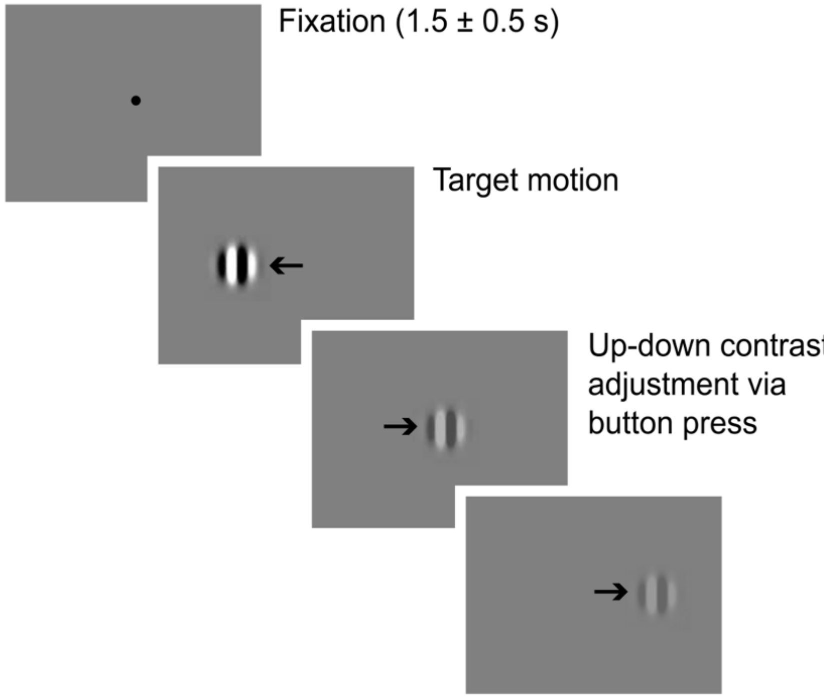
Spatial frequency sensitivity, the ability to perceive spatial information on a scale ranging from fine, high-frequency to broad, low-frequency, is also known to be impaired in PwPD (Davidsottir et al., 2005Ming et al., 2016). Given the evidence suggesting a visual component to FOG, particularly in response to lines and patterns, several research groups have explored the relationship between PwPD and spatial frequency sensitivity.

Ming et al. (2016) conducted a comprehensive investigation of visual contrast sensitivity across multiple spatial frequencies in individuals with early-stage PD, employing Gabor patches (sinusoidal gratings) at five distinct spatial frequencies (0.5, 1, 2, 4, and 8 cycles per degree) to systematically examine visual processing capabilities under both static and dynamic viewing conditions (Figure 5). Using a method of adjustment procedure, participants (13 PwPD and 12 age-matched controls) adjusted luminance contrast until stimuli were just barely visible, with simultaneous high-resolution eye movement recording. In static conditions, participants maintained fixation on stationary Gabor patches, while dynamic conditions required smooth pursuit tracking of stimuli moving at 10°/s or 30°/s. The authors found that PD participants demonstrated significantly elevated contrast sensitivity thresholds specifically at the intermediate frequency of 2 cycles per degree compared to healthy controls in static conditions while no significant differences emerged at other spatial frequencies, indicating selective rather than global visual processing impairment. The addition of motion eliminated group differences, with no significant differences between PwPD and controls for moving stimuli and both groups showing similar motion gains at low spatial frequencies and motion losses at high spatial frequencies.

The authors concluded that their findings support selective visual system vulnerabilities in PD rather than global dysfunction, proposing that spatiotemporal contrast sensitivity profiles may serve as easily measurable nonmotor biomarkers, with the preservation of motion processing capabilities despite static spatial frequency deficits highlighting different neural pathways for processing static versus dynamic visual information in PD.

**Figure 5**

*Experimental Stimuli, Ming et al. (2016)*




*Note:* Ming et al. (2015) used Gabor patches (static and dynamic) of varying spatial frequencies to examine the visual capabilities of PwPD.

Davidsdottir et al. (2005) investigated the interaction of visual and visuospatial impairments with motor symptoms in PD via a self-report questionnaire. Eighty-one participants reported visual and visuospatial difficulties in daily life, including double vision, depth perception challenges, FOG and hallucinations. Participants also answered questions about their compensatory strategies for managing visual and gait disturbances. Freezing of gait was assessed with the Freezing of Gait Questionnaire (FOG-Q). For 18 participants, the results of recent contrast sensitivity tests were available. Seventy-eight participants reported at least one visual or visuospatial problem, the most common being double vision (50%), spatial relation difficulties (39%), hallucinations (37%) and issues with depth perception (23%). FOG was commonly reported, with varying degrees of severity and frequency across participants. FOG severity correlated with spatial and visual deficits, particularly contrast sensitivity. Participants who reported freezing episodes also exhibited impaired sensitivity at the intermediate spatial frequency of 1.5 cpd, a relationship that was significant, and greater difficulty with spatial awareness tasks (e.g., depth perception).

The documented ability of specific spatial frequency patterns to both alleviate episodes of FOG (Bryant et al., 2010; Cao et al., 2020) and be associated with increased freezing severity (Davidsdottir et al. 2005) demonstrates that the visual system is directly involved in PD motor control. However, freezing has primarily been studied in gait, and we do not understand if and how FOUL is related to FOG, or whether spatial constraints, known inducers of FOG, would similarly affect FOUL. Understanding whether similar visual-spatial processing mechanisms underlie both FOG and FOUL could provide important insights into the generalizability of freezing mechanisms across different motor domains.

**Freezing of Upper Limbs (FOUL) in Parkinson's Disease**

Freezing of upper limbs in PD refers to a transient inability to initiate or continue voluntary movements of the arms, analogous to the more widely recognized phenomenon of FOG (Vercruysse et al., 2012). The concept of freezing in PD has been described almost exclusively in relation to gait disturbances, and much of the current PD research focuses on FOG, posture, or other balance problems, given their strong associations with fall risk and decreased quality of life (Nieuwboer & Giladi, 2013). This emphasis has limited broader exploration of whether freezing phenomena extend beyond gait-related activities, including tasks involving FOUL or other types of motor planning.

**Finger Tapping Tasks**

Ziv et al. (1999) investigated FOUL (referred to as manual motor blocks; MMB) using a finger tapping task. The authors defined FOUL as when the interval between two sequential touches on a key exceeds the mean intertap interval between touches by two or more SD. Thirty-nine PD patients and 17 age-matched controls completed this study. Sixteen of the individuals with PD were determined to experience FOG, of at least grade 2, defined as occasional motor blocks appearing suddenly during normal walking and/or start hesitation not requiring persistent walking aid (Achiron et al., 1993). The participant was seated comfortably with the forearm and hand resting on a table, positioned to face the test apparatus, and the index finger placed on the lateral key. Upon hearing the "start" signal, the individual was instructed to tap as rapidly as possible for a duration of 15 seconds. This procedure was repeated across five consecutive trials, each separated by a fixed 20-second interval. PD participants showed significantly more motor blocks, occurring in approximately 7.0% of tapping intervals, compared to 4.6% in controls. Motor blocks were significantly related to FOG, with FOG patients experiencing a 1.43-fold increase in motor blocking.

Barbe et al. (2014) sought to determine if patients with PD who exhibit freezing also had high movement variability in their upper limbs and if these changes were correlated to FOG. Eleven patients with and without verified FOG completed 16 finger taps (index finger on thumb) and 16 forearm diadochokinetic movements (alternating pronation and supination), both ON and OFF medication, with no cues or inducing triggers present during movements. Their gait was also assessed. Participants' upper limb movements were recorded using a motion-capture system, and to evaluate gait, patients walked across a six-metre-long gangway 16 times during both ON and OFF periods. FOUL episodes were defined as a reduction in movement amplitude by at least 50% compared to the average amplitude of the trial, lasting for a minimum duration of 0.5 seconds, and were detected in both freezers and non-freezers in both medication states. Verified freezers had shorter stride lengths and increased stride variability in the OFF state.

Delval et al. (2017) also used a finger-tapping task to assess FOUL. Fifteen participants with PD and FOG were instructed to tap their index finger as big and fast as possible on their thumb 30 times with and without a metronome (set to 4 Hz). Each hand was tested separately, and the trials were randomized. A foot task was also employed. The participants sat in a chair with both feet on the floor and were instructed to raise their foot as high as possible and stomp it with and without following a metronome set to 4 Hz. Each foot was tested separately, and the trials were randomized. In the hand task, three participants exhibited freezing in the absence of the metronome, and seven exhibited freezing while following the metronome. For the foot task, nine participants froze in the absence of the metronome, and eleven while following the metronome. Freezing in either effector (hand or foot) was not correlated with any measure of FOG in these participants.

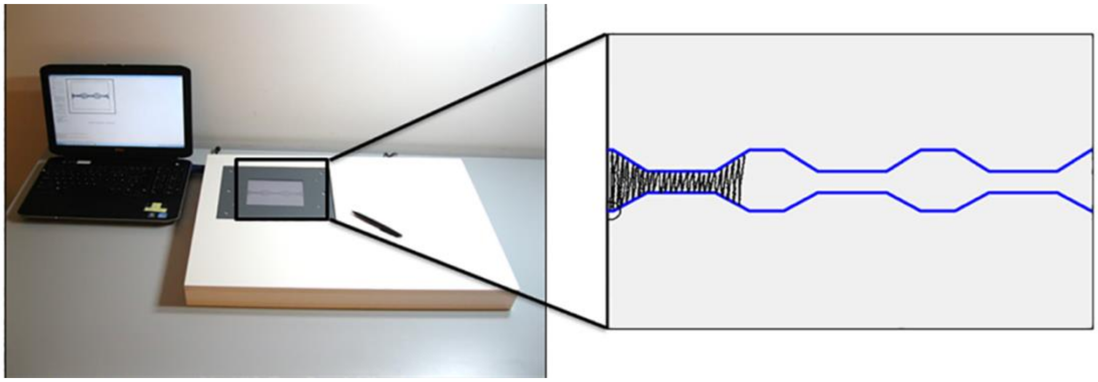
**Writing Tasks**

Nieubower et al. (2009) were interested in whether freezing-like episodes in upper limbs, defined as a period lasting more than 1 second during which one or both limbs showed no movement, preceded by a reduction in movement amplitude and/or an increase or irregularity in cycling frequency, occur during a bimanual rhythmic writing task and whether it is related to FOG severity. They also tested whether spatiotemporal and coordination measures differed in controls, freezers and non-freezers in different amplitude and speed conditions. Furthermore, they looked at the effect of visual cueing, displaying parallel target lines on a tablet, on spatiotemporal and coordination measures in the same subgroups. Twenty patients with PD (ten with FOG) in their OFF-medication state and five age-matched controls participated in the study. To elicit FOG in a laboratory setting, participants completed 20 gait trials during which they were required to turn in short and long trajectory conditions. Following the gait trials, participants performed a bimanual rhythmic writing task using a stylus in the left and right hands on a graphics tablet. Participants were instructed to perform alternating movements rhythmically at small (2cm) and large (4cm) amplitudes and their preferred and maximum speeds. FOUL occurred in seven freezers and one non-freezer and was significantly correlated to FOG scores. FOUL occurred bimanually and more often when the non-dominant hand had to do a more difficult task than the dominant hand. So, when there was an imbalance in task complexity, with one hand (especially the non-dominant one) doing something harder, participants were more likely to freeze. The effects of visual cueing came close to reaching the .05 threshold of statistical significance for reducing FOUL.

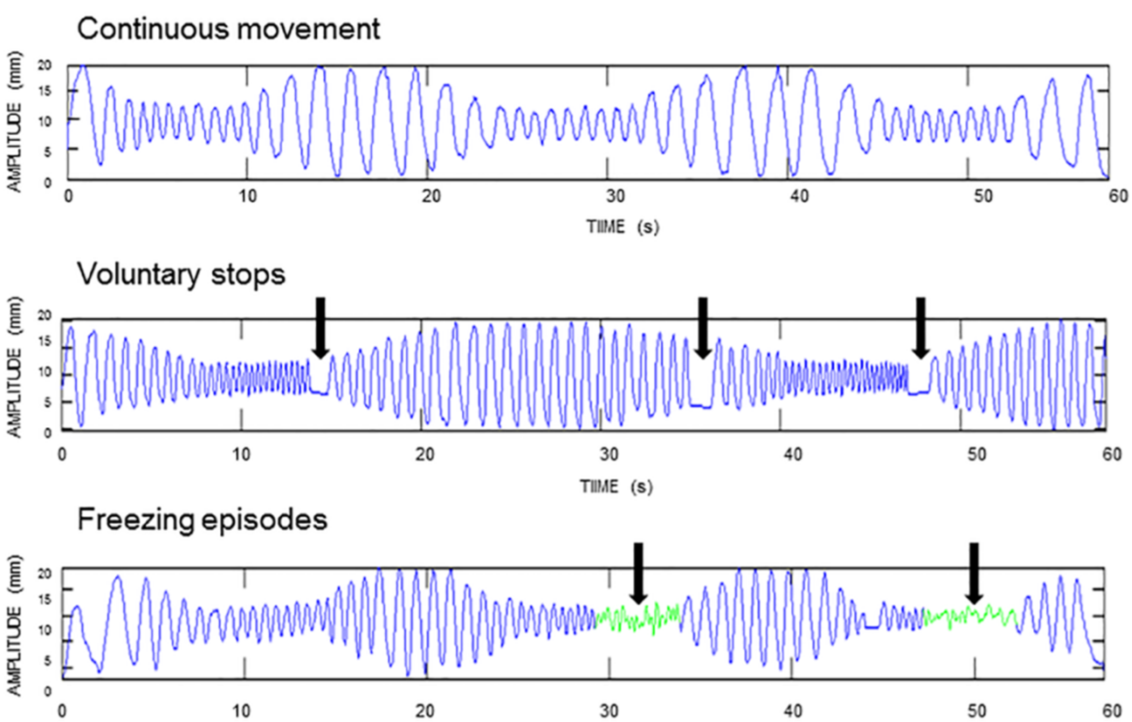
Heremans et al. (2015) investigated how FOUL affects writing amplitude in PD patients, particularly those experiencing FOG, using a novel "Funnel Task." The study involved 34 PD patients, 17 with FOG and 17 without, and 16 controls. The task required that the participants make rhythmic up and down motions with a pen, moving from left to right across a 13 cm long figure with alternating increasing amplitudes (2cm) and decreasing freezing was defined as an involuntary stop or apparent absence of effective writing movements for at least one second (Figure 6). The authors visually determined episodes as ineffective movement cycles immediately preceded by or characterized as decreased writing amplitude (<50% of the target amplitude), irregular cycling frequency, and/or increased freezing index. Ten participants with

PD experienced FOUL (eight with FOG and two without). Most of the episodes happened when participants transitioned to small or decreasing writing sizes. The occurrence and number of FOUL episodes were significantly related to the presence and severity of FOG. These findings suggest that difficulties in amplitude control contribute to upper limb freezing in PwPD, especially those with FOG. This parallels observations in FOG, indicating a common underlying problem in regulating movement amplitude in PD.

**Figure 6**



*The Funnel Task*




*Note:* The top panel depicts the task design, the bottom panel depicts what the authors considered continuous movements compared to voluntary stops and episodes of freezing.

## Objectives and Hypotheses

FOUL in PD has previously been investigated using tasks such as repetitive finger tapping (Ziv et al., 1999), writing (Nieuwboer et al., 2009), and pronation–supination movements (Vercruysse et al., 2012). Although these tasks demand reversals and have demonstrated freezing-like episodes analogous to FOG; they do not allow for easy examination of visuospatial factors affecting freezing nor have they tested other movement situations that invoke freezing, like corners and narrows.

The objective of the current study was to expand this line of research by testing whether FOUL could be elicited using visually-guided reaching tasks that mimic locomotor scenarios known to induce FOG. We developed a novel upper-limb reaching task that included three spatially-constrained conditions: reversal, corner, and tunnel trials, which parallel those known to elicit FOG in gait research. We hypothesized that these reaching conditions, particularly the transition points, would elicit freezing-like episodes in the upper limb like those observed during gait.

Given prior findings that PwPD, particularly those who freeze, exhibit impaired sensitivity to intermediate and higher spatial frequencies rather than lower (Davidsdottir et al., 2005), we also manipulated the visual backgrounds for our displays. Targets were presented on visual backgrounds with low and high spatial frequency patterns, as well as the control background. We hypothesized that, compared to the low-frequency background, the high-frequency background would produce the most significant incidence of freezing-like behaviour.

By analyzing the kinematic features of movement performance such as reaction time, movement time, velocity, distance covered, path curvature, and features of transition movements, we aimed to determine whether environmental and perceptual triggers of FOG also induce FOUL, supporting the conceptualization of freezing as a global motor control deficit in PD that is influenced by visual cues.

## Method

This study was approved by Trent University's Research Ethics Board (file # 28575) and all participants provided written informed consent (Appendices A & B) to participate before beginning any aspect of data collection.

### Participants

Control participants were included if they were within the same age range as PwPD and had no history of neurological or psychiatric disorders, no medications affecting visual perception, and normal or corrected-to-normal vision. All participants were excluded if they had cognitive impairment or psychiatric disorders that could affect task performance, uncorrectable visual impairment, or a history of stroke or other neurological conditions beyond PD for the PD group. People with PD were recruited in several ways: by making presentations to a community-based exercise program for PwPD, *On the Move!*, hosted by Dr. Liana Brown of Trent University, through presentations given to the Northumberland and Durham Parkinson disease support groups, email recruitment and using social media posts (Appendices C &D). Participants were compensated for with a $5 CAD Tim Horton's gift card for completing each part of the study (the Questionnaires and Motor tasks; $10 CAD total).

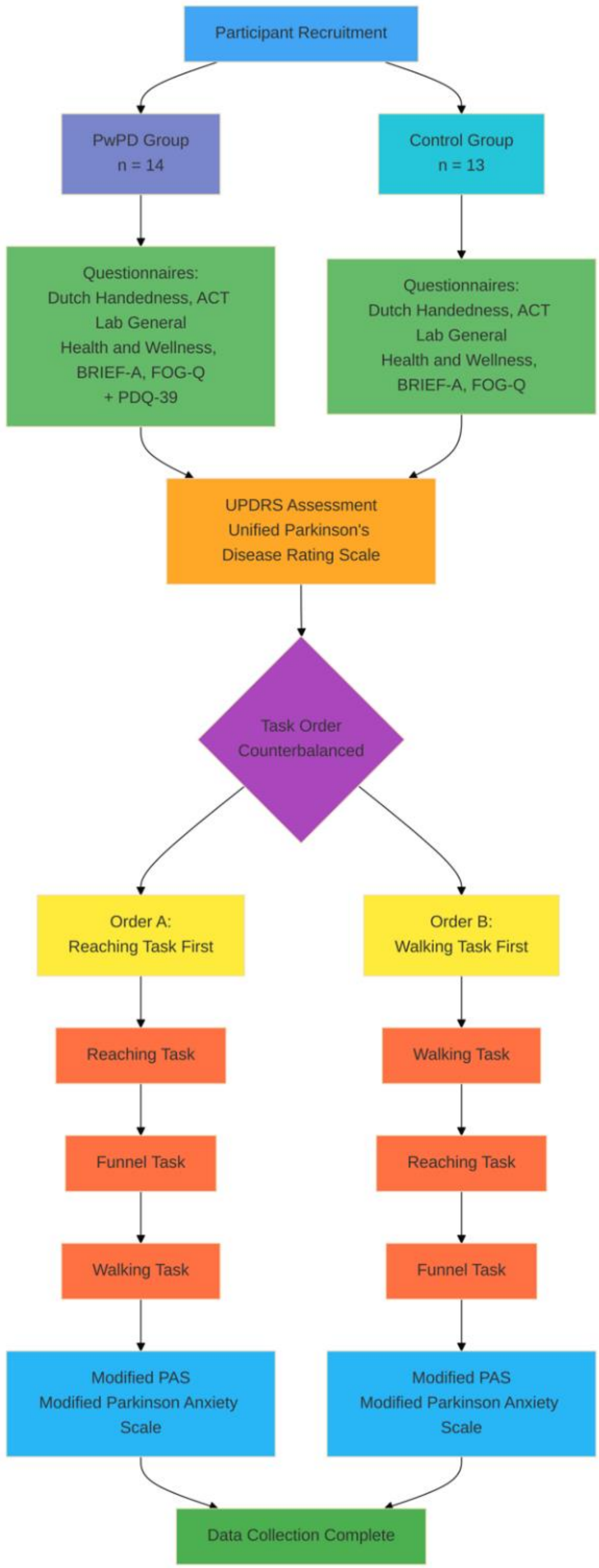
### Research Design

This study employed a 2 × 3 × 3 repeated measures design. The between-subjects factor was group, with two levels: PwPD and control participants. The within-subjects' factors were task (reversal, corner, tunnel) and background condition (control, low spatial frequency, and high spatial frequency). The reaching tasks included several kinematic dependent variables that captured temporal and spatial features of movement execution analogous to episodes of FOG.

**Materials and Tasks**

**Figure 7**

*Study Overview Flow Chart*



*Note:* Study overview flow chart. The chart depicts group membership, materials and order of tasks.

**Questionnaires**

Participants had the choice to complete the following questionnaires online through Qualtrics before attending their in-lab study session or in the lab upon their arrival. The questionnaires administered were (in order) as follows: The Dutch Handedness Questionnaire (Appendix E), The Action and Cognition Lab (ACT) General Health and Wellness Questionnaire (Appendix F), Behaviour Rating Inventory of Executive Function – Adult (BRIEF-F; Appendix G), Parkinson's Disease Questionnaire – 39 (PDQ-39; PwPD only; Appendix H), Freezing of Gait Questionnaire (FOG-Q; Appendix I) and finally, after the motor tasks, participants filled out a modified version of the Parkinson Anxiety Scale (M-PAS; Appendix J).

***The Dutch Handedness Questionnaire***

The Dutch Handedness Questionnaire (van Strien, 2003) is a self-assessment that consists of 16 hand preference items. Participants are asked to report the hand they use for a series of activities. Each item is coded from 0 to 2, with "left" receiving a score of 0, "right" receiving a score of 2, and "both" receiving a score of 1. Their handedness is scored as the total score, with strong right-handers classified as people with scores greater than 27 and strong left-handers having scores less than 5.

***The Action and Cognition (ACT) Lab General Health and Wellness Questionnaire***

The ACT Lab General Health and Wellness Questionnaire is a nine-section, self-assessment of demographic and general health and wellness information. Participants were asked to report their age, biological sex, current or past employment, and level of education, followed by ratings of the overall health, levels of activity, sleep habits, and perceived amount of social support before indicating any current or past illness or injury. The questionnaire asks them to report their current medications and medication schedule.

***Behaviour Rating Inventory of Executive Function – Adult (BRIEF-A)***

The BRIEF-A Self-Assessment (Roth, 2005) is a 75-item standardized measure that captures views of an adult's executive functions or self-regulation in their everyday lives. The 75 items fall within nine scales that measure the following aspects of executive functioning: Inhibit, Self-Monitor, Plan/Organize, Shift, Initiate, Task Monitor, Emotional Control, Working Memory, and Organization of Materials. The clinical scales form two broader indexes: Behavioural Regulation (BRI) and Metacognition (MI), and these indexes form the overall summary score, the Global Executive Composite (GEC). The BRIEF-A also includes three validity scales (Negativity, Inconsistency, and Infrequency). All 75 items are rated in terms of frequency on a 3-point scale: 0 (never), 1 (sometimes), 2 (often). Raw scores for each scale are summed, and T scores ($M$ = 50, $SD$ = 10) are used to interpret the individual’s level of executive functioning.

***Parkinson’s Disease Questionnaire – 39 (PDQ-39)***

The Parkinson’s Disease Questionnaire-39 (PDQ-39; Peto et al., 1995) is a 39-item self-report questionnaire assessing health-related quality of life for people with Parkinson's disease, evaluating difficulties across eight dimensions. Mobility**:** How easily a person can move around. Activities of Daily Living: How well a person can perform daily tasks like dressing, bathing, and eating. Emotional Well-being: How a person is feeling emotionally, including mood and anxiety. Stigma: How a person thinks about their condition and the social perception of it. Social Support: The level of support a person receives from family, friends, and others. Cognition: How well a person can think and process information. Communication: How well a person can communicate with others. Bodily Discomfort: The level of physical pain and discomfort a person experiences. Participants are asked to rate statements on a 5-point scale (0 = Never, 1 = Rarely, 2 = Sometimes, 3 = Often, 4 = Always). The PDQ-39 provides scores for each of the eight scales, as well as a summary score that reflects the overall quality of life. A higher score indicates a lower quality of life. The subscale scores standardized by taking the participant's actual score divided by the maximum possible score for the subscale and multiplied by 100.

***Modified Parkinson's Anxiety Scale (M-PAS)***

The Parkinson's Disease Anxiety Scale (PAS; Leentjens et al., 2014) is a 12-item self-report questionnaire developed to assess anxiety symptoms that are specifically relevant to individuals with PD. Unlike general anxiety inventories, the PAS was designed to capture a range of anxiety experiences common in PD, including both persistent and episodic symptoms, as well as avoidance behaviours that may not align with standard psychiatric classifications but interfere with daily functioning. Items are rated on a 5-point Likert scale from 0 ("not at all") to 4 ("severe") and are grouped into three subscales: persistent anxiety (e.g., general worry), episodic anxiety (e.g., acute anxiety or panic), and avoidance behaviour (e.g., withdrawal from social or functional activities). Higher scores indicate greater anxiety severity, and both subscale and total scores can be computed. The PAS has demonstrated strong internal consistency (Cronbach's $\alpha = .87$), good convergent validity with established anxiety and depression measures, and sensitivity to PD-specific anxiety profiles, making it a reliable tool for both clinical evaluation and research. We modified this questionnaire to tap into reaching-task related anxiety. Instead of the questions beginning with, "In the past four weeks, to what extent did you experience the following symptoms?" We asked participants, "During the reaching tasks, to what extent did you experience the following symptoms?" We changed the wording on ten questions and eliminated two questions, which were deemed not applicable to the reaching tasks. One related to excessive worrying about everyday matters and the other related to avoiding specific objects or situations (such as flying, blood, heights, spiders, or needles).

***Movement Disorder Society – Unified Parkinson Disease Rating Scale (MDS-UPDRS)***

Motor section (III) of the MDS-UPDRS is a performance-based rating scale that is widely used to assess the severity of motor symptoms in PD across a variety of domains through direct observation and physical examination. Part III consists of 33 items organized into 18 sub-scored motor tasks, each rated on a 5-point ordinal scale ranging from 0 (normal) to 4 (severe impairment). The domains assessed include speech, facial expression, rigidity (evaluated in neck and all four limbs), finger tapping, hand movements, and pronation-supination of hands (testing bradykinesia), toe tapping and leg agility, arising from a chair, posture, gait, postural stability, global bradykinesia, rest tremor amplitude and constancy, and action or postural tremor of the hands. The total motor score ranges from 0 to 132, with higher scores indicating greater motor impairment. The scale is sensitive to changes over time and is considered the gold standard for clinical trials and longitudinal studies in PD. All members of the research team are certified to administer and score this assessment. The MDS-UPDRS evaluation was conducted in a dedicated MDS-UPDRS testing room and videotaped using the video- and sound-recording features of a lab-dedicated iPhone (Apple Corporation, Cupertino, CA, USA). The videos were transferred to a folder in Trent University's OneDrive secure cloud storage service for storage and scoring. The use of the MDS-UPDRS for this study was approved by the International Parkinson and Movement Disorders Society (February 2024).

***Reaching Tasks***

Participants completed the reaching tasks while seated at a three-tiered table. This table was comprised of a clear glass surface on which the reaching would take place, a middle tier of one-way mirror that projected the brightness-controlled, screen contents of an 27" LCD monitor (68.6 cm diagonal; resolution: 1920 × 1080 pixels; aspect ratio 16:9; LG 27M41D-8, [LG Electronics, Yeongdeungpo-gu, Seoul, South Korea]) installed in the top tier of the table. The tiers were equally spaced, giving participants the impression that the display appeared at the same depth as the table on which their arm moved. The participants sat in a chair with armrests and an adjustable seat. The chair's distance and height was adjusted to ensure that participants could see and perform the reaching tasks comfortably on the table surface. The participant's view of the display was stabilized using a chin rest while viewing the projected images at a distance of 41cm (1 cm = a visual angle of 1.4°).

Visual stimuli were presented, and motion tracking data were collected using custom routines coded using MATLAB (Mathworks, Natick, MA, USA) with Psychophysics Toolbox 3.0 (Brainard, 1997; Pelli, 1997; Kleiner & Pelli, 2007) and ProkLiberty toolbox from prokopenko.org). Real-time kinematic data were collected at a rate of 100 Hz using a Polhemus Liberty motion tracking system (Polhemus, Colchester, VT, USA). One marker, attached to the fingertip of the participant's dominant hand using medical tape, was used to track reaching movements. All raw data files were saved and stored on a personal computer.

***Calibration***

Prior to running each participant, I calibrated the display to the motion-tracker position data. Participants were asked to move their fingertip to a set of target locations while their hand was fully visible. Data were collected for 1 second when the participant indicated that their fingertip was aligned with the target. Simple linear regression was used to model the relationship between tracker-provided finger position and display location, separately for horizontal (x) and depth (y) dimensions.

***Display and Visual Stimuli***

There were three reaching tasks, reversals, corners and a tunnel. A red start circle (50 pixels in diameter, 1.6cm) was displayed first. For the reversal task, a blue target circle of identical size appeared at a distance of 15 cm (centre to centre) further away in depth from the start position. For the corner task, the initial target remained in the same position, but there was a second blue target, of identical size, 15 cm to the left or the right of the initial target. The second target position was determined by participant handedness: right-handed participants reached to a second target on the right and vice versa. The tunnel task stimuli were identical to the reversal task, with the addition of an orange, rectangular tunnel 3.1 cm wide by 1.6 cm high positioned at 11.3 cm (centre to centre) from the red starting circle. The only visual information the participants had about the position of their hand was by way of a green cursor circle (20 pixels in diameter, 0.6 cm), which represented their fingertip, and was updated in real time using calibrated motion tracker data; they could not see their hand.

Target stimuli were presented against one of three background images: a stippled background (control), a low spatial frequency Gabor patch, or a high spatial frequency Gabor patch. A Gabor patch is a visual stimulus composed of a sinusoidal grating (alternating between black [RBG 0, 0, 0] and white [RBG 255, 255, 255]) confined within a Gaussian envelope, which causes the pattern to fade toward the edges gradually. This combination allows the stimulus to be spatially localized while preserving information about spatial frequency, orientation, and contrast. The Gabor patches used in the current study had spatial frequencies of .14 and .89 cycles per degree (cpd; Figure 8).

Gabor patches are widely used in vision research and psychophysics to probe the tuning properties of the visual system, as they closely resemble the stimulus preferences of simple cells in the primary visual cortex (V1) of non-human primates. Their controlled spatial and frequency characteristics make them ideal for studying perceptual processes such as contrast sensitivity, orientation discrimination, and spatial frequency perception (Campbell & Robson, 1968; De Valois & De Valois, 1990).

There were three reaching tasks, reversals, corners and a tunnel (Figure 9). The start circle was displayed first. For the reversal task, the target appeared at trial onset. For the corner task, the initial target was presented in the same position as for the reversal task, but there was a second target presented to the left or the right of the initial target. The second target position was determined by participant handedness: right-handed participants reached to a second target on the right and vice versa. The tunnel task target was identical to the reversal task, with the addition of an orange, rectangular tunnel positioned at 75% of the distance between the start and target.

**Figure 8**

*Display Backgrounds*

A B C

*Note:* Display backgrounds. A: Control, B: Low Frequency Gabor (.14cpd), C: High Frequency Gabor (.89cpd). Spatial frequency is commonly expressed in cycles per degree (cpd), which refers to the number of repeating pairs of dark and light bars (cycles) that fit within one degree of visual angle. This unit considers both the physical properties of the visual stimulus (such as the number of cycles per centimetre) and the viewer's distance from the screen, thereby standardizing spatial resolution in terms of how the eye perceives the pattern. Lower spatial frequencies appear as coarse, broad bands. They are typically associated with global shape and motion perception, while higher spatial frequencies represent finer detail and are essential for tasks requiring precision, such as reading or edge detection.

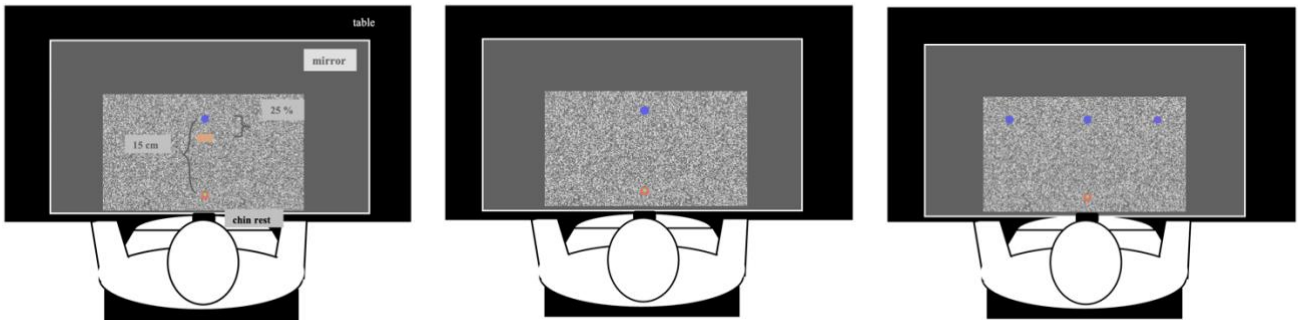
Other than the light from displays, the reaching tasks took place in a darkened room. The reaching study was organized using a 3-task (reversal, corner, tunnel) by 3-background (control, low frequency, high frequency) repeated measures design. The reaching tasks were presented in single blocks of 21 trials (63 trials in total) and their order was counterbalanced. Backgrounds were presented pseudorandomly such that an equal number of trials with each background was presented within each task block. The experimental trials were preceded by a 9-trial practice block in which the participant practiced the task they were scheduled to complete first. The participants were verbally instructed on how to complete each task. If needed, I provided haptic instruction by guiding their hand from the starting position to the target(s) before they began their practice reaches. Each experimental task began with all targets displayed indefinitely on the screen while I read the instructions. When I was satisfied the participant was ready to start, I pressed a key to initiate the experiment. Once the target appeared, participants had 4 seconds to complete the movement trial. The control background was presented for 2 seconds between each trial to wash out visual aftereffects from the background displays.

***Instructions***

The instruction for the reversal task were as follows: "The green dot represents you, where the tip of your finger is. The red circle is the starting position for each trial. On all subsequent trials, the blue target will appear after the red circle. Once you see the blue target, the goal is for you to move your finger as quickly as possible towards the blue target, and, without stopping, return your finger to the red circle. Are you ready?" When the participant replied "Yes," I pressed the space bar to begin the experiment. The instructions for the corner task differed in that the participants were told that two blue targets would appear after the red target, followed by, "Once you see the blue targets, the goal is for you to move your finger as quickly as possible towards the blue target straight ahead and turn the corner without stopping, finally coming to a complete stop in the middle of the second blue target. For the tunnel, the participants were advised that a blue target and orange tunnel would appear after the red target, followed by, "Once you see the blue target and orange tunnel, the goal is for you to move your finger as quickly as possible through the orange tunnel, towards the blue target straight ahead, coming to a complete stop in the middle of the blue target."

**Figure 9**

*Overhead View of the Reaching Tasks*




*Note:* From left to right, experimental set ups for the tunnel, reversal and corner tasks. The figure depicts the participant sitting at the reaching table, chin in rest. The only performance-based visual feedback during the tasks was provided by the green light cursor representing the tip of their finger.

***Funnel Task***

Following the reaching trials, while participants were still connected to the motion tracker, they moved to a desk adjacent to the reaching table to complete the Funnel Task (described previously) using a blue ballpoint pen. They completed three trials, each with a time limit of 30 seconds. The data for this task was not analyzed as part of this thesis.

***Walking***

Walking data were not analyzed as part of this thesis; however, the walking tasks will be briefly described here. The walking tasks featured scenarios analogous to the reaching tasks: a reversal (walking to a target and then returning to the start location), a corner (walking to a target straight ahead, and without stopping, turning the corner and walking to a second target) and walking through a doorway towards a target, analogous to the virtual reaching-tunnel. These tasks were completed on flooring with high and low spatial frequency patterns and a grey control flooring with a subtle control pattern. Walking tasks were completed in the walking lab and performance was captured using video and wireless accelerometers. The design mirrored the reaching design, as a 2 × 3 × 3 mixed factorial design. The between-subjects factor was group, with two levels: PwPD and control participants. The within-subjects' factors were task (reversal, corner, doorway) and flooring condition (grey, control, low spatial frequency, and high spatial frequency). More detail will be provided in a future study report.

**Procedure**

On the day of study, participants were greeted by me and a research assistant at the doors for Blocks C and D of the Life and Health Sciences Building. We walked a designated path through the faculty office hallway to the reaching lab. Here, the participant's consent was reviewed, their study start-time and time of last dose of medication was recorded, and a microphone was attached to their shirt collar to record their natural speech throughout the experiment. If the participant completed the questionnaires online at home, we then walked next door to the dedicated MDS-UPDRS testing room; this portion of the study took between seven and ten minutes. If the participant did not complete the questionnaires at home, they were completed in the lab. This task required 30 – 40 minutes of time before the MDS-UPDRS testing.

The reaching tasks, completed in a dedicated reaching room beside the MDS-UPDRS room, took 15 minutes and the Funnel Task an additional three to four minutes. From here, participants walked a dedicated path through the psychology office hallway to the elevator which took us to the second floor where the dedicated walking room was located. This portion of the study took approximately 20 minutes to complete, after which, we walked back to the elevator and returned to the reaching lab where the participant filled out the M-PAS through Qualtrics on a personal computer.

At the end of the experiment, I detached the microphone from the participant's collar and explained the rationale for the study, discussed the debriefing form (they were provided a hard copy) and answered any questions that arose. They were then accompanied by me and the research assistant to the parking lot and thanked for their participation.

## Statistical Analysis and Predictions

### *Data Processing and Preparation*

Reaching performance measures for the first reaching movement were extracted from recorded motion-tracking data files using a custom MATLAB script. Position data was filtered using a dual-pass Butterworth filter with a cutoff frequency of 8 Hz and differentiated to determine tangential velocity and acceleration over time.

### *Movement Identification*

To accurately distinguish intentional reaching movements from background noise and involuntary tremors, a dynamic velocity threshold was utilized. Although Parkinsonian resting tremors occur at a high frequency of 4–7 Hz, they typically produce minimal displacement, resulting in low movement speeds (Gironell et al., 2018). Our criterion required that once the velocity exceeded 3 cm/s, it remained above this threshold across multiple subsequent samples. This process involved continuous checks at several intervals to ensure the velocity did not drop below 3 cm/s, distinguishing voluntary reaching from tremor activity. If the velocity fell below this threshold again within those samples, the movement was not classified as a voluntary reach.

This approach ensured that only intentional movements were included in the analysis, thereby, minimizing the misclassification of tremor-related activity.

**Outlier Detection and Removal**

Prior to analysis, data were subjected to outlier detection using a conservative plus or minus three standard deviation criterion applied within each participant and experimental condition combination. For each subject-condition combination (3 tasks × 3 backgrounds = 9 conditions per participant), data points falling outside the range of condition-specific mean ± 3 standard deviations were flagged as potential outliers. This within-subject, within-condition approach preserved individual differences while removing aberrant data points that may reflect measurement error or attentional lapses. Following application of this procedure, no data points met the outlier criteria and were removed from the dataset.

**Dependent Variables**

***Primary Kinematic Measures***

Given that the tunnel task contains only one movement segment while the reversal and corner tasks contain two, dependent measures were extracted from the first movement segment, which was common to all three tasks.

Reaction time was defined as the interval (ms) between target onset and the initiation of limb movement, as determined from the motion tracker's velocity profile. Movement time is the duration from movement onset to the movement endpoint (ms). Peak velocity is the highest speed achieved during the movement (cm/s) and the percentage of time to peak velocity and percentage time after peak velocity represent normalized time accelerating and decelerating, respectively. Distance (cm) was calculated at the total distance travelled from start to end point of the movement. Mean speed (cm/s) was calculated as the average velocity between movement onset and endpoint, determined by dividing the linear distance traveled by movement time.

Signed curvature was defined as the largest perpendicular deviation from a straight line (in cm) connecting the start and end points of the movement segment, quantifying the extent to which the trajectory deviated from linearity.

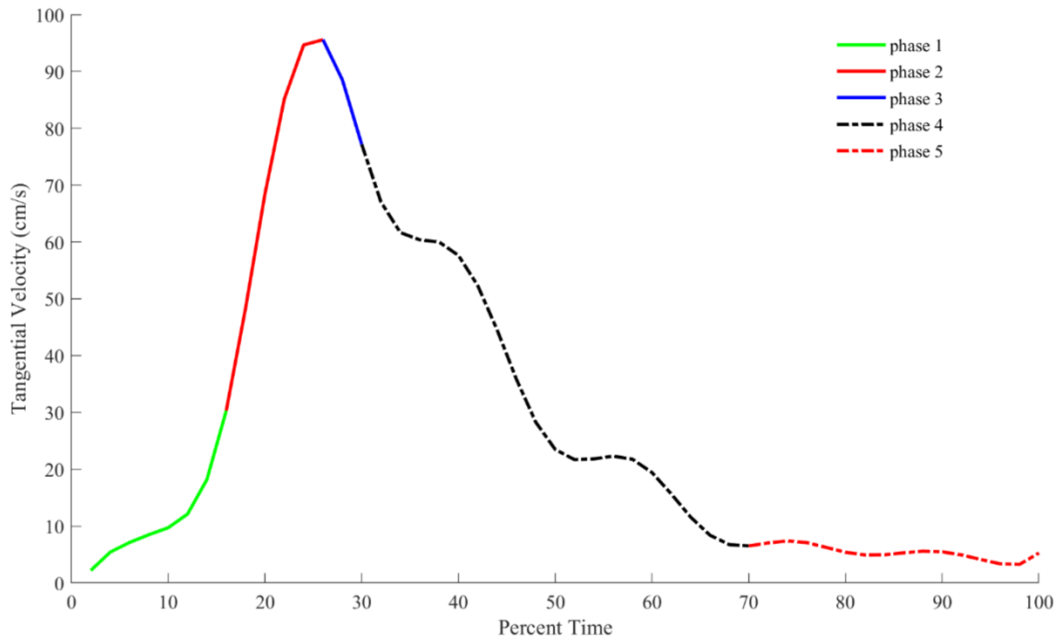
End-point accuracy was quantified by calculating the difference between the hand's final position and the target's center. This was assessed using three metrics. Signed horizontal error and depth error represented the constant error, calculated as the difference between the target and endpoint coordinates in the medial-lateral (horizontal) and anterior-posterior (sagittal) dimensions, respectively, which captured any directional bias in the movement. The overall magnitude of the endpoint error was measured as the resultant error, which is the straight-line Euclidean distance between the final hand position and the target (cm).

### ***Movement Phase Segmentation***

Movement trajectories were segmented into five distinct phases based on kinematic landmarks extracted from velocity and acceleration profiles (Figure 10). Phase one was from movement onset to peak acceleration, capturing initial motor output. Phase two was from peak acceleration to peak velocity, reflecting rapid speed build-up (not analyzed for this project). Phase three was from peak velocity to peak deceleration, representing onset of braking. Phase four was from peak deceleration to end of first movement segment, indicating final trajectory adjustments. Phase five encompassed any secondary movements made enroute to the target, including time spent dwelling on the target during reversals and corners before initiating the second movement. This phase captures the details of movement transitions, ensuring a comprehensive analysis of pauses and hesitations.

**Figure 10**

*Movement Phases as a Percentage of Total Movement Time*




*Note:* Discrete movement phases as a percentage of Total Movement Time. Phase 1: Movement onset to peak acceleration. Phase 2: Peak acceleration to peak velocity Phase 3: Peak velocity to peak deceleration. Phase 4: Peak deceleration to end of first movement segment. Phase 5: Secondary movements made enroute to the target. Including time spent dwelling on the target during reversals and corners before initiating the second movement.

## Predictions

Based on the established characteristics of FOG and the theoretical framework of freezing as a global motor control deficit, we made several specific predictions about how freezing-like phenomena would manifest in upper limb reaching tasks:

### ***Movement Initiation Deficits***

Analogous to start hesitation observed in FOG, we predicted that PwPD would demonstrate significantly longer reaction times compared to controls when initiating reaching movements, particularly in spatially constrained conditions. This initiation difficulty should be most pronounced in the tunnel condition, which most closely parallels the narrow doorway scenarios known to provoke FOG episodes.

### ***Movement Execution Impairments***

Similar to the reduced step amplitude and prolonged stride times characteristic of FOG, we predicted that PwPD would exhibit significantly longer movement times and slower peak velocities during reaching execution in comparison to controls. These temporal disruptions should occur without corresponding improvements in endpoint accuracy, indicating genuine motor control deficits rather than strategic speed-accuracy trade-offs.

### ***Movement Fragmentation***

Reflecting the trembling-in-place and akinetic subtypes observed in FOG, we predicted that PwPD would demonstrate altered movement phase characteristics in comparison to controls, including prolonged deceleration phases and increased dwelling time between movement segments. These temporal redistributions should indicate difficulties with movement sequencing and online motor control like the movement fragmentation observed during gait freezing episodes, including start hesitation during movement initiation, turn hesitation when changing directions, destination hesitation when approaching targets, and hesitation in tight spaces when navigating spatial constraints (Giladi et al., 2003). Of particular interest were group x phase interactions, as phase differences that occur equally in both groups would reflect normal movement segmentation patterns, whereas group x phase interactions would indicate PD-specific changes in movement timing and planning.

### *Transition-Related Difficulties*

Consistent with FOG occurring most frequently during transitions such as turning and direction changes, we predicted that tasks requiring these transitions, which requires sequential movement segments and directional transitions, would reveal specific deficits in inter-segment planning and execution, manifested as increased pause times between movement components. We expected group differences to be especially likely when examining measures that focused on transitions, such that differences between tasks would affect PwPD more than controls resulting in group x task interactions. These interactions would indicate that PwPD are disproportionately challenged by transition demands compared to controls, rather than reflecting general task difficulty that affects both groups equally.

### *Spatial Frequency Sensitivity*

Based on documented visual-spatial processing deficits in individuals with FOG, we predicted that high spatial frequency backgrounds would exacerbate movement difficulties in PwPD, producing longer movement times and increased kinematic variability compared to low spatial frequency conditions. We anticipated observing group x background interactions, such that the variation in background would affect the movements of PwPD more than controls.

### *Correlation with Freezing Severity*

Finally, we predicted that kinematic measures reflecting upper limb motor control difficulties would correlate significantly with established measures of gait freezing severity, supporting the conceptualization of freezing as a global motor control phenomenon that affects both locomotor and manipulative movement systems.

## Statistical Analysis Plan

Given our predictions above, we planned to look for group differences in all scenarios. For most of our analyses, we predicted that PwPD would perform worse than controls. For each dependent variable, a 2 (group: control, PwPD) × 3 (task: reversal, corner, tunnel) × 3 (background: control, low spatial frequency, high spatial frequency) mixed ANOVA was conducted. Group served as the between-subjects factor, while task and background served as within-subjects' factors. Significant main effects and interactions were followed up with simple main effects analysis comparisons using Bonferroni correction for multiple comparisons. Effect sizes were calculated using partial eta-squared ($\eta p^2$) for ANOVA effects and Cohen's *d* for pairwise comparisons.

### *Group Comparison Analyses*

Demographic and clinical characteristics were compared between groups using independent samples t-tests for continuous variables (age, education, UPDRS-III scores) and chi-square tests for categorical variables (sex distribution). BRIEF-A scale scores and M-PAS total scores were compared using independent samples t-tests.

### *Movement Phase Analyses*

For movement phase variables (percentage of distance covered and percentage of time spent), separate mixed ANOVAs were conducted for each task condition due to the different phase structures across tasks. These analyses used a 2 (group) × 3 (background) × 4 or 5 (phase) ANOVA, depending on the specific task requirements.

***Correlation and Regression Analyses***

Within the PwPD group, linear regression analyses were conducted to examine relationships between kinematic measures and freezing severity as measured by the FOG-Q total scores served as the dependent variable, with kinematic measures that revealed significant group differences (movement time, time spent decelerating and curvature) entered as predictors. A separate analysis was conducted for each predictor with the three background conditions all being entered together at step one.

All statistical analyses were performed using IBM SPSS version 28. For primary hypotheses related to group, task, background effects, scores on the BRIEF-A, general health rating and UPDRS-III comparisons, one-tailed significance tests were used ($\alpha = .05$) based on directional predictions derived from existing literature. For demographic comparisons and exploratory analyses, two-tailed tests were employed ($\alpha = .05$). Effect sizes were interpreted using Cohen's conventions (small: $d = 0.2$, $\eta p^2 = 0.01$; medium: $d = 0.5$, $\eta p^2 = 0.06$; large: $d = 0.8$, $\eta p^2 = 0.14$).

***Assumption Testing***

Prior to conducting parametric analyses, assumptions of normality, homogeneity of variance, and sphericity were evaluated. Normality was assessed using Shapiro-Wilk tests. Homogeneity of variance was evaluated using Levene's test. For repeated measures ANOVAs, sphericity was assessed using Mauchly's test, with Greenhouse-Geisser corrections applied when sphericity assumptions were violated.

## Results

The PwPD ($n$ = 14) and control ($n$ = 13) groups did not differ significantly in their age, handedness, or their level of education, with the majority of participants having earned a college diploma or undergraduate degree (Table 1). A chi-square test of independence was conducted to examine the relationship between group and sex (male vs. female). The association between group and sex was not statistically significant, indicating that the distribution of sex did not differ significantly between groups.

Despite significant differences on the Metacognition Index subscale of the BRIEF-A, indicating greater executive dysfunction in the PD group ($M$ = 61.00, $SD$ = 14.53) than in controls ($M$ = 52.15, $SD$ = 8.92), $t(21.81) = 1.92$, $p = .034$, $d = .072$, their global executive functioning (GEC) did not differ significantly between groups. Nevertheless, PwPD (Table 2) rated their overall health significantly worse than controls. The groups did not differ significantly in their reported levels of anxiety related to the day of study and reaching tasks as measured by the M-PAS (Table 3 for questionnaire and testing results). The MDS-UPDRS examination revealed that PwPD had significantly higher levels of motor impairment compared to controls, as expected. These results suggest that although PwPD experience objectively greater motor impairment and disease severity, and perceive their general health more negatively, they do not report significantly greater overall executive dysfunction or situational anxiety related to the testing environment when compared to controls.

**Table 1**

*Demographic Characteristics of Sample*

| Variable | Controls (*n* = 13) Mean (SD) | PwPD (*n* = 14) Mean (SD) | Test Statistic | *p* | Effect Size |
|---|---|---|---|---|---|
| Age (years) | 68.54 (8.38) | 70.14 (7.91) | $t(25) = 0.51$ | .613 | $d = .20$ |
| Sex (#M/#F) | 7/6 | 8/6 | $\chi^2(1) = 0.33$ | .568 | $\varphi = .11$ |
| Years of Education | 6 (1) | 5 (1) | $t(25) = -1.19$ | .248 | $d = -.45$ |
| Handedness Score | 29 (6) | 30 (2) | t(25) = -.983 | .335 | $d = -.38$ |

*Note:* Demographic information for the sample. Both samples were strongly right-handed (scores approaching the maximum of 32). One control participant was left-handed.

**Table 2**

*Characteristics of the PwPD Sample (n = 14)*

| Participant # | Sex | Number of Years with PD | First Symptom Location | Levodopa/ Carbidopa | Deep Brain Stimulation | FOG-Q Total Score | MDS-UPDRS | Hoehn & Yahr Scale |
|---|---|---|---|---|---|---|---|---|
| 1 | Male | 11 | Left/right legs (gait) | Yes | Yes | 1 | 45 | 2 |
| 2 | Male | 2 | Tremor Left | Yes | No | 6 | 34 | 2 |
| 4 | Male | 11 | Right hand | Yes | No | 6 | 41 | 2 |
| 5 | Male | 6 | Right hand | Yes | No | 1 | 79 | 3 |
| 6 | Male | 6 | Right arm | Yes | No | 19 | 25 | 2 |
| 7 | Male | 9 | Right hand | Yes | No | 6 | 44 | 3 |
| 8 | Female | 3 | Left foot | Yes | No | 14 | 28 | 2 |
| 9 | Female | 8 | Left hands | Yes | No | 7 | 29 | 2 |
| 11 | Female | 2 | Left | Yes | No | 8 | 21 | 2 |
| 16 | Female | 9 | No response | Yes | No | 3 | 49 | 4 |
| 17 | Female | 4 | Right hand | Yes | No | 0 | 1 | 1 |
| 19 | Male | 5 | Right hand and arm | Yes | No | 3 | 32 | 2 |
| 23 | Female | 11 | Left arm | Yes | No | 6 | 32 | 2 |
| 26 | Male | 8 | Right hand tremor | Yes | No | 14 | 44 | 2 |

*Note:* Table depicting the characteristic of our PD sample. First symptom location recorded as the participant reported. FOQ-Q scores can range from 0 -24, with higher scores indicating more severe (more frequent and distressing experiences with) FOG. We did not check for rigidity of the neck; therefore, the total score for the MDS-UPDRS Motor Section (Part III) ranges from 0 to 128. Each of the 32 items is rated on a 5-point scale (0-4), with 0 being normal and 4 indicating severe impairment. A higher total score signifies more severe motor impairment. The Hoehn and Yahr (H&Y) Scale is a clinical staging system for PD that describes the progression of motor symptoms, with stages ranging from 0 (no signs of disease) to 5 (wheelchair-bound or bedridden).

**Table 3**

*Questionnaire and Testing Results for Controls and PwPD*

| Variable | Controls (*n* = 13) Mean (SD) | PwPD (*n* = 14) Mean (SD) | Test Statistic | *p* | Effect Size |
|---|---|---|---|---|---|
| Health Rating (0-100) | 84.69 (8.83) | 71.50 (17.78) | *t*(25) = -2.41 | .012* | *d* = -0.93 |
| MDS-UPDRS UPDRS-III | 8 (9) | 36 (17) | *t*(25) = 5.05 | < .001* | *d* = 1.95 |
| BRIEF-A | | | | | |
| Inhibit | 52.00 (6.80) | 52.00 (5.10) | *t*(25) = 0.00 | .500 | *d* = 0.00 |
| Shift | 52.62 (8.71) | 53.93 (10.61) | *t*(25) = 0.35 | .365 | *d* = 0.13 |
| Emotional Control | 49.77 (9.52) | 51.50 (8.45) | *t*(25) = 0.50 | .311 | *d* = 0.19 |
| Self-Monitor | 47.31 (9.45) | 45.93 (11.31) | *t*(25) = -0.34 | .367 | *d* = -0.13 |
| BRI Total | 51.08 (9.19) | 51.93 (6.77) | *t*(25) = 0.28 | .393 | *d* = 0.10 |
| Initiate | 51.38 (13.71) | 58.57 (10.91) | *t*(25) = 1.51 | .071 | *d* = 0.58 |
| Working Memory | 54.38 (7.05) | 64.57 (15.75) | *t*(18.3) = 2.20 | .021* | *d* = 0.82 |
| Plan/Organize | 56.38 (12.86) | 61.14 (13.60) | *t*(25) = 0.93 | .180 | *d* = 0.36 |
| Task Monitor | 51.77 (7.05) | 58.36 (12.32) | *t*(20.96) = 1.72 | .050 | *d* = 0.65 |
| Organization of Materials | 48.15 (7.58) | 56.71 (17.80) | *t*(17.87) = 1.67 | .059 | *d* = 0.61 |
| MI Total | 52.15 (8.92) | 61.00 (14.53) | *t*(21.81) = 1.92 | .034* | *d* = 0.72 |
| Global Executive Composite (GEC) | 51.77 (7.80) | 57.64 (10.57) | *t*(25) = 1.63 | .058 | *d* = 0.63 |
| M-PAS Total | 0.92 (1.66) | 3.21 (5.70) | *t*(25) = 1.39 | .176 | *d* = 0.54 |

*Note:* BRIEF-A values are T scores, which have a mean of 50 and a standard deviation of 10; higher scores indicate greater levels of executive dysfunction. The BRIEF-A consists of two primary indices: the Behavioral Regulation Index (BRI) and the Metacognition Index (MI), each with several subscales. The BRI includes subscales such as Inhibit, Shift, and Emotional Control, assessing regulation of behavior and emotional responses. The MI comprises subscales like Initiate, Working Memory, Plan/Organize, and Task Monitor, focusing on managing tasks and cognitive processes. Together, these indices contribute to the Global Executive Composite (GEC), which provides an overall measure of executive functioning capabilities. M-PAS = Modified Parkinson Disease Anxiety Scale. Significance for all tests was determined by a one tailed test (a =.05).

To check the typicality of our PD sample, Pearson correlations were conducted to examine the relationships between motor symptom severity (MDS-UPDRS score), disease duration (years since diagnosis), and quality of life subdomains measured by the PDQ-39 (Table 4 for PDQ-39 means, standard deviations and z scores; all participants' z scores fell within one standard deviation of the norm). Higher MDS-UPDRS scores were significantly associated with higher scores on several PDQ-39 subscales, including mobility, $r(14) = .72$, $p = .004$, 95% CI = [.30, .90]; activities of daily living, $r(14) = .69$, $p = .007$, 95% CI = [.25, .89]; and communication, $r(14) = .63$, $p = .017$ 95% CI = [.14, .87]. Significant positive correlations also emerged between MDS-UPDRS and the PDQ-39 summary index (the average of subscales) $r(14) = .72$, $p = .004$, 95% CI = [.30, .90]. Years since diagnosis did not correlate significantly with any of the PDQ-39 subscales (*ps* > .05). These results suggest that greater motor symptom severity is associated with reduced quality of life across multiple functional domains, while disease duration alone may be a less reliable predictor.

**Table 4**

*PDQ-39 Subscales and Mean Dimension Scores by PwPD (n = 14)*

| Subscale | PwPD (*n* = 14)<br>*M* (*SD*) | *z*<br>*M* (*SD*) |
|---|---|---|
| Mobility | 21.43 (21.54) | -.76 (.76) |
| Activities of Daily Living | 27.08 (17.51) | -.61 (.73) |
| Emotional Wellbeing | 19.35 (10.29) | -.92 (.54) |
| Stigma | 7.59 (11.54) | -.90 (.50) |
| Social Support | 19.05 (22.04) | .41 (2.19) |
| Cognition | 22.54 (22.06) | -.48 (1.14) |
| Communication | 22.61 (19.73) | -.22 (.82) |
| Bodily Discomfort | 38.69 (21.34) | -.29 (.92) |
| PDQ-39 Summary Index (SI Score) | 22.29 (18.26) | -.65 (.56) |

*Note.* Each dimension is scored from 0 to 100, with lower scores reflecting better health-related quality of life. Dimension score = sum of scores of each item in the dimension divided by the maximum possible score of all the items in the dimension, multiplied by 100. Max dimension scores before transformation: Mobility (10 items) = 40; Activities of Daily Life (6 items) = 24; Emotional Wellbeing (6 items) = 24; Stigma (4 items) = 16; Social Support (3 items) = 12; Cognition (4 items) = 16; Communication (3 items) = 12, Body Discomfort (3 itmes) = 12. The PDQ-39 Summary Index (PDSI or PDQ-39 SI) is the average of the eight dimension subscale scores. Normative data: Hagell et al, 2007; *n* = 202, mean age = 69.8(10.0); PD duration = 8.7(6.6), H&Y Stage (median (Q1-Q3); min-max) = III(II-IV); I-V. Z scores were calculated by subtracting our sample mean from the population (norm) mean and dividing it by the population standard deviation; therefore a negative score reflects that our participants have better health-related quality of life compared to the population.

**Reaching Analyses**

***Reaction Time***

Reaction time measures the time needed to initiate the movement after target appearance. A one-tailed test revealed no significant main effect of group, $F(1, 25) = 1.977$, $p = .086$, partial $\eta^2 = .073$, indicating that overall reaction times did not significantly differ between PwPD and controls. There was no significant main effect of task on reaction time (two-tailed test), $F(2, 50) = 1.002$, $p = .374$, partial $\eta^2 = .039$. A one-tailed test revealed no significant main effect of background, F(2, 50) = 2.786, $p = .071$, partial $\eta^2 = .100$ was also not significant. No significant two or three-way interactions were observed, all one-tailed test *p*s >.05.

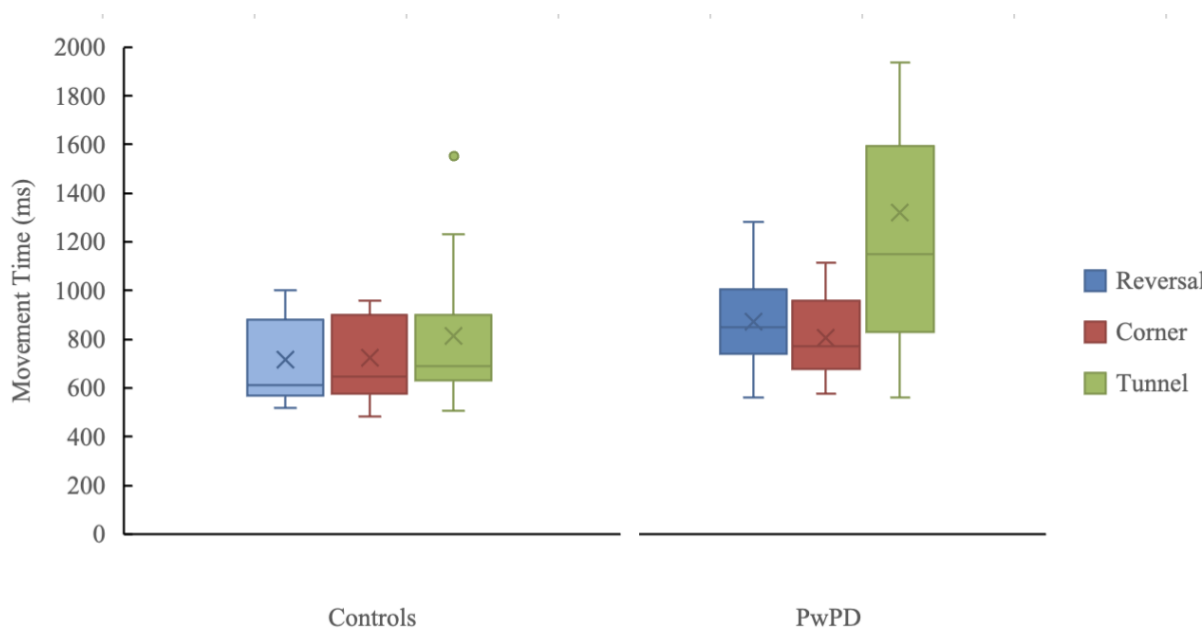
***Movement Time***

Movement time measures the duration of the reaching movement. A significant main effect of group was found using a one-tailed test, $F(1, 25) = 4.53$, $p = .022$, $\eta^2_p = .153$, with PwPD (*M* = 978 ms, *SD* = 270 ms, 95% CI [827,1129]) demonstrating significantly longer movement times than controls (M = 752 ms, *SD* = 274 ms, 95% CI [596, 909]). The main effect of task was also significant (two-tailed test), $F(2, 50) = 7.75$, $p = .001$, $\eta^2_p = .237$, indicating that movement time differed across tasks. Post hoc tests significantly longer movement times for the tunnel task (*M* = 1054 ms, *SD* = 593 ms, 95% CI [819, 1288]) compared to the corner task (*M* = 757 ms, *SD* = 172 ms, 95% CI [690, 824]), $p = .010$, and the reversal task (*M* = 785 ms, *SD* = 192 ms, 95% CI [710, 860]), $p = .010$. No difference was observed between the reversal and corner tasks, $p = .117$. A one-tailed test revealed a significant main effect of background, $F(2, 50) = 3.49$, $p = .038$, $\eta^2_p = .123$. Planned pairwise comparisons indicated that the high-frequency background (*M* = 875 ms, *SD* = 286 ms, 95% CI [762, 987]) resulted in significantly longer movement times than the control background (*M* = 852 ms, *SD* = 265 ms, 95% CI [747, 957]), *p*

= .017. A one-tailed test revealed a significant two-way interaction between task and group was observed, $F(1, 25) = 3.52$, $p = .018$, $\eta^2_p = .123$, indicating that the length of movement time differed between groups depending on task type (Figure 11). A simple main effects analysis revealed that in the tunnel task, PwPD ($M = 1292$ ms, $SD = 590$ ms, 95% CI [966.89, 1617.04]) exhibited significantly longer movement times than controls ($M = 815$ ms, $SD = 183$ ms, 95% CI [749.39, 958.22]), $p = .023$. No other interactions were observed (all one-tailed test *ps* > .05).

**Figure 11**

*Group x Task Interaction on Movement Time*




*Note:* PwPD exhibited significantly longer movement times in the tunnel task compared to controls, $p = .023$. No other significant interactions were observed. For all box plots, the central box represents the interquartile range (IQR), with edges at the 25th percentile (Q1) and 75th percentile (Q3). The horizontal line within the box marks the median, while the "x" indicates the mean. Whiskers extend to the most extreme data points within 1.5 times the IQR from the box edges. Points beyond the whiskers represent outliers, but this is not the definition that was used to formally identify outliers for analyses (i.e., we used the mean plus-or-minus 3 standard deviations as this definition).

***Distance***

Distance captures the total distance the participant moved during the reaching trial. A one-tailed test revealed that the main effect of group was non-significant, $F(1, 25) = 1.680$, $p = .104$, $\eta^2_p = .063$. There were no significant main effects of task (two-tailed test), $F(2, 50) = 1.451$, $p = .507$, $\eta^2_p = .027$, or background (one-tailed test), $F(2, 50) = 0.193$, $p = .825$, $\eta^2_p = .008$. There were no significant two-way or three-way interactions among task, background, and group (all one-tailed test *ps* > .05).

***Peak Velocity***

Peak velocity captures the highest velocity achieved during the movement. No significant main effects for group (one-tailed test) or task (two-tailed test), and no interactions among task, background, or group were significant (all one-tailed test *p*s > .15). There was a significant main effect of background (one-tailed test), $F(2, 50) = 4.511$, $p = .016$, partial $\eta^2 = .153$, indicating that peak velocity differed across background conditions. Planned pairwise comparisons revealed significantly higher peak velocity in the control background ($M = 40.28$ cm/s, $SD = 14.04$ cm/s, 95% CI [34.72, 45.83]) compared to the low-frequency background ($M = 39.07$ cm/s, $SD = 13.21$ cm/s, 95% CI [33.83, 44.30]), $p = .010$. Differences between control and high-frequency ($p = .065$), and between low- and high-frequency backgrounds, ($p = .337$), were not statistically significant.

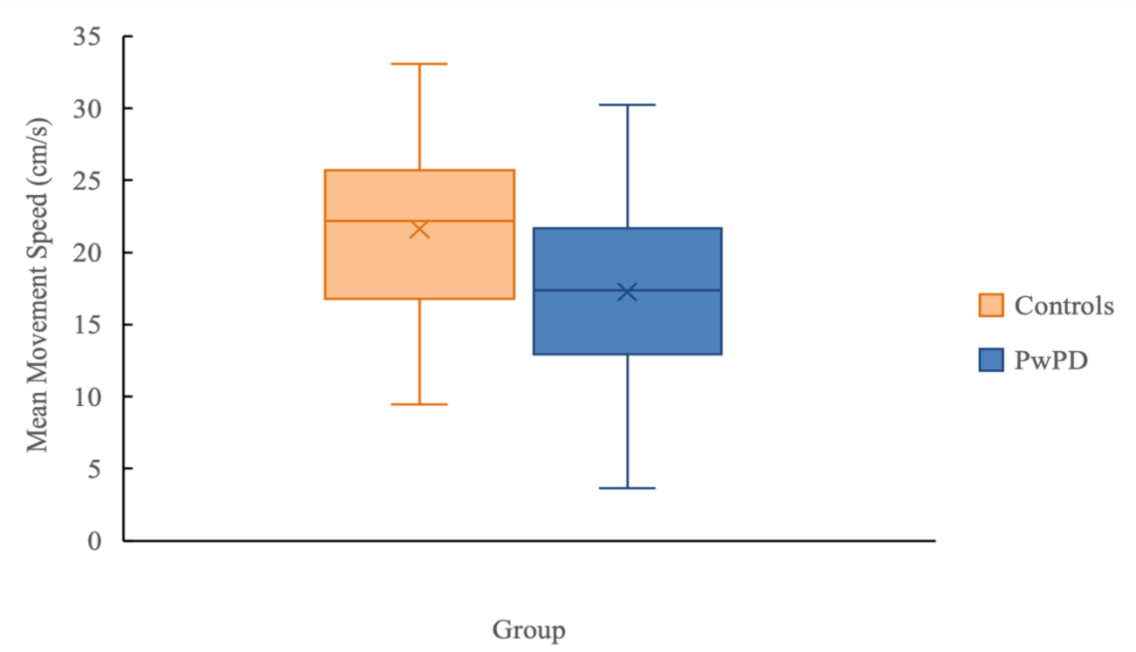
***Mean Movement Speed***

Mean movement speed captures the average of the participants' speed during their reaches. A one-tailed test revealed a significant main effect of group, $F(1, 25) = 4.18$, $p = .026$,

$\eta^2_p$ = .143. People with PD (*M* = 17.25 cm/s, *SD* = 5.54, 95% CI [18.45, 25.78]) moved significantly more slowly than controls (*M* = 21.62 cm/s, *SD* = 5.55 cm/s, 95% CI [14.20, 20.30]; Figure 12). A significant main effect of task was observed (two-tailed test), $F(2, 50) = 9.60$, $p < .001$, $\eta^2_p$ = .278, indicating that movement speed varied across task types (Figure 13). Pairwise comparisons revealed that participants moved significantly slower in the tunnel task (*M* = 17.72 cm/s, *SD* = 6.50 cm/s, 95% CI [15.15, 20.29), compared to the reversal (*M* = 20.29 cm/s, *SD* = 5.61 cm/s, 95% CI [18.06, 22.52], $p = .002$) and corner task (*M* = 20.29 cm/s, *SD* = 5.56 cm/s, 95% CI [18.08, 22.49], $p = .003$). A significant main effect of background was also found (one-tailed test), $F(2, 50) = 4.70$, $p = .007$, $\eta^2_p$ = .158 (Figure 14). Planned pairwise comparisons revealed that participants exhibited significantly faster movements in the control condition (*M* = 19.71cm/s, SD= 5.72 cm/s, 95% CI [17.45, 21.97]) compared to the low-frequency (*M* = 19.28 cm/s, SD = 5.72 cm/s, 95% CI [17.15, 21.42], $p = .009$) and high-frequency conditions (*M* = 19.31 cm/s, *SD* = 6.62 cm/s, 95% CI [17.08, 21.53] $p = .010$). No other interactions were significant, one-tailed tests *p*s >.05.

**Figure 12**

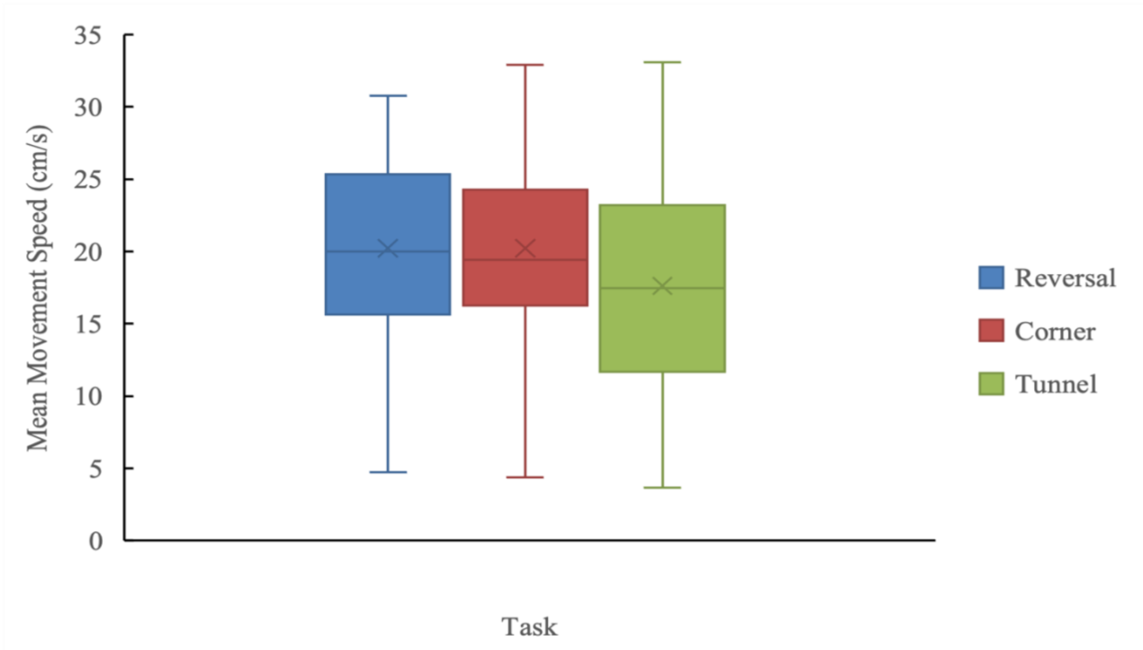
*Main Effect of Group on Mean Movement Speed*




*Note:*. PwPD demonstrated significantly slower speeds compared to controls, $p = .026$.

**Figure 13**

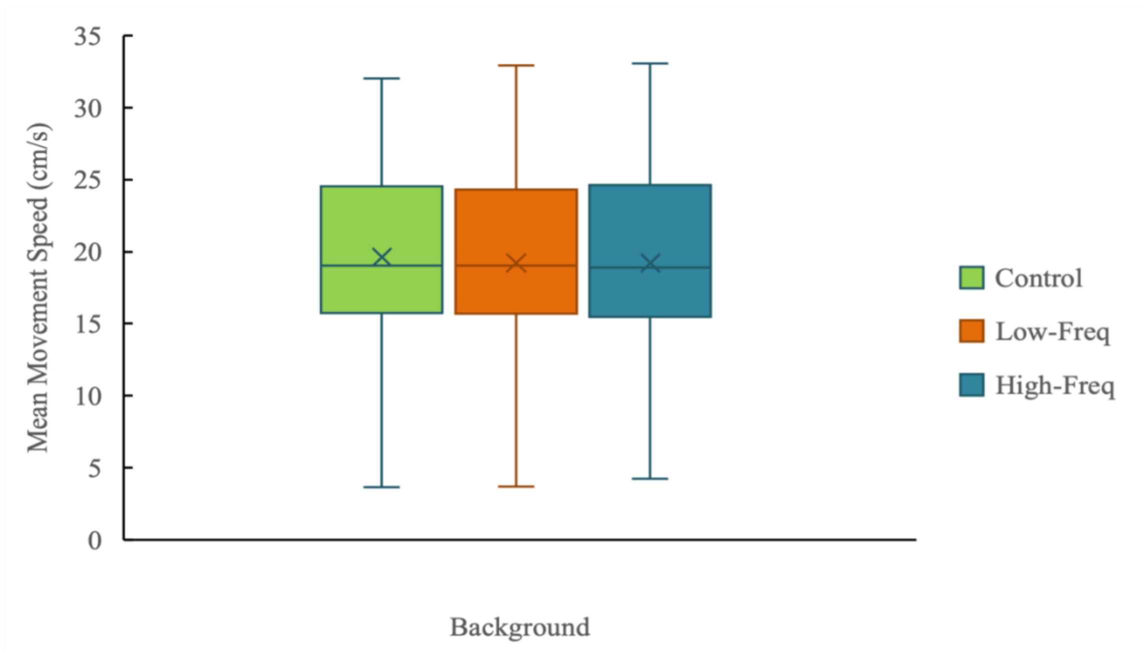
*Main Effect of Task on Mean Movement Speed*




*Note:* Mean speeds were significantly slower in the tunnel task compared to the reversal ($p$ = .002) and the corner ($p$ = .003) tasks.

**Figure 14**

*Main Effect of Background on Mean Movement Speed*




*Note:* Mean speeds were significantly faster in the control condition compared to the low-frequency ($p$ =.009) and high-frequency ($p$ = .010) conditions.

***Percent Time in Deceleration***

We also examined the percentage of total movement time participants spent in the deceleration phase (i.e., the time after peak velocity). One-tailed tests revealed no significant main effects of group, $F(1, 25) = 0.01$, $p = .456$, or background, $F(2, 50) = 0.19$, $p = .826$. There was a significant main effect of task (two-tailed test), $F(2, 50) = 11.94$, $p < .001$, $\eta^2_p = .323$, indicating that percent time in deceleration varied across task conditions. Pairwise comparisons revealed that the tunnel task ($M$ = 63.29%, $SD$ = 8.74%, 95% CI [59.84, 66.75] was associated with significantly longer time in deceleration than both the reversal ($M$ = 57.88%, $SD$ = 5.76%, 95% CI [44.35, 60.12] and corner ($M$ = 56.61%, $SD$= 8.16%, 95% CI [53.38, 59.84] tasks, $ps$ < .001. There was no significant difference between the reversal and corner tasks ($p$ = .308).

There was a significant task × background interaction (one-tailed test), $F(4, 100) = 2.72$, $p = .017$, $\eta^2_p = .098$. Planned follow-up comparisons showed that the tunnel task resulted in significantly longer percent time in deceleration under the control background (*M* = 64.59%, *SD* = 7.80%, 95% CI [61.51, 67.67) compared to both the reversal (*M* = 56.29%, *SD* = 7.28%, 95% CI = [53.35, 59.22]), and corner (*M* = 56.42%, *SD* = 9.41%, 95% CI = [52.69, 60.14]) tasks, $ps < .001$. Compared to the reversal (*M* = 58.44% , *SD* = 5.36%, 95% CI [56.33, 60.55]), and corner tasks (*M* = 56.65%, *SD* = 8.21%, 95% CI [53.39, 59.90]), the tunnel (*M* = 62.94%, *SD* =9.67% , 95% CI [59.10, 66.78]), also resulted in significantly longer percent time in deceleration under the low-frequency background, *ps* = .028 and .002 , respectively. The group × task, group × background, and group × task × background interactions were all nonsignificant (one-tailed test $p$s > .05).

### ***Peak Deceleration***

Peak deceleration is the maximum rate of velocity reduction. There were no significant main effects or interactions involving group or background, all one-tailed $p$s > .05. There was a significant main effect of task (two-tailed test), $F(2, 50) = 3.48$, $p = .038$, partial $\eta^2 = .122$. Estimated marginal means indicated that peak deceleration was highest in the tunnel task (*M* = –267 cm/s$^2$, *SD* = 203 cm/s$^2$, 95% CI = -348, 186], followed by reversal (*M* = –219 cm/s$^2$, *SD* = 135 cm/s$^2$, 95% CI [-272, -166]) and corner (*M* = –193 cm/s$^2$, *SD* = 125 cm/s$^2$, 95% CI [-242,-144]). Planned pairwise comparisons showed that the tunnel condition elicited significantly greater deceleration compared to both the reversal and corner tasks ($p < .05$).

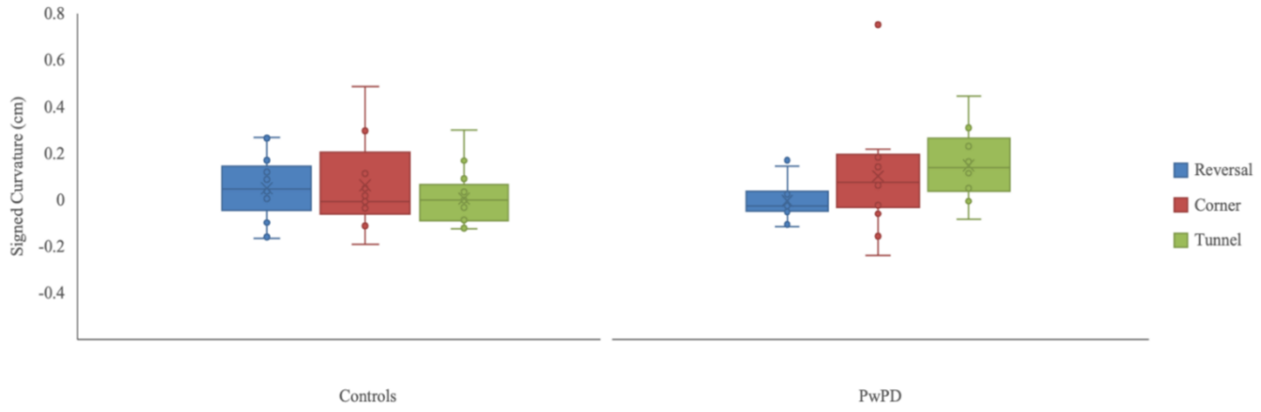
***Signed Curvature***

Signed curvature was the largest perpendicular deviation from a straight line connecting the start and end targets. The main effect of group was not significant (one-tailed test), $F(1, 25) = .278$, $p = .301$, $\eta p^2 = .011$. There were no significant main effects of task (two-tailed test), $F(2, 50) = 0.889$, $p = .417$, $\eta^2_p = .034$, or background (one-tailed test), $F(2, 50) = 0.216$, $p = .404$, $\eta^2_p = .009$.

However, a one-tailed test revealed a significant interaction between task and group, $F(2, 50) = 4.026$, $p = .012$, partial $\eta^2 = .139$, indicating that the effect of task on movement curvature differed between PwPD and control participants (Figure 15). In the control group, mean curvature was slightly right biased during the reversal task ($M = .07$ cm, $SD = .11$ cm, 95% CI [.02, .12]) compared to PwPD, whose reaches significantly deviated to the left of the trajectory ($M = –.17$ cm, $SD = .11$ cm, 95% CI [–.067, .03]), $p = .010$. The tunnel task also resulted in significant group differences, control participants exhibited little deviation from the path trajectory ($M = .01$ cm, $SD = 1.34$ cm, 95% CI [–.07, .08]) compared to PwPD, who deviated to the right of the path trajectory ($M = .13$ m, $SD = .15$ cm, 95% CI [.06, .21]), $p = .110$. No other comparisons were significant (one-tailed test *p*s >.05).

**Figure 15**

*Group x Task Interaction for Signed Curvature*




*Note:* Controls significantly differed from PwPD in the reversal task, *p* = .010 and reversal task, *p* = .110. Positive values are rightward biased movements; negative values are leftward biased movements.

A one-tailed test revealed a significant three-way interaction among task, background, and group, *F*(4, 25) = 3.116, *p* = .009, partial $\eta^2$ = .111. A simple main effects analysis revealed that in the tunnel task, under the low-frequency background, PwPD (*M* = .12, *SD* = .15, 95% CI [.04, .21] demonstrated a rightward bias, which was significantly different compared to control participants (*M* = -.02, *SD*= .14, 95% CI [–.11, .07]), who deviated very little from the path trajectory, *p* = .015. No other pairwise comparisons reached significance.

***Absolute Curvature***

Absolute curvature was the participants' maximum deviation from a straight line, irrespective of left or rightward bias. A follow-up analysis on participants' absolute curvature, a measure that eliminates the influence of left or right bias, revealed a significant main effect of background only (one-tailed test), *F*(2, 50) = 3.45, *p* = .040, $\eta^2_p$ = .121. The absolute curvature was lowest in the control background condition (*M* = .38 cm, *SD* = 1.14 cm, 95% CI [.33, .42]), higher in the low-frequency background (*M* = .38 cm, *SD* = .10 cm, 95% CI [ .34, 42]), and highest in the high-frequency background (*M* = .42 cm, *SD* = .16 cm, 95% CI [.36, .47]). Although there was a significant main effect, none of the pairwise comparisons reached statistical significance.

### *End Point Errors*

End point errors were the difference between the hand's final end point and the centre of the target. There were no main effects or interactions for any of the measures of end point error (in depth, along the horizontal axis, or the resultant of these two directions), all one and two-tailed test ps>.05.

## Movement Phases

### *Percentage of Distance Covered By Phase*

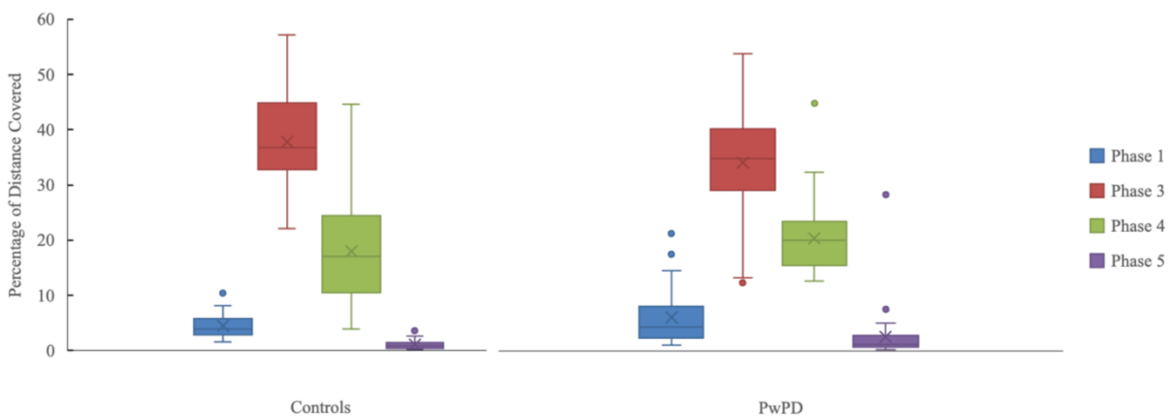
We know from past research that percentage of movement distance covered, and percentage of total reaching time varies with the phases we have defined in a systematic way, so we are expecting to find significant main effects of phase. This analysis was conducted to determine if percentage of distance covered is distributed differently over the phases for our groups, tasks, and backgrounds. For this reason, effects are only reported for distance and time if any of these factors interacts with phase.

### *Reversal*

A one-tailed test revealed that the group × phase interaction approached significance, $F(3, 25) = 2.107$, $p = .053$, $\eta^2_p = .518$, indicating that the pattern of percentage of distance across phases differed between groups (Figure 16). Simple main effects analysis revealed that compared to controls (*M* = 1.11% *SD* = 2.19%, 95% CI [-.147, 2.357], PwPD (*M* = 2.45%, *SD*= 2.19 %, 95% CI [1.24, 3.65], $p = .013$) covered a greater percentage of distance during phase five, but less in phase three (Controls: *M* = 37.82%, *SD* = 7.83%, 95% CI [33.34, 42.31], PwPD: *M* = 32.35%, *SD* = 7.85 %, 95% CI [28.03, 36.67]). No other interactions were approached significance.

**Figure 16**

*Group x Phase Interaction for Percentage of Distance Covered, Reversal*




*Note:* Compared to controls, PwPD covered less distance in phase three and more in phase five.

***Corner***

No interactions involving group, task or background and phase were observed, all one-tailed *ps* >.05.

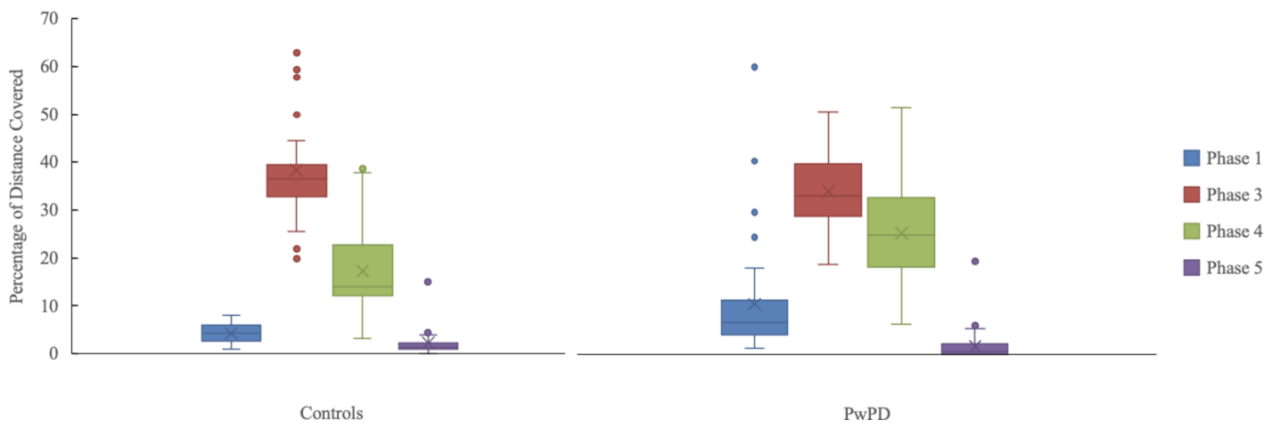
***Tunnel***

A one-tailed test revealed a significant phase x group interaction, $F(3, 25) = 4.315$ $p = .004$, partial $\eta^2 = .850$ (Figure 17). PwPD (*M* = 10.08%, *SD* = 7.89%, 95% CI [5.88, 14.28]) covered a significantly greater percentage of distance during phase one compared to controls (*M* = 4.23%, *SD* = 2.89%, 95% CI [-.129, 8.59]), $p = .029$ and phase four (PwPD, *M* = 24.24%, *SD* = 7.99%, 95% CI[ 19.84, 28.64]; controls, *M* = 17.23%, *SD* =8.00%, 95% CI [12.66, 21.79], *p* =

.016), but covered a significantly less percentage of distance in phase three (*M* = 32.61%, *SD* = 7.73%, 95% CI[28.35, 36.87]) compared to controls (*M* = 38.42%, *SD* = 7.75%, 95% CI[34.00, 42.84]) $p = .031$. No interaction was found between group and phase five.

**Figure 17**

*Group x Phase Interaction for Percentage of Distance Covered, Tunnel*




*Note:* Compared to controls, PwPD covered a significantly greater percentage of distance during phases one and four but covered a significantly less percentage of distance in phase three.

## Percentage of Total Reaching Time by Phase

### *Reversal*

No interactions involving group, task or background and phase were observed, all one-tailed test *p*s >.05.

### *Corner*

A one-tailed test revealed a significant background × phase interaction, $F(6, 150) = 3.091$, $p = .007$, $\eta^2 = .110$, indicating that the percentage of time spent in different movement phases varied depending on the background condition. Simple main effects analysis revealed that in phase one, the control background (*M* = 13.69%, *SD* = 3.28%, 95% CI [12.46, 14.93]) resulted in a significantly longer percentage time compared to the low-frequency (*M* = 12.16%, *SD* = 2.86%, 95% CI [11.07, 13.25], *p* = .028). In phase three, the low-frequency background resulted in significantly longer percentage times (*M* = 23.27%, *SD* = 5.98%, 95% CI [20.99, 25.54]) compared to the high-frequency (*M* = 19.81%, *SD* = 5.2%, 95% CI [17.83, 21.79]), *p* = .009. Finally, in phase five, the high-frequency background (*M* = 14.49%, *SD* = 4.06%, 95% CI [12.95,16.03]) resulted in significantly longer percentage time compared to the low-frequency (*M* = 12.47, *SD* =3.36, 95% CI [11.20, 13.75], *p* = .016).

***Tunnel***

No interactions involving group, task or background and phase were observed, all one-tailed test *p*s >.05.

***Predicting Severity of Freezing***

We designed this experiment with the goal of using a reaching task to reveal freezing behaviours. We have several measures of reaching that distinguish controls from PwPD, but we do not yet know whether they are related to freezing. We used a questionnaire, the FOG-Q, to both categorize freezers and non-freezers in our PD group, and to measure freezing severity. In this next analysis, we used regression analyses to determine whether variation in any of the reaching measures that significantly distinguished PwPD from controls (movement time, time spent in deceleration and signed curvature) can explain freezing severity.

The corner task was omitted from these analyses because when we observed interactions between group and task, the corner did not demonstrate group differences. Freezing severity was the dependent variable and movement time, time spent in deceleration and signed curvature were the predictors. We checked the ANOVA to see if the model was significant, and if it was, we examined the partial correlations to determine which variables were significant predictors. All background conditions were entered simultaneously as predictors in each model.

***Reversal Task***

The reversal task analyses revealed differential predictive validity across kinematic measures. Movement time emerged as a robust predictor of freezing severity. The overall regression model was statistically significant, $R^2 = .64$, $F(3, 10) = 5.90$, $p = .014$, such that the variation in movement time explained 64% of the variance in FOG-Q scores. Examination of the partial correlations for each predictor showed that the spatial frequency backgrounds demonstrated opposing predictive patterns. The low-frequency background served as a significant positive predictor, B = 0.044, SE = 0.015, 95% CI [0.010, 0.079], $\beta = 1.75$, $t(10) = 2.85$, $p = .017$, with a partial correlation of .67, indicating that longer movement times corresponded to greater freezing severity. Conversely, the high-frequency background functioned as a significant negative predictor, B = -0.036, SE = 0.013, 95% CI [-0.065, -0.007], $\beta = -1.43$, $t(10) = -2.77$, $p = .020$, with a partial correlation of -.66, suggesting that longer movement times in this condition were associated with reduced freezing severity; however, these results are likely due to the high correlations between predictors. The control background did not significantly predict FOG-Q scores, B = 0.006, SE = 0.011, $p = .634$.

Time spent in deceleration produced a model that was statistically significant, $F(3, 10) = 6.127$, $p = .012$, and explained 65% of the variance in FOG-Q scores ($R^2 = .648$, Adjusted $R^2 = .542$). However, none of the individual background conditions reached significance, *p*s >.05.

Curvature measures failed to demonstrate predictive utility, with the overall model showing no statistical significance, $R^2 = .18$, $F(3, 10) = 0.73$, $p = .558$.

***Tunnel Task***

To examine the predictive relationships between kinematic variables and freezing severity, separate multiple linear regression analyses were conducted for the tunnel task. For each task, three distinct models examined whether movement time, time spent in deceleration or curvature across background conditions (control, low-frequency, and high-frequency) predicted FOG-Q total scores in PwPD. All background conditions were entered simultaneously as predictors in each model.

The tunnel task analyses yielded different patterns compared to the reversal task. Both movement time and time spent decelerating in the tunnel task showed promising but non-significant trends. The movement time model approached statistical significance, $R^2 = .51$, $F(3, 10) = 3.50$, $p = .058$, explaining approximately 51% of FOG-Q score variance. Similarly, the time in deceleration model approached significance, $R^2 = .52$, $F(3, 10) = 3.54$, $p = .056$, accounting for approximately 52% of the variance in freezing severity. None of the individual predictors in either tunnel task model reached conventional significance levels.

Curvature measures again failed to predict freezing severity, with the overall model remaining non-significant, $R^2 = .37$, $F(3, 10) = 1.99$, $p = .179$, and no individual curvature predictors achieving significance.

## Discussion

The present study investigated whether freezing of upper limbs (FOUL) could be elicited using visually-guided reaching tasks that incorporated established triggers of freezing of gait (FOG), which is characterized by sudden, brief episodes of changes in step length and height or the inability to step, which people with Parkinson's disease (PwPD) describe as feeling like their feet are glued to the floor despite the intention to move (Gilaldi et al., 2003; Rahman et al., 2008).

Parkinson's disease (PD) affects both the magnitude (Blin et al., 1991) and temporal aspects (Hausdorff et al., 2003) of gait, while also disrupting how individuals process visual information (Davidsdottir et al., 2005). Freezing episodes commonly occur during specific environmental contexts that require transitions, including reversals, turning corners, and navigating through doorways (Rahman et al., 2008, Schaafsma et al., 2003). These contexts share the common requirement for movement transitions, changes in direction, shifts in motor programs, or adaptations to spatial constraints, that appear to be particularly challenging for the compromised motor control systems in PD.

While the mechanisms underlying freezing remain poorly understood, research has demonstrated that visual stimuli can both trigger and reduce freezing episodes (Cao et al., 2020; Rahman et al., 2008; Schaafsma et al., 2003). Transverse lines and laser beams positioned on walking surfaces can increase step length or assist in overcoming freezing episodes (Bryant et al., 2010; Cao et al., 2020) through a mechanism termed 'paradoxical kinesia' (Dietz et al., 2016). This is particularly noteworthy given evidence that PwPD show alterations in their capacity to process visual patterns (Davidsdottir et al., 2005; Ming et al., 2015). The relationship between visual processing and motor control is interesting given that PwPD exhibit documented deficits in visual-spatial frequency sensitivity, with impairments most pronounced in the intermediate and high-frequency ranges (Davidsdottir et al., 2005; Ming et al., 2016). These visual processing deficits may contribute to freezing episodes by compromising the integration of visual information needed for effective motor control.

Freezing has traditionally been conceptualized as a gait-specific phenomenon; however, emerging evidence suggests it may represent a more global motor control deficit. Freezing-like episodes have been observed in the upper limbs during finger tapping, rapid alternating movements, and writing tasks, suggesting that the underlying pathophysiology may extend beyond locomotor systems (Barbe et al., 2014; Heremans et al., 2015; Nieuwboer et al., 2009; Ziv et al., 1999).

Previous investigations of upper limb freezing have primarily used repetitive tasks that do not incorporate the specific environmental triggers, or visual processing demands known to influence FOG. Our study addressed these gaps by developing novel reaching paradigms that incorporated established FOG triggers, specifically directional reversals, corner navigation, and spatial constraints (tunnel condition) while manipulating visual-spatial frequency backgrounds to examine how visual processing demands influence motor performance.

The results demonstrate significant kinematic differences between PwPD and controls across multiple movement parameters, such as movement time, movement speed, movement phases and signed curvature. We observed particularly pronounced effects in spatially constrained conditions that parallel known FOG triggers and differential effects of spatial frequency backgrounds on the relationship between movement parameters and freezing severity. These findings provide important evidence supporting the conceptualization of freezing as a global motor control deficit in PD that extends beyond gait-specific dysfunction, while revealing how environmental context and visual processing demands interact to influence motor control in PD.

**Task Manipulation Effects on Reaching Performance**

Our primary hypothesis that spatially constrained reaching conditions would elicit freezing-like behaviours in the upper limb was supported by several converging findings. People with PD demonstrated significantly longer movement times across all task conditions compared to controls, with the most pronounced differences observed in the tunnel condition. This pattern was consistent across multiple kinematic measures. People with PD also showed slower movement speeds, with the tunnel task producing the slowest speeds for both groups, and extended deceleration phases, with the tunnel condition producing significantly longer percentage of time decelerating compared to reversal and corner tasks (all participants spending more movement time decelerating in tunnel vs. other conditions). These converging results align with established literature showing that spatial constraints are potent triggers for episodes of FOG (Almeida & Lebold, 2010; Cowie et al., 2010). The general slowing is consistent with bradykinesia, a cardinal feature of PD, but the disproportionate effect in spatially constrained conditions suggests additional mechanisms beyond simple motor slowing (Berardelli et al., 2001).

Movement phase analyses revealed complementary evidence of altered motor control organization in PwPD, with distinct patterns emerging across different task demands. In tasks requiring movement sequencing (reversal), PwPD showed evidence of planning and transition difficulties: they covered less distance during phase three but more distance during final adjustments (phase five), which captures hesitations before initiating subsequent movement segments. This finding is particularly relevant to FOG, as turn hesitation and destination hesitation are well-documented triggers for freezing episodes (Giladi et al., 2003; Rahman et al., 2008). The increased percentage of movement distance covered in this transitional phase suggests that PwPD have trouble with movement sequencing and inter-segment planning, consistent with theories of FOG that emphasize deficits in movement transitions (Nieuwboer & Giladi, 2013).

Interestingly, the corner task did not show the same pattern in phase five, despite also requiring a sequential movement segment. This difference may reflect the distinct motor planning demands of these tasks, in our study, the reversal required a complete directional change and movement to a new target location, while the corner task could be navigated using a continuous curved trajectory to reach the same general target area. The corner navigation may have been processed as a single (albeit curved) movement rather than two discrete movement segments, allowing participants to maintain momentum through the turn rather than pausing to plan a second movement.

In contrast, spatially constrained movements (tunnel) revealed altered proportional allocation of movement distance across phases in PwPD. People with PD allocated significantly more distance to the initial motor output phase, reflecting extended acceleration from movement onset to peak acceleration, possibly as a compensatory strategy for controlled motor output in constrained spaces where spatial constraints are known trigger factors for freezing episodes (Fietzek et al., 2017). Conversely, PwPD allocated significantly less distance to phase three, suggesting more efficient velocity-to-deceleration transitions; however, they also allocated significantly more distance to final trajectory adjustments (phase four), indicating enhanced precision demands for endpoint control. This redistribution pattern, extended initial acceleration and final adjustments with streamlined braking initiation, suggests PwPD reorganize movement execution to emphasize gradual motor output and precise trajectory control while avoiding abrupt velocity changes, consistent with compensatory strategies that help prevent freezing episodes in spatially constrained environments (Peterson et al., 2015; Tosserams et al., 2022).

Movement trajectory analyses provided additional evidence of genuine motor control difficulties rather than strategic compensations. People with PD showed altered trajectory patterns in both reversal and tunnel conditions, deviating significantly to the left in reversal tasks and showing a rightward bias in tunnel tasks under low-frequency backgrounds, while controls demonstrated minimal trajectory deviations. Importantly, these trajectory deviations occurred without corresponding increases in endpoint errors, confirming that PwPD were not trading speed for accuracy but rather experiencing genuine movement control difficulties. The altered distribution of movement distance and time across phases similarly occurred without any endpoint accuracy differences, indicating that PwPD were using a more feedback-dependent approach due to genuine motor planning deficits rather than strategic choices.

**Behavioural Implications: Path Constraints vs. Endpoint Constraints**

It is crucial to distinguish between endpoint constraints, which were identical across all tasks (same target location), and path constraints, which were unique to the tunnel condition. The fact that PwPD showed the most pronounced movement disruptions, including prolonged movement times, altered trajectories and increased percentage of distance covered in the initiation and deceleration phases in the tunnel task suggests that the presence of spatial boundaries along the movement path, even when those boundaries do not alter the final target location, is particularly challenging for the motor system in PD. This finding has important implications for understanding the mechanisms underlying both upper limb motor control and

FOG in PD. The motor system in PD appears to be not only sensitive to the spatial demands of the target endpoint, but also highly responsive to the spatial context of the entire movement trajectory.

This aligns with several established theoretical frameworks of FOG that provide specific explanations for how environmental context triggers freezing episodes. Nieuwboer and Giladi (2013) propose that freezing occurs when cognitive and motor demands exceed the processing capacity of compromised basal ganglia circuits, which normally function as a central executive coordinating spatial navigation, obstacle avoidance, and movement sequencing. The tunnel condition directly tests this framework by requiring simultaneous trajectory planning, continuous spatial monitoring, online corrections, and accurate target acquisition, demands that overwhelm compromised basal ganglia circuits and explain the overall prolonged movement times and altered movement patterns we observed in PwPD during spatially constrained conditions. Complementing this framework, cognitive-motor interference research (Yogev-Seligmann et al., 2008; Heremans et al., 2013) proposes that freezing results from competition between cognitive and motor processes for limited attentional resources, with spatial constraints creating cognitive demands that compete with motor control and force adoption of cautious, cognitively-controlled movement strategies, explaining the prolonged deceleration phases we observed. The doorway effect (Cowie et al., 2010) suggests that narrow spatial apertures disrupt spatial scaling processes in PD by requiring continuous spatial monitoring throughout movement rather than just endpoint accuracy, directly paralleling our finding that path constraints had greater impact than endpoint constraints and explaining the trajectory deviations observed in tunnel reaches. Collectively, these theoretical frameworks explain why the tunnel condition created a convergence of processing demands, motor planning overload, cognitive-motor interference, and compromised spatial scaling, that was most challenging for the compromised motor control systems in PD.

People with PD exhibit altered movement curvature during reaching tasks possibly due to multiple motor control impairments. Proprioceptive deficits compromise the brain's ability to accurately process limb position and movement feedback, resulting in degraded sensory information that interferes with precise movement planning and execution (Konczak et al., 2009). Additionally, PD disrupts predictive motor control mechanisms, including the brain's forward model that normally anticipates movement outcomes and enables proactive adjustments (Mazzoni et al., 2012). These sensory and predictive control deficits, combined with physical manifestations such as rigidity and abnormal muscle tone, collectively impair the motor system's capacity to generate smooth, accurate movement trajectories, resulting in the irregular hand paths and altered curvature patterns observed in our reaching tasks. The task-specific nature of these deviations suggests that different spatial constraints may engage different compensatory mechanisms, though this hypothesis requires further investigation with neuroimaging or electrophysiological methods (Stout et al., 2015).

**Neural Systems Implications**

The pattern of movement changes observed in spatially constrained conditions suggests that situations requiring precise spatial control may place particularly high demands on compromised basal ganglia circuits in PD. The increased proportion of movement distance allocated to phase one during tunnel reaches may reflect dysfunction in the basal ganglia's role in movement scaling and motor program selection. The basal ganglia, particularly the subthalamic nucleus and globus pallidus, are crucial for scaling movement amplitude and selecting appropriate motor programs based on environmental demands (Mink, 1996; Redgrave et al., 2010). When spatial constraints introduce additional complexity to movement planning, these already compromised circuits may fail to appropriately scale the initial acceleration phase, resulting in a redistribution where more movement distance is required to achieve adequate velocity within the constrained space. This altered distance allocation pattern may reflect the basal ganglia's impaired ability to optimize movement vigor and amplitude scaling in response to spatial environmental demands, manifesting as compensatory extension of the acceleration phase to ensure safe navigation through constrained pathways.

The differential effects observed between single-segment (tunnel) and multi-segment (reversal) tasks provide some evidence that PD may particularly affect transition and planning processes between movement segments. This is consistent with theories suggesting that the basal ganglia play a critical role in movement sequencing and the coordination of complex motor behaviours (Jin & Costa, 2015).

People with PD exhibit altered movement curvature during reaching tasks due to multiple motor control impairments. Proprioceptive deficits compromise the brain's ability to accurately process limb position and movement feedback, resulting in degraded sensory information that interferes with precise movement planning and execution (Konczak et al., 2009). Additionally, PD disrupts predictive motor control mechanisms, including the brain's forward model that normally anticipates movement outcomes and enables proactive adjustments (Contreras-Vidal & Buch, 2003). These sensory and predictive control deficits, combined with physical manifestations such as rigidity and abnormal muscle tone, collectively impair the motor system's capacity to generate smooth, accurate movement trajectories, resulting in the irregular hand paths and altered curvature patterns observed in reaching tasks.

**Visual Manipulation Effects on Reaching Performance**

Our hypothesis regarding the differential effects of spatial frequency backgrounds received mixed support, with findings suggesting that both spatial frequency conditions generally challenged movement control compared to the control background. Contrary to our expectations, both low-frequency and high-frequency backgrounds resulted in slower movement execution compared to the control condition, indicating that the presence of spatial frequency patterns, regardless of their specific characteristics, may disrupt normal movement control processes. This pattern was consistent across multiple kinematic measures: movement speed analyses revealed that both spatial frequency conditions resulted in significantly slower movements compared to the control background, movement time was significantly longer in the high-frequency condition compared to control, and peak velocity was significantly reduced in the low-frequency condition compared to control.

The most significant finding was that spatial frequency backgrounds differentially predicted freezing severity in the reversal task, with movement time serving as a robust predictor that explained 64% of the variance in FOG-Q scores. Specifically, longer movement times in the low-frequency background were significantly associated with higher freezing severity, while longer movement times in the high-frequency background were associated with lower freezing severity. However, given the high correlation between movement times across background conditions, this opposing pattern should be interpreted cautiously.

**Behavioural Implications: Visual Patterns as Movement Challenges**

The finding that both spatial frequency backgrounds generally slowed movement execution compared to the control condition suggests that the presence of visual patterns, regardless of their specific spatial frequency characteristics, may place additional demands on the visual-motor integration systems that are already compromised in PD. This pattern contrasts with the established literature on visual cueing for FOG, where external visual cues such as transverse lines, laser beams, and floor patterns typically help individuals with PD overcome FOG episodes and improve gait parameters (Bryant et al., 2010; Cao et al., 2020; Gal et al., 2019). The key difference may lie in the nature of the visual manipulation. While therapeutic visual cues provide discrete, actionable information that can guide movement (such as lines to step over), the spatial frequency backgrounds in our study may have created visual "noise" that interfered with normal movement processing. Both low and high spatial frequency patterns may have competed for visual processing resources, disrupting the smooth integration of visual information with motor commands. This concept parallels the doorway effect in FOG, where doorways function as both spatial constraints and visual boundaries that must be processed simultaneously. The visual perception of doorway frames may create additional processing demands that, when combined with spatial navigation requirements, contribute to freezing episodes by overwhelming already compromised visual-motor integration systems.

**Neural Systems Implications**

The finding that both spatial frequency backgrounds generally disrupted movement control may reflect the complex interactions between compromised basal ganglia function and visual processing deficits in PD. The basal ganglia, particularly the caudate nucleus and putamen, receive substantial input from visual cortical areas including the dorsal stream through cortico-striatal pathways (Kunimatsu et al., 2019). When both basal ganglia function and visual processing are compromised in PD, additional visual processing demands may create a "bottleneck" that further disrupts visually-guided movement control.

The dorsal visual stream, which is crucial for visual-motor integration and spatial processing (Goodale & Milner, 1992), shows documented dysfunction in PD (Lord et al., 2012).

The disruption we observed with both spatial frequency backgrounds may reflect compromised dorsal stream function, where any additional visual processing demands interfere with the already impaired visual-motor transformation processes (Mahon et al., 2013). This could explain why both low and high spatial frequency patterns challenged movement control, as the compromised dorsal stream may struggle to effectively filter and integrate visual information regardless of its specific characteristics.

**Strengths**

This study has several notable strengths. Our reaching paradigms allowed for systematic examination of visuospatial factors affecting motor control while testing movement situations that directly parallel established FOG triggers. The use of real-time kinematic analysis captured subtle changes in movement dynamics that would not be apparent through observational assessment alone as kinematic data offers a more precise and quantitative understanding of movement patterns. The integration of spatial frequency manipulations with reaching tasks represents a novel methodological approach that could be adapted for future research, for both FOG and FOUL, opening new pathways for exploring how visual processing influences motor control. Our movement phase analysis enabled examination of different aspects of motor control beyond movement time measures, allowing for a more comprehensive assessment of motor function by identifying specific areas of dysfunction. Finally, the kinematic abnormalities we observed occurred without corresponding increases in endpoint variability, indicating that PwPD were not trading speed for accuracy suggesting an inherent issue in coordinating movements for PwPD. This finding highlights a true difference in motor function between the control and PwPD groups.

**Limitations**

Our study's limitations include a relatively small sample size, which may affect the generalizability of our findings as well as the statistical conclusion validity. By examining only the initial movement of each task, we limited our ability to assess freezing patterns that may be attributed to movement sequencing deficits. Additionally, we did not specifically compare movement patterns between PwPD who experience clinical freezing episodes versus those who do not, which limits our ability to establish direct connections between the observed movement changes and actual freezing behaviour. Lastly, the cross-sectional nature of our study prevents us from concluding whether the observed kinematic abnormalities predict the development of clinical freezing episodes.

**Future Directions**

The findings of this study open several important avenues for future research. In the short term, the next step is to continue to analyse the current dataset to compare the movement patterns of PwPD who experience freezing (as identified by the FOG-Q) with those who do not, allowing us to test the hypothesis that the observed movement abnormalities are more pronounced in freezers. Additionally, we plan to conduct a detailed statistical analysis exploring correlations between our reaching findings and the walking and funnel task data that was collected as part of this project to provide a comprehensive view of motor control dynamics.

From there, a more in-depth analysis of the movement data is needed to identify specific instances of freezing within the trials. This could involve developing an algorithm to detect periods of akinesia or trembling in the movement data. Once freezing episodes have been identified, we can then compare the movement patterns of trials with and without freezing to better understand the motor control deficits that precede and accompany freezing events.

Collaborating with other researchers to validate these findings in larger, more diverse cohorts could strengthen the evidence base.

**Conclusions**

This study provides evidence that upper limb reaching tasks can elicit kinematic abnormalities in PwPD that share some characteristics with FOG episodes, particularly in conditions that parallel known FOG triggers. The findings suggest that upper limb motor control deficits in PD may reflect similar underlying pathophysiological mechanisms as FOG, though the extent of this relationship requires further investigation. The differential effects of task constraints on movement phases provide insights into the temporal organization of movement in PD, suggesting that both movement preparation and inter-segment planning may be affected. However, several important questions remain unanswered, including whether the observed kinematic changes represent precursors to clinical freezing episodes or distinct motor control phenomena. Future research with larger samples, more comprehensive movement sequencing paradigms, broader spatial frequency ranges, and longitudinal designs will be necessary to more definitively establish the relationship between upper limb motor control deficits and freezing phenomena in PD.

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Appendix A

Information and Consent Form – Motor Tasks

DEPARTMENT OF PSYCHOLOGY
**Liana E. Brown, PhD**
Associate Professor

Telephone (705) 748-1011 x7238
Fax (705) 748-1580
Email lianabrown@trentu.ca

**Letter of Information and Consent Form**

**Project Title:** Freezing in Parkinson's Disease
**Primary Investigator:** Jennifer Stevenson
**Graduate Supervisor:** Liana E. Brown, PhD

**Thank you for thinking about participating in our study.**

**0. Purpose:**
The purpose of this study is to learn more about what causes freezing – a problem that some people with Parkinson's get where they feel stuck in one spot. We also believe there is a visual component to freezing and we will be testing the idea that freezing will occur differently when you see different background information. We also believe that speech can be affected by freezing and will be recording your natural speech throughout the study.
.

**1. Participation inclusion/exclusion criteria:**
To participate in this study, you must be a person with Parkinson's Disease or a healthy, age-matched control participant who has not been diagnosed with any neurological issues. If you are a person with Parkinson's Disease, you are currently in your ON-medication state.

**2. Procedures to be followed:**

Upon arrival to the lab, a small recording device will be clipped to your collar to record your natural speech throughout the study. For this part of the study, you will complete the motor section of the Unified Parkinson Disease Rating Scale (UPDRS; if applicable). Our evaluation will include some in-person testing of walking and reaching in different conditions; your performance of these tests will be videotaped. The reaching testing will take place in the ACT Lab, LHS C110 and the walking testing will take place in LHS C111. We will attach markers to your hand and arm and ask you to reach for targets presented on a tabletop. The walking task will involve walking to targets that are shown on the floor, about 6 feet apart. We will record the speed and accuracy of your movements. There will be at least 2 research assistants ensuring that you understand what you need to do and that you do the task safely.

This testing will take about 60 minutes. Finally, you will be asked to complete a questionnaire related to feelings of anxiety related to the tasks and the study in general.

**3. Benefits**

There are no direct benefits to the participants of this study. However, the results of the study will help shed light on how freezing is elicited in other effectors (upper limbs) and how visual conditions impact freezing.

**4. How the data will be used:**

We declare that we have no potential conflicts of interest: we will not experience any specific personal or financial gain or loss from the results of this study. The researcher has no plan at this time to develop commercial venture from the findings of this research. The results of this study may be presented at a conference and then published as a report in a journal. The information will be used to make presentations to the Peterborough Parkinson Support Group and the Parkinson's Society.

**5. Voluntary participation:**

Your participation is entirely voluntary. You are free to stop participating in the study at any time or to decline answering specific questions or complete specific tasks. To withdraw from the study, you simply need to inform the investigator of your wish to withdraw.

You may stop the testing at any point. However, the data from the tasks that you have completed up until the point of withdrawal may be useful to us, and we may ask your permission to include it in our analyses. If you decline, we will automatically and immediately destroy your testing data.

**6. Statement of confidentiality:**

Your participation in this study is entirely confidential. Only Jennifer Stevenson and Liana Brown will have access to identifying information. To ensure participation is confidential, all data will be distinguished by a code number and stored on a computer that is encrypted and password protected. In the event that data from this evaluation is published, no personally identifying information will be disclosed.

**7. Discomfort and risks:**

By participating in this study, you will experience no more discomfort than you would normally experience during everyday tasks. If you wish to end the study, you may do so without penalty. Just let us know at any time if you would like to stop. We will stop the study immediately.

Completing the UPDRS (if applicable) may be upsetting because you may be reminded that the disease has affected your movement ability. These tests are not different from the assessments that you undergo biannually with your neurologist.

Before the reaching task, an experimenter will be applying markers to your body to track your movements. These markers will be attached with tape, and there is a chance you may experience discomfort when the markers are removed.

There is a risk that you might fall during the experiment as we will be testing your balance and asking you to complete a walking task.. There will always be two experimenters present during the motor tasks to reduce the likelihood of a fall occurring.

Answering the questions about anxiety may upset you as well, especially if you have experienced anxiety recently. If any aspect of our assessment is making you worry, we encourage you to contact your neurologist or family physician to ensure that they are informed of your concerns.

**8. Post-experiment feedback and right to ask questions:**

You will be given an opportunity to ask any questions you may have, and all such questions or inquiries will be answered to your satisfaction. After you have finished participating, you will given more opportunities to ask questions and we will gladly answer. If you would like to receive the study's findings and/or have questions in the future, contact Liana Brown at 705-748- 1011 x7238 or lianabrown@trentu.ca or Jennifer Stevenson, jenniferstevenson@trentu.ca.

**9. Compensation:**

You will receive a $5 Tim Horton's Gift Card for completing this portion of the study.

**10. Consent**

I have read the consent form and have had the nature of the study explained to me. All questions have been answered to my satisfaction. I understand that all of the study procedures used have been reviewed and received clearance from the Research Ethics Board at Trent University (File# 28575). If I have comments or concerns resulting from my participation that I do not feel comfortable talking about with the Primary Investigator, I understand that I can contact the Research Ethics Board by phoning Anna Kisiala, Research Compliance Officer, at 705-748-1011 x 7986 or by emailing her at akisiala@trentu.ca. By signing below, I consent to participate in this study. I understand that I may withdraw this consent at any time without penalty.

By typing or writing my name below, I consent to:

- ☐ participate in the study
- ☐ complete the UPDRS (if applicable)
- ☐ Complete a series of walking tasks to examine freezing of gait (videotaped)
- ☐ Complete a series of reaching tasks to examine freezing of upper limbs (videotaped)
- ☐ complete a questionnaire related to anxiety levels
- ☐ allow recording of my speech throughout the study to assess freezing of speech

Participant:

________________ _________________________ ________________________

Signature Print Name Date

Appendix B
Information and Consent Form - Questionnaires

DEPARTMENT OF PSYCHOLOGY
**Liana E. Brown, PhD**
Associate Professor

Telephone (705) 748-1011 x7238
Fax (705) 748-1580
Email lianabrown@trentu.ca

TRENT UNIVERSITY

**Letter of Information and Consent Form**

**Project Title:** Freezing in Parkinson's Disease
**Primary Investigator:** Jennifer Stevenson
**Graduate Supervisor:** Liana E. Brown, PhD

**Thank you for thinking about participating in our study.**

**0. Purpose:**

The purpose of this study is to learn more about what causes freezing – a problem that some people with Parkinson's get where they feel stuck in one spot. We also believe there is a visual component to freezing and we will be testing the idea that freezing will occur differently when you see different background information.

**1. Participation inclusion/exclusion criteria:**

To participate in this study, you must be a person with Parkinson's Disease or a healthy, age-matched control participant who has not been diagnosed with any neurological issues.

**2. Procedures to be followed:**

For this part of the study, you will be asked to complete surveys (all available online or in person) focused on your general health and wellness, your handedness, whether you have ever experienced an episode of freezing while walking, attention, organizational skills and decision making, and Parkinson's Disease-related questions. You can complete these surveys at home at your leisure. The time needed to complete all the surveys is about 25 minutes.

**3. Benefits**

There are no direct benefits to the participants of this study. However, the results of the study will help shed light on how freezing is elicited in other effectors (upper limbs) and how visual conditions impact freezing.

**4. How the data will be used:**
We declare that we have no potential conflicts of interest: we will not experience any specific personal or financial gain or loss from the results of this study. The researchers have no plan at this time to develop commercial venture from the findings of this research. The results of this study may be presented at a conference and then published as a report in a journal. The information will be used to make presentations to the Peterborough Parkinson Support Group and the Parkinson's Society.

**5. Voluntary participation:**
Your participation is entirely voluntary. You are free to stop participating in the study at any time or to decline answering specific questions. To withdraw from the study, you simply need to inform the investigator of your wish to withdraw.

You may stop the testing at any point. However, the data from the tasks that you have completed up until the point of withdrawal may be useful to us, and we may ask your permission to include it in our analyses. If you decline, we will automatically and immediately destroy your testing data.

**6. Statement of confidentiality:**
Your participation in this study is entirely confidential. Only Jennifer Stevenson and Liana Brown will have access to identifying information. To ensure participation is confidential, all data will be distinguished by a code number and stored on a computer that is encrypted and password protected. In the event that data from this evaluation is published, no personally identifying information will be disclosed.

**7. Discomfort and risks:**

By participating in this study, you will experience no more discomfort than you would normally experience during everyday tasks. If you wish to end the study, you may do so without penalty. Just let us know at any time if you would like to stop. We will stop the study immediately.

Answering the questions on the quality-of-life questionnaire may upset you as well, especially if you have experienced recent declines. If any aspect of our assessment is making you worry, we encourage you to contact your neurologist or family physician to ensure that they are informed of your concerns. If you are a person with Parkinson's disease, your neurologist is the best person to talk to about solving new issues that come up as you live with Parkinson's.

**8. Post-experiment feedback and right to ask questions:**
You will be given an opportunity to ask any questions you may have, and all such questions or inquiries will be answered to your satisfaction. After you have finished participating, you will given more opportunities to ask questions and we will gladly answer. If you would like to receive the study's findings and/or have questions in the future, contact Liana Brown at 705-748- 1011 x7238 or lianabrown@trentu.ca or Jennifer Stevenson, jenniferstevenson@trentu.ca.

**9. Compensation:**
You will receive a $5 Tim Horton's Gift Card for completing this portion of the study.

**10. Consent**

I have read the consent form and have had the nature of the study explained to me. All questions have been answered to my satisfaction. I understand that all of the study procedures used have been reviewed and received clearance from the Research Ethics Board at Trent University (File# ) . If I have comments or concerns resulting from my participation that I do not feel comfortable talking about with the Primary Investigator, I understand that I can contact the Research Ethics Board by phoning Anna Kisiala, Research Compliance Officer, at 705-748-1011 x 7986 or by emailing her at akisiala@trentu.ca. By signing below, I consent to participate in this study. I understand that I may withdraw this consent at any time without penalty.

By typing or writing my name below, I consent to:

- ☐ participate in the study.
- ☐ complete a series of questionnaires asking about my general health, handedness, executive functioning, my experience of Parkinson's Disease (if applicable), and my quality of life.
- ☐

Participant:

| _________________ | ___________________________ | __________________________ |
|---|---|---|
| Signature | Print Name | Date |

Appendix C

Recruitment Email to Parkinson's Support Group

October 2023

Dear Lanny Thomas,

Trent University's Jennifer Stevenson and Dr. Liana Brown are conducting research into if and how freezing of gait in Parkinson's Disease is related to freezing more generally, such as freezing of upper limbs. We are also interested in how visual stimuli influence freezing in Parkinson's Disease.

The purpose of this letter is to invite members of the Peterborough Chapter of Parkinson Canada to participate in our study. The study will consist of filling out questionnaires (which can be completed online or on paper) and attending Dr. Brown's lab at Trent University to complete walking and reaching activities.

If you or members of the Peterborough PD community are interested in learning more about this research, please contact Jennifer Stevenson (jenniferstevenson@trentu.ca) or Dr. Liana Brown (lianabrown@trentu.ca) so we can provide more details and answer any questions you may have.

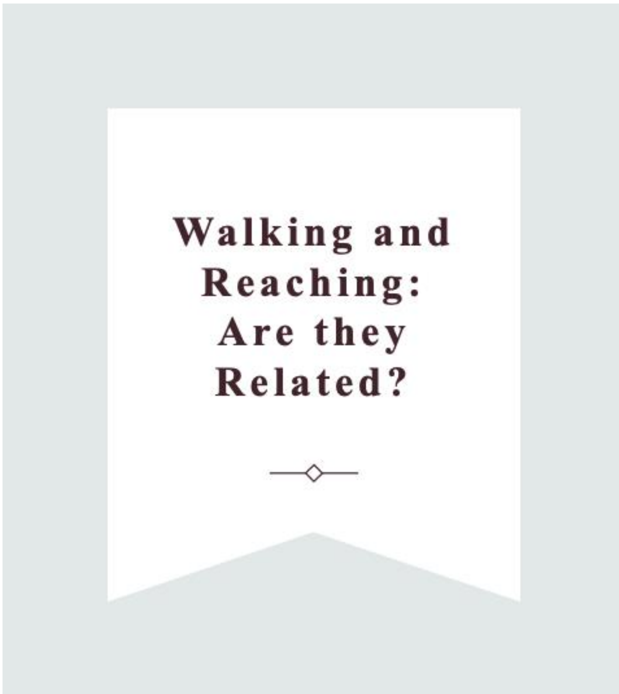
Sincerely,

Jennifer Stevenson, M.Sc. Candidate

Trent University

# Appendix D

## Recruitment Post for Social Media




**Research Participants Wanted**

The Action and Cognition (ACT) Lab is recruiting healthy participants over the age of 60 years to participate in our in-person study.

The study involves completing several questionnaires followed by walking and reaching activities. You will form the healthy control group of a study of people with Parkinson's Disease.

Participants will receive a $10 Tim Horton's Gift Card for their time.

If you are interested in learning more about this study or signing up, please email jenniferstevenson@trentu.ca or lianabrown@trentu.ca

CIHR IRSC Canadian Institutes of Health Research Instituts de recherche en santé du Canada

TRENT UNIVERSITY

This study had been approved by Trent University REB#

# Appendix E

## Dutch Handedness Questionnaire

Instructions: A number of activities in which you can use either your left or your right hand are specified below. Indicate which hand you usually use for these activities. Visualize the activity in question if you are not immediately sure of an answer. If you don't have a clear preference, indicate that you use both hands. For tasks that require both hands, please indicate the hand that does the primary action. For example, when unscrewing a water bottle one hand does the primary action of unscrewing, and the other hand secondary action of stabilizing/holding the bottle.

Hold scissors

○ Left

○ Right

○ Both

Draw

○ Left

○ Right

○ Both

Screw the top off bottle

○ Left

○ Right

○ Both

Deal cards

○ Left

○ Right

○ Both

Hold a toothbrush when brushing teeth

○ Left

○ Right

○ Both

Q6 Use a bottle opener

○ Left

○ Right

○ Both

Throw a ball

○ Left

○ Right

○ Both

Hold a hammer

○ Left

○ Right

○ Both

Write your name

○ Left

○ Right

○ Both

Hold a racket when playing tennis

- ◯ Left
- ◯ Right
- ◯ Both

Turn a key

- ◯ Left
- ◯ Right
- ◯ Both

Cut with a knife (without a fork)

- ◯ Left
- ◯ Right
- ◯ Both

Stir with a spoon

- ◯ Left
- ◯ Right
- ◯ Both

Use an eraser on paper

- ◯ Left
- ◯ Right
- ◯ Both

Strike a match

- ○ Left
- ○ Right
- ○ Both

Open a box lid

- ○ Left
- ○ Right
- ○ Both

## Appendix F

## Action and Cognition Lab General Health and Wellness Questionnaire

Here we would like to ask you some questions about your current health and wellness. Please answer the questions as best as you can and feel free to ask us any questions, you'd like about the information being requested. You may decline to answer any of the questions (just skip past the questions you do not want to answer). All your information will be kept confidential.

Date of Birth (year/month/day)

______________________________________________________

Sex

- ○ Female
- ○ Male
- ○ Other

What occupational category do you belong to?

- ○ Student
- ○ Administrator
- ○ Tradesperson
- ○ Academic (Teaching and/or Research)
- ○ Self-employed/Businessperson
- ○ Hospitality
- ○ Other: ______________________________________________

Current or Past Occupational Title

______________________________________________________

______________________________________________________

What is the highest level of education you've completed?

- ◯ did not finish elementary school
- ◯ finished elementary school
- ◯ did not finish high school
- ◯ finished high school
- ◯ started post-secondary school but did not graduate
- ◯ completed a college diploma or bachelor's degree
- ◯ completed a post-graduate degree

Overall, how is your general health?

________________________________________________________

________________________________________________________

How would you rate your general health right now on a scale of 0 (poor) to 100 (never better)?

| | 0 10 20 30 40 50 60 70 80 90 100 |
|---|---|
| Slide the arrow to the left or right to indicate your answer. | |

Q11 Do you consider yourself especially concerned about your health right now?

| | Not Concerned at All | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Extremely Concerned |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Concern about Health | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |

On average, how often do you visit your family doctor?

○ less than once per year

○ once per year

○ 2-5 times per year

○ once per month

○ more than once per month

On average, how long do you sleep at night?

○ less than 4 hours

○ 4-6 hours

○ 7-10 hours

○ more than 10 hours

Typically, how often do you exercise?

○ never

○ once per week

○ 2-3 times per week

○ 4-6 times per week

○ every day

How active is your lifestyle?

- ◯ Sedentary - e.g. I work a desk job.
- ◯ Slightly active - accompanied by 5 minute walks
- ◯ Moderately active - work/volunteer activities demand travel
- ◯ Very active - work/volunteer activities demand heavy lifting and movement

Do you smoke?

- ◯ Yes
- ◯ No

Do you drink?

- ◯ Yes
- ◯ No

Do you have emotional support from friends and relatives?

- ○ 0
- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7
- ○ 8
- ○ 9
- ○ 10

How often do you attend social gatherings?

- ○ never
- ○ less than once per month
- ○ at least once per month
- ○ 2-4 times per month
- ○ more than 4 times per month

Do you feel lonely?

- ○ never
- ○ rarely
- ○ sometimes
- ○ often
- ○ always

How often do you feel stressed in a typical week?

- ○ never
- ○ rarely
- ○ sometimes
- ○ often
- ○ always

Indicate any conditions you are experiencing or have previously experienced.

- ☐ Chronic cough
- ☐ Shortness of breath
- ☐ Bronchitis
- ☐ Asthma
- ☐ Emphysema
- ☐ Other ____________________________________________

Indicate any conditions you are experiencing or have previously experienced.

- ☐ High blood pressure/hypertension
- ☐ Low blood pressure
- ☐ Chronic Congestive Heart Failure
- ☐ Heart attack
- ☐ Stroke
- ☐ Pacemaker or similar device
- ☐ Heart disease
- ☐ Phlebitis/Varicose veins

How long ago was your stroke?

______________________________________________________________

Please describe any lingering problems associated with your stroke.

______________________________________________________________

______________________________________________________________

______________________________________________________________

Indicate any conditions you are experiencing or have previously experienced.

- ☐ Imperfect Vision
- ☐ Imperfect Hearing
- ☐ Recurring headaches
- ☐ Migraine headaches
- ☐ Concussion
- ☐ Traumatic Head/Brain Injury
- ☐ Nerve pain/tingling in face
- ☐ Epileptic Seizure

Is your vision corrected with glasses or contact lenses?

- ○ Yes
- ○ Somewhat
- ○ No

Is your hearing corrected with hearing-aids?

- ○ Yes
- ○ Somewhat
- ○ No

How long ago was your concussion?

__________________________________________________________

Please describe any lingering problems associated with your concussion.

__________________________________________________________

______________________________________________________________

How long ago was your traumatic head/brain injury?

______________________________________________________________

Please describe any lingering problems associated with your traumatic brain injury.

______________________________________________________________

Have you been diagnosed with epilepsy?

○ Yes

○ No

How long ago were you diagnosed with epilepsy?

______________________________________________________________

What medications do you take to treat epilepsy?

______________________________________________________________

How often do you experience seizures (while medicated)?

○ less than once per year

○ once per year

○ 2-5 times per year

○ once per month

○ 2-3 times per month

○ once per week

○ once per day

○ multiple times per day

Indicate any conditions you are experiencing or have previously experienced.

- ☐ Loss of touch in hands
- ☐ Loss of touch in feet
- ☐ Loss of taste or smell
- ☐ Nerve pain/tingling in hands
- ☐ Nerve pain/tinging in feet

Indicate any conditions you are experiencing or have previously experienced.

- ☐ Parkinson's Disease
- ☐ Dystonia
- ☐ Huntington's Disease
- ☐ Dementia

What year and month were you diagnosed with Parkinson's Disease?

______________________________________________________

Which body part and side did you notice first (e.g., right hand)?

______________________________________________________

What was your most recent UPDRS (United Parkinson Disease Rating Score)?

______________________________________________________

Indicate any conditions you are experiencing or have previously experienced.

- ☐ Osteoporosis
- ☐ Prolonged steroid use
- ☐ Inflammatory disease
- ☐ Collagen disease
- ☐ Sleep disorder
- ☐ Arthritis
- ☐ Kidney disease
- ☐ Skin conditions
- ☐ Diabetes
- ☐ Allergies/hypersensitivity
- ☐ Cancer
- ☐ Blood-related condition
- ☐ Do you have any other medical conditions? (e.g. digestive conditions, haemophilia, osteoporosis, mental illness?)

_____________________________________________________

What kind of diabetes do you have?

______________________________________________________________

Is there a family history of diabetes?

◯ Yes

◯ No

What medications do you take to treat diabetes?

______________________________________________________________

Do you experience other conditions as a result of diabetes?

______________________________________________________________

What kind of kidney disease do you have?

______________________________________________________________

What medication do you take to treat kidney disease?

______________________________________________________________

Do you need dialysis?

◯ Yes

◯ No

How often do you receive dialysis?

______________________________________________________________

Do you experience other conditions as a result of kidney disease?

______________________________________________________________

______________________________________________________________

Describe your blood-related condition:

______________________________________________________________

Indicate any areas where you are experiencing pain or discomfort.

- ☐ Neck
- ☐ Back
- ☐ Shoulder
- ☐ Arm
- ☐ Elbow
- ☐ Hand
- ☐ Hip
- ☐ Leg
- ☐ Knee
- ☐ Feet

Do you have any internal pins, wires, artificial joints or special equipment?

- ○ Yes
- ○ No

What joints are pinned, wired, or have been replaced?

________________________________________________________

________________________________________________________

________________________________________________________

Please list current prescription medications you take and indicate condition it treats. When you report the medication, you can provide either the trade name or the drug name written on the container.

For example, you might write...

Lozol for high blood pressure OR indapamide for high blood pressure

________________________________________________________

________________________________________________________

Is there anything else you'd like to tell us about your health?

________________________________________________________

________________________________________________________

# Appendix G
## The BRIEF-A

The following questions will consist of statements. We would like to know if you have had problems with these behaviours over the past month. Please answer all the items the best that you can. Please do not skip any items. Indicate your response by selecting if the behaviour is Never a problem if the behaviour is Sometimes a problem if the behaviour is Often a problem. For example, if you never have trouble making decisions you would select Never for this item: "I have trouble making decisions"

I have angry outbursts

- ○ Never
- ○ Sometimes
- ○ Often

I make careless errors when completing tasks

- ○ Never
- ○ Sometimes
- ○ Often

I am disorganized

- ○ Never
- ○ Sometimes
- ○ Often

I have trouble concentrating on tasks (such as chores, reading, or work)

- ○ Never
- ○ Sometimes
- ○ Often

I tap my fingers or bounce my legs

- ◯ Never
- ◯ Sometimes
- ◯ Often

I need to be reminded to begin a task even when I am willing

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have a messy closet

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble changing from one activity or task to another

- ◯ Never
- ◯ Sometimes
- ◯ Often

I get overwhelmed by large tasks

- ◯ Never
- ◯ Sometimes
- ◯ Often

I forget my name

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble with jobs or tasks that have more than one step

- ◯ Never
- ◯ Sometimes
- ◯ Often

I overreact emotionally

- ◯ Never
- ◯ Sometimes
- ◯ Often

I don't notice when I cause others to feel bad or get mad until it is too late

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble getting ready for the day

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble prioritizing activities

- ○ Never
- ○ Sometimes
- ○ Often

I have trouble sitting still

- ○ Never
- ○ Sometimes
- ○ Often

I forget what I am doing in the middle of things

- ○ Never
- ○ Sometimes
- ○ Often

I don't check my work for mistakes

- ○ Never
- ○ Sometimes
- ○ Often

I have emotional outbursts for little reason

- ○ Never
- ○ Sometimes
- ○ Often

I lie around the house a lot

- ◯ Never
- ◯ Sometimes
- ◯ Often

I start tasks (such as cooking, projects) without the right materials

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble accepting different ways to solve problems with work, friends, or tasks

- ◯ Never
- ◯ Sometimes
- ◯ Often

I talk at the wrong time

- ◯ Never
- ◯ Sometimes
- ◯ Often

I misjudge how difficult or easy tasks will be

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have problems getting started on my own

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble staying on the same topic when talking

- ◯ Never
- ◯ Sometimes
- ◯ Often

I get tired

- ◯ Never
- ◯ Sometimes
- ◯ Often

I react more emotionally to situations than my friends

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have problems waiting my turn

- ◯ Never
- ◯ Sometimes
- ◯ Often

People say that I am disorganized

- ○ Never
- ○ Sometimes
- ○ Often

I lose things (such as keys, money, wallet, homework, etc.)

- ○ Never
- ○ Sometimes
- ○ Often

I have trouble thinking of a different way to solve a problem when stuck

- ○ Never
- ○ Sometimes
- ○ Often

I overreact to small problems

- ○ Never
- ○ Sometimes
- ○ Often

I don't plan ahead for future activities

- ○ Never
- ○ Sometimes
- ○ Often

I have a short attention span

- ◯ Never
- ◯ Sometimes
- ◯ Often

Q39 I make inappropriate sexual comments

- ◯ Never
- ◯ Sometimes
- ◯ Often

When people seem upset with me, I don't understand why

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble counting to three

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have unrealistic goals

- ◯ Never
- ◯ Sometimes
- ◯ Often

I leave the bathroom a mess

- ○ Never
- ○ Sometimes
- ○ Often

I make careless mistakes

- ○ Never
- ○ Sometimes
- ○ Often

I get emotionally upset easily

- ○ Never
- ○ Sometimes
- ○ Often

I make decisions that get me into trouble (legally, financially, socially)

- ○ Never
- ○ Sometimes
- ○ Often

I am bothered by having to deal with changes

- ○ Never
- ○ Sometimes
- ○ Often

I have difficulty getting excited about things

- Never
- Sometimes
- Often

I forget instructions easily

- Never
- Sometimes
- Often

I have good ideas but cannot get them on paper

- Never
- Sometimes
- Often

I make mistakes

- Never
- Sometimes
- Often

I have trouble getting started on tasks

- Never
- Sometimes
- Often

I say things without thinking

- ◯ Never
- ◯ Sometimes
- ◯ Often

My anger is intense but ends quickly

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble finishing tasks (such as chores, work)

- ◯ Never
- ◯ Sometimes
- ◯ Often

I start things at the last minute (such as assignments, chores, tasks)

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have difficulty finishing a task on my own

- ◯ Never
- ◯ Sometimes
- ◯ Often

People say that I am easily distracted

- ○ Never
- ○ Sometimes
- ○ Often

I have trouble remembering things, even for a few minutes (such as directions, phone numbers)

- ○ Never
- ○ Sometimes
- ○ Often

People say that I am too emotional

- ○ Never
- ○ Sometimes
- ○ Often

I rush through things

- ○ Never
- ○ Sometimes
- ○ Often

I get annoyed

- ○ Never
- ○ Sometimes
- ○ Often

I leave my room or home a mess

- ◯ Never
- ◯ Sometimes
- ◯ Often

I get disturbed by unexpected changes in my daily routine

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble coming up with ideas for what to do with my free time

- ◯ Never
- ◯ Sometimes
- ◯ Often

I don't plan ahead for tasks

- ◯ Never
- ◯ Sometimes
- ◯ Often

People say that I don't think before acting

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble finding things in my room, closet, or desk

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have problems organizing activities

- ◯ Never
- ◯ Sometimes
- ◯ Often

After having a problem, I don't get over it easily

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble doing more than one thing at a time

- ◯ Never
- ◯ Sometimes
- ◯ Often

My mood changes frequently

- ◯ Never
- ◯ Sometimes
- ◯ Often

I don't think about consequences before doing something

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have trouble organizing my work

- ◯ Never
- ◯ Sometimes
- ◯ Often

I get upset quickly or easily over little things

- ◯ Never
- ◯ Sometimes
- ◯ Often

am impulsive

- ◯ Never
- ◯ Sometimes
- ◯ Often

I don't pick up after myself

- ◯ Never
- ◯ Sometimes
- ◯ Often

I have problems completing my work

- ○ Never
- ○ Sometimes
- ○ Often

Appendix H

PDQ-39 Questionnaire

Please pick one box for each question.
Due to having Parkinson's disease, how often during the last month have you...

1. Had difficulty doing the leisure activities which you would like to do?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

2. Had difficulty looking after your home, e.g. DIY, housework, cooking?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

3. Had difficulty carrying bags of shopping?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

4. Had problems walking half a mile?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

5. Had problems walking 100 yards?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

6. Had problems getting around the house as easily as you would like?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

7. Had difficulty getting around in public?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

8. Needed someone else to accompany you when you went out?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

9. Felt frightened or worried about falling over in public?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

10. Been confined to the house more than you would like?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

11. Had difficulty washing yourself?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

12. Had difficulty dressing yourself?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

13. Had problems doing up your shoe laces?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

14. Had problems writing clearly?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

15. Had difficulty cutting up your food?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

16. Had difficulty holding a drink without spilling it?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

17. Felt depressed?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

18. Felt isolated and lonely?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

19. Felt weepy or tearful?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

20. Felt angry or bitter?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

21. Felt anxious?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

22. Felt worried about your future?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

23. Felt you had to conceal your Parkinson's from people?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

24. Avoided situations which involve eating or drinking in public?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

25. Felt embarrassed in public due to having Parkinson's disease?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

26. Felt worried by other people's reaction to you?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

27. Had problems with your close personal relationships?

☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

28. Lacked support in the ways you need from your spouse or partner?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

29. Lacked support in the ways you need from your family or close friends?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

30. Unexpectedly fallen asleep during the day?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

31. Had problems with your concentration, e.g. when reading or watching TV?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

32. Felt your memory was bad?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

33. Had distressing dreams or hallucinations?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

34. Had difficulty with your speech?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

35. Felt unable to communicate with people properly?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

36. Felt ignored by people?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

37. Had painful muscle cramps or spasms?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

38. Had aches and pains in your joints or body?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

39. Felt unpleasantly hot or cold?
☐ Never ☐ Occasionally ☐ Sometimes ☐ Often ☐ Always

# Appendix I
## The FOG-Q

This questionnaire will ask you about your experiences with walking (gait), falling and freezing. You can skip any question you do not wish to answer.

During your worst state - Do you walk:

- ◯ Normally
- ◯ Almost normally - somewhat slow
- ◯ Slow but fully independent
- ◯ Need Assistance or walking aid
- ◯ Unable to walk

Are your gait difficulties affecting your daily activities and independence?

- ◯ Not at all
- ◯ Mildly
- ◯ Moderately
- ◯ Severely
- ◯ Unable to walk

Do you feel that your feet get glued to the floor while walking, making a turn or when trying to initiate walking (freezing)?

- ◯ Never
- ◯ Very rarely - about once a month
- ◯ Rarely - about once a week
- ◯ Often - about once a day
- ◯ Always - whenever walking

How long is your longest freezing episode?

- ○ Never happened
- ○ 1 - 2 s
- ○ 3 - 10 s
- ○ 11 - 30 s
- ○ Unable to walk for more than 30

How long is your typical start hesitation episode (freezing when initiating the first step)?

- ○ None
- ○ Takes longer than 1 s to start walking
- ○ Takes longer than 3 s to start walking
- ○ Takes longer than 10 s to start walking
- ○ Takes longer than 30 s to start walking

How long is your typical turning hesitation: (freezing when turning)

- ○ None
- ○ Resume turning in 1 - 2 s
- ○ Resume turning in 3 - 10 s
- ○ Resume turning in 11 - 30 s
- ○ Unable to resume turning for more than 30 s

Appendix J

Modified Parkinson Anxiety Scale (PAS)

**A. Persistent Task-Related Anxiety**

**Please mark one circle for each item below**

During the reaching tasks, to what extent did you experience the following symptoms?

**A.1. Feeling anxious or nervous**

- o Not at all, or never
- o Very mild, or rarely
- o Mild, or sometimes
- o Severe, or (nearly) throughout the entire task

**A.2. Feeling tense or stressed**

- o Not at all, or never
- o Very mild, or rarely
- o Mild, or sometimes
- o Severe, or (nearly) throughout the entire task

**A.3.Being unable to relax**

- o Not at all, or never
- o Very mild, or rarely
- o Mild, or sometimes
- o Severe, or (nearly) throughout the entire task

**A.4. Fear of something bad happening during the tasks**

- o Not at all, or never
- o Very mild, or rarely
- o Mild, or sometimes
- o Severe, or (nearly) throughout the entire task

**B. Episodic Anxiety**
**Please mark one circle for each item below**

During the reaching tasks, did you experience episodes of the following symptoms?

**B.1. Panic or intense fear**

- o Never
- o Rarely
- o Sometimes
- o Often
- o Almost the entire time

**B.2. Shortness of breath**

- o Never
- o Rarely
- o Sometimes
- o Often
- o Almost the entire time

**B.3. Heart palpitations or heart beating fast (not related to physical effort associated with the tasks)**

- o Never
- o Rarely
- o Sometimes
- o Often
- o Almost the entire time

**B.4. Fear of losing control**

- o Never
- o Rarely
- o Sometimes

- Often
- Almost the entire time

**C. Avoidance Behaviour**
**Please mark one circle for each item below**

In the morning before attending the lab for this study, to what extent did you fear or wish to avoid the following situations?

**C.1. Social interactions (where one might be observed, or evaluated by others, such as talking to unknown people, for example, the experimenter or other individuals at Trent University)**

- Never
- Rarely
- Sometimes
- Often
- Almost the entire morning

**C.2.Public settings (situations from which it may be difficult or embarrassing to escape, such as queues or lines, crowds at Trent University, narrow hallways at Trent University)**

- Never
- Rarely
- Sometimes
- Often
- Almost the entire morning