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The measurement of visual sampling during real-world activity in Parkinson's disease and healthy controls: A Structured Literature Review

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Abstract

Background: Visual sampling techniques are used to investigate the complex role of vision during real-world activies in Parkinson's disease. Earlier research is limited to static simple tasks or measurement of eye movements alone, but more recent investigations involve more real-world activities. The approach to the objective measurement of eye movements varies with respect to instrumentation, testing protocols, and mediating factors that may influence visual sampling.

Objectives: The aim of this review was to examine previous work measuring visual sampling during real-world activities in Parkinson's disease to inform the development of robust protocols. Within this review a real-world activity was considered to be a goal-orientated motor task involving more than one body segment such as reaching or walking.

Methods: Medline, Embase, PsychInfo, Scopus, Web of Knowledge, PubMed and the Cochrane library databases were searched. Two independent reviewers and an adjudicator screened articles that described quantitative visual sampling in people with Parkinson's disease and healthy controls.

Results: Twenty full-text articles were screened and 15 met inclusion/exclusion criteria. A wide range of instruments and outcome measures were reported which were generally used in a task-dependent manner. Instrument reliability and validity was insufficiently reported in all studies. Few studies considered mediators of visual sampling such as visual or cognitive deficits.

Conclusions: Future research is required to accurately characterise visual impairments in Parkinson's disease and during real-world activities. Composite use of instruments may be required to achieve reliability and validity of visual sampling outcomes which need to be standardised. Recommendations also include assessment of cognition and basic visual function.

Keywords: Parkinson's disease, visual sampling, motor task, eye-tracking, eye movements, vision

1 Introduction

Visual sampling (VS) is the combination of fixations and saccades that are required to gather information about our environment when performing a real-world activity. VS has been assessed using a variety of methods since the 1700's, evolving from simple photographic technology to more recently the use of mobile infra-red eye-tracking (Land, 2006, Porterfield and Neill, 1752). Eye-tracking involves two distinguishable movements of the eye; activity that stabilizes the fovea (fixations) on areas of interest (AOI), and activity that rapidly shifts the fovea to bring AOI into high visual acuity (saccades) (Anderson and MacAskill, 2013). A combination of fixations and saccades provide the mechanisms through which we sample our visual environment (McPeek et al., 2000, Deubel, 2003, Tatler, 2009). Advancements in eye-tracking technology have enabled VS to be monitored during real-world activity (e.g. walking, obstacle crossing, driving). This progress is vital as VS is a critical feature of motor control, which is task-dependent and relates to specific goals (Marigold and Patla, 2007). For example: during locomotion over even ground in healthy control subjects long fixation durations are not necessarily required, yet saccadic frequency, amplitude and duration of fixations increase in healthy subjects when walking over uneven terrain (Land, 2006, Patla and Greig, 2006). The co-ordination of the eyes, head, trunk and other body segments during real-world activity requires visuomotor control to guide and organise linked-segment interactions. Motor control and visual mechanisms are also inter-linked with attentional networks, which are governed by cognitive ('top-down') processes (Botha and Carr, 2012). Therefore, disease-specific impairments of motor control (Joti et al., 2007, Konczak et al., 2009) and cognition (Archibald et al., 2013) potentially mediate visual function.

Parkinson's disease (PD) is a progressive neurodegenerative disease associated with impaired motor control (Konczak et al., 2009) and a range of cognitive and visual deficits. Motor symptoms such as bradykinesia (slow movement) and akinesia (impaired movement) are evident in limb and eye movements in PD during real-world activity. For example, bradykinesia can affect reaching (Schettino et al., 2006), pointing (Adamovich et al., 2001, Bekkering et al., 2001, Boisseau et al., 2002, Klockgether and Dichgans, 1994) and force control (Vaillancourt et al., 2001b, Vaillancourt et al., 2001a). In addition, impaired visuo-perceptual and basic visual

functions such as reduced contrast sensitivity are reported by up to 81% (Verbaan et al., 2007) and 78% (Davidsdottir et al., 2005) of PD subjects respectively. These symptoms are seen at an early stage in PD and are associated with functional decline, freezing of gait (FOG) and falls. Investigation into VS during real-world activity in PD is warranted, to further clarify the links between these motor, cognitive and visual impairments. Eye-tracking technology has been used to further understand the visual strategies of PD subjects since the 1960's (Terao et al., 2011, van Stockum et al., 2012), demonstrating VS impairments, such as hypometric voluntary (van Stockum et al., 2012, Anderson and MacAskill, 2013) and variable reflexive (Chambers and Prescott, 2010) saccades. However until recently most research using eye-trackers involved small sample sizes (Anderson and MacAskill, 2013). Similarly most PD studies of VS are limited to static examination of eye movements alone or involve simple single-segment motor tasks (e.g. mouse clicks). Of the PD studies investigating VS during real-world activity, a wide range of protocols have been used indicating a lack of standardisation, which limits VS interpretation. Investigators who want to conduct similar research are left with the choice between numerous protocols, which differ in many respects. In the process of developing robust protocols it is often helpful to have evidence-based recommendations. We therefore examined previous work that assessed VS during real-world activities in PD and healthy control (HC) participants, in order to provide some guidance regarding the selection of appropriate methodology.

We focused the review on the following: 1) VS instrumentation used during real-world activities involving both PD and HC; 2) commonly reported VS outcomes; 3) PD specific influences on these visual outcomes; and, 4) recommendations concerning protocol. For the purpose of this review a real-world activity was considered to be a goal-orientated motor task, which involved more than one body segment (such as walking, reaching, turning etc.).

2 Methods

2.1 Search Strategy

The key terms were "Parkinson's disease", "visual sampling" and a "motor task". A list of synonyms was created for each key term (Figure 1). Key terms were matched

and exploded with medical subject headings (MeSH) in each separate database where appropriate. Databases searched included Medline (from 1950), Embase (from 1974), PsychInfo (from 1806), Scopus, Web of Knowledge (from 1900), PubMed (from 1950) and the Cochrane library (from 1800) to February 2013. Studies were relevant if they incorporated terminology which focused on VS during a real-world activity in both PD and healthy control subjects in the title, abstract or keywords. Articles with titles related to ‘sleep’, ‘monkeys’, ‘rats’ and ‘hallucinations’ were excluded using separate key terms.

An initial title screen for relevant articles was performed by the reviewer (SS) once the searched database results had been combined. After the initial title screen, both the titles and abstracts of the selected articles were reviewed by two independent reviewers (SS, LA). A review of the full text was required if it was not clear from the title or abstract whether the study met the review criteria.

2.2 Inclusion and Exclusion Criteria

Articles were included if they reported use of a measurement instrument to quantify VS (i.e. saccades and fixations) during performance of a real-world activity. Studies were included only if they tested a HC cohort for comparison with PD cohorts so that PD-specific differences could be identified. Whereby articles included another clinical cohort (i.e. progressive supranuclear palsy), or an additional static visual task, only the data relating to PD and HC cohorts whilst sampling the visual environment during a real-world activity was reviewed.

Articles were excluded if they involved simple motor tasks relying on single-segment movement (such as; button pressing with a finger or wrist flexion/extension only) as they were not considered real-world activities. Visual tracking studies were excluded as they primarily involve smooth pursuit eye movements, and only saccades and fixations were reviewed. Only articles written in English were considered for review and any abstracts, case studies, reviews, commentaries, discussion papers, editorials or conference proceedings were excluded.

2.3 Data Extraction

Data was extracted by the reviewer (SS) using a custom form to support standardised extraction (Appendix). Data was synthesised into table format by the reviewer (SS) and a second reviewer (LA) confirmed the entered data (Tables 1, 2 and 3). Data included demographic, VS and motor task measurement instruments, VS outcomes, study protocol and key findings.

3 Results

3.1 The Evidence Base

The search strategy yielded 2814 articles, excluding duplicates (Figure 2 - Adapted from Moher et al. (2009)). An initial screening resulted in 287 articles of interest of which 14 were identified for inclusion by the first reviewer (SS) and 20 by the second reviewer (LA), with 6 disagreements. A consensus was made for inclusion of 15 articles for review after consultation with the third reviewer (SL).

Reasons for exclusion were: performance of a simple motor task (n=3) (Shimizu et al., 1981, Weinrich and Bhatia, 1986, Yoshida et al., 2005); not including a healthy control group (n=1) (Inzelberg et al., 2008); and, eye movement data removed as artifact of EEG data (n=1) (Tropini et al., 2011). The majority of screened studies (n=220) were excluded because they were either not relevant or did not provide a quantitative measurement of VS (e.g. restricted vision). Of the title screened studies that used a quantitative VS measure, 47 were excluded for not meeting inclusion criteria (Supplementary data 1).

3.2 Participants

The reviewed articles (n=15) investigated HC's with a mean age of 60.9 (±7.2) years. One article (Uc et al., 2006) did not report HC demographics. The mean age of the PD subjects was 62.7 (±7.1) years. Both male and female participants were recruited to the majority of the studies, although one study (Lee et al., 2012) did not report gender characteristics. Generally, PD participants were assessed when they were 'ON' medication, and one study (Sacrey et al., 2011) assessed PD subjects both 'ON' and 'OFF' medication.

3.3 Reliability and Validity

Of the articles reviewed, none commented upon the validity and reliability of the instrumentation used. One study assessed inter-rater reliability (Uc et al., 2006), reporting a 95% agreement between examiners using the 'Landmark and Traffic Sign Identification Task'. Similarly, there was a lack of detail reported about the manufacturers specification of the equipment used. Two studies (Marx et al., 2012, Lee et al., 2012) provided the manufacturer specifications regarding the precision and degree of accuracy of their eye-tracking devices, but provided no evidence to substantiate this information.

3.4 Instruments

VS was measured using a variety of instruments in the reviewed articles, which depended upon the movement evaluated. For example; activities which involved head movement or the need for wireless equipment (e.g. walking, driving, turns-in-place) used mobile devices such as head-mounted eye-trackers, camcorders or electrooculography (EOG). Whereas other studies which restricted head movement (via a chin rest) used EOG or a desk-mounted infra-red eye tracker. Fourteen articles described various biomechanical instruments: head-mounted eye-trackers (e.g. infra-red and video-oculography) (n=5); EOG (n=7); 2D video camcorders (n=2); and a static infra-red eye-tracker (n=1). The temporal resolution used to sample eye tracking data was found to vary considerably, even when using similar devices (frequency range = 30-1000 Hz, see Table 1).

Only one study did not measure VS directly (Uc et al., 2006), and instead used a quantitative performance-based test called the 'Landmark and Traffic Sign Identification Task' (LTIT), which had been used with stroke patients and Alzheimer's subjects previously (Uc et al., 2005b, Uc et al., 2005a). The LTIT requires subjects to visually sample (via saccades (McPeek et al., 2000)) the environment and locate (and fixate on) specific landmarks/traffic signs during driving resulting in an VS score (PD=47.8% and HC=58.7%).

3.5 Outcome measures

The majority of the studies provided no visual outcome (saccade and fixation) definitions. Five studies (Desmurget et al., 2004, Heremans et al., 2012, Lohnes and Earhart, 2011, Marx et al., 2012, Muilwijk et al., 2013) did provide outcome definitions, but definitions varied between studies. Twelve studies specified the VS outcome variables obtained, which often involved saccade or fixation measurements (such as saccade frequency, duration, velocity, amplitude, latency, fixation frequency and duration, Table 2). Three studies (Uc et al., 2006, Vitório et al., 2012, Vitorio et al., 2013) reported overall VS (i.e. combined saccade and fixation measurement). However, Table 3 demonstrates that many saccadic and fixation outcomes were not reported in the reviewed studies, likely because they were not deemed relevant to the study.

3.6 Interpretation of outcomes

The influence of PD on VS outcomes was inconsistent likely due to small sample sizes, with several studies reporting non-significant differences between PD and HC subjects (Anastasopoulos et al., 2011, Marx et al., 2012, Ventre-Dominey et al., 2002, Vitório et al., 2012, Vitorio et al., 2013). PD-specific visual outcomes were (summarised in Table 3) impaired during all of the real-world activities compared to HC participants. These differences appear to be task-dependant with several VS outcome measures (i.e. saccade frequency, amplitude and velocity) change according to task demand. For example, during level gait, PD subjects made larger, faster but less frequent saccades in comparison to HC (Galna et al., 2012, Marx et al., 2012). However, during other tasks (e.g. upper-limb tasks and turns-in-place) these related outcomes were oppositely impaired (i.e. reduced saccade velocity and amplitude and increased frequency) (Anastasopoulos et al., 2011, Desmurget et al., 2004, Lohnes and Earhart, 2011, Sacrey et al., 2009, Sacrey et al., 2011, Ventre-Dominey et al., 2002, Ventre-Dominey et al., 2001), illustrating a selective effect of impairment.

Notable methodological limitations were found. The association of VS and PD motor (i.e. FOG), cognitive and visual deficits was reported in four of the reviewed studies (Galna et al., 2012, Lee et al., 2012, Uc et al., 2006, Lohnes and Earhart, 2011), however the majority did not report or control for cognition or basic visual function

(visual acuity and contrast sensitivity). Many studies either excluded or did not assess cognition (Desmurget et al., 2004, Lohnes and Earhart, 2011, Marx et al., 2012, Sacrey et al., 2009, Vitório et al., 2012, Vitorio et al., 2013). Two studies (Galna et al., 2012, Uc et al., 2006) assessed basic visual function and several studies did not include participants who wore glasses (Anastasopoulos et al., 2011, Sacrey et al., 2009, Sacrey et al., 2011). Two studies (Sacrey et al., 2009, Sacrey et al., 2011) reported including contact lens wearers, most likely because contact lenses do not affect measurement tools, such as optical eye-trackers, to the same extent as glasses.

4 Discussion

This review examined 15 studies reporting VS in PD subjects during real-world activities. Explicitly reviewing; (i) how VS was measured; (ii) the specific outcomes assessed and how they were defined; and (iii) the differences reported between PD and HC subjects in these outcomes during real-world activities. This review has demonstrated that the measurement of VS during real-world activities in PD is emerging, but further work is warranted to establish the validity and reliability of VS instrumentation, and the nature of task-dependent VS impairments in PD.

4.1 Instruments

Several studies showed progression from constrained seated activities (e.g. chin rest in place and pointing on a computer screen) to unconstrained real-world activities (e.g. walking or driving), which was achievable only by using mobile VS instrumentation (Land, 2006, Lohnes and Earhart, 2011, Marx et al., 2012). However, the progression from constrained to unconstrained mobile instrumentation came at the cost of reduced temporal resolution, illustrating the trade-off between mobility and accuracy. Mobile eye-trackers generally have temporal resolutions of 30-60Hz, whereas static devices have higher resolutions of 200-1000Hz. This impacts on instrument validity, as saccade velocity based algorithms require at least a 50Hz system to accurately detect a saccade and 200Hz to accurately measure saccade durations (Holmqvist and Nystrom, 2011). Importantly, clear evidence of validity and reliability of instrumentation is essential for confidence in these

measures we found this was not adequately addressed with only one study (Uc et al., 2006) examining this and two studies (Lee et al., 2012, Marx et al., 2012) providing inadequate information. Many studies used EOG, which permits data collection during unconstrained tasks at a high temporal resolution (200-1000Hz). However, inaccuracy with EOG measurements/data have been reported, especially for the detection of small corrective saccades (<2°) (Desmurget et al., 2004), which may be important as healthy adults have been shown to undershoot targets by <2° at visual angles of >10° (Robinson et al., 1993). Similarly, EOG limits VS characteristic selection (Galna et al., 2012), as no spatial data is collected and only horizontal saccades can be accurately obtained (with eye-lid movement significantly affecting vertical saccades) (Wilson et al., 1992). Therefore, both these issues must be considered when using mobile eye-tracking equipment or reporting EOG measurements alone.

In the absence of a 'gold standard' instrument it may be prudent to use a combination of devices, such as EOG and infra-red eye-tracking, to obtain the high temporal resolution and spatial outcomes required. EOG and mobile infra-red eye-tracking are reported to have 'exceptional' comparison during horizontal saccades, although this was not quantified (Lohnes and Earhart, 2011). Reporting the reliability and validity of eye-tracking methodologies is advocated due to the internal (e.g. parallax (Pelz and Canosa, 2001) and calibration error (Nystrom et al., 2013, Pelz and Canosa, 2001) and external (e.g. head movement (Marx et al., 2012)) influences upon eye-tracking. Overall our findings indicate the need for reporting the reliability and validity of the instruments used to measure VS during real-world tasks.

4.2 Outcomes

Visual outcome results from small cohorts may not be an accurate representation of the general population and furthermore create a lack of statistical power and inconsistency in findings. This was evident in this review with many non-significant outcomes reported by studies with small participant numbers (Tables 1 and Supplementary data 2). For example; (Galna et al., 2012) stated that VS frequency was decreased in PD (n=21) compared to HC when walking, while Vitório et al. (2012) stated that it was similar (n=12) even though they found a non-significant

decrease in VS frequency. Since 2011, sample sizes have increased (Table 1) coinciding with the use of mobile eye-tracking devices, which offer relatively quick data acquisition and analysis.

Currently, there are no gold-standard algorithms/definitions for the detection of visual outcomes (Nystrom and Holmqvist, 2010) or for reporting visual outcome measures. This may explain why many of the reviewed studies (Anastasopoulos et al., 2011, Galna et al., 2012, Sacrey et al., 2009, Sacrey et al., 2011, Ventre-Dominey et al., 2002, Ventre-Dominey et al., 2001) did not provide definitions for visual outcomes reported. As a result, velocity thresholds for saccades vary hugely in eye movement literature from 30°/sec (Chan et al., 2005, Chen et al., 2010) to 350°/sec (Beenen et al., 1986), but usually range from 30-100°/sec (Holmqvist and Nystrom, 2011, pp. 152). Depending upon the thresholds set for outcome detection, valuable information may be discarded or irrelevant data included. For example, a velocity-based algorithm with a 130°/sec threshold will detect saccades over 3° (Duchowski, 2007), and below this threshold, data would be classed as a fixation. However, depending on the specific aims and methodology, this algorithm may not be relevant or accurate.

Despite the lack of consistency, many studies used visual outcome definitions and reported visual outcomes in a task-dependent manner (Land, 2006, Owsley, 2011, Peltsch et al., 2011, Hayhoe and Ballard, 2005, Marigold and Patla, 2007). In the reviewed studies, upper limb tasks reported latencies or durations, whereas during whole body tasks (e.g. walking, driving etc.) frequencies or overall scores were provided. Similarly, low velocity thresholds (e.g. 30°/sec (Chan et al., 2005, Peltsch et al., 2011, Versino et al., 2005)) tend to be used for constrained studies, whereas during unconstrained studies higher thresholds (e.g. 50-60°/sec (Marx et al., 2012, Desmurget et al., 2004, Muilwijk et al., 2013)) are used to exclude interference from other visual events (e.g. vestibular ocular reflex). Substantial variation makes direct comparisons between studies and real-world activities difficult. Comparison of several reviewed studies that did report the same visual outcome measures (Anastasopoulos et al., 2011, Desmurget et al., 2004, Galna et al., 2012, Marx et al., 2012) indicated possible task-dependent impairments in PD subjects, but due to a lack of available studies and methodological variations, definitive conclusions cannot be drawn. This confirms the need for quantification of VS during real-world activities

to determine the effect of a real-world activity and the consequences of PD on 'real-life' situations (Marx et al., 2012). Creating a gold-standard for visual event detection and outcome measure reporting is challenging due to variations in instrumentation and differing methodologies. Therefore, current research should report visual event definitions and either use a task-dependent or an adaptable algorithm (Nystrom and Holmqvist, 2010).

PD influenced real-world activity performance and VS outcomes in all of the reviewed studies. A common phenomenon of PD is freezing of gait (FOG), which has been linked to reduced function and increased falls incidence (Okuma, 2006, Vercruysse et al., 2012). Only two of the reviewed studies (Anastasopoulos et al., 2011, Lohnes and Earhart, 2011) reported VS in relation to FOG. They demonstrated reduced velocity and latency of saccades in PD subjects who experience FOG, while other aspects such as saccade amplitude and frequency remained similar to non-FOG subjects. Reduced saccade latency during turns-in place was attributed to a compensatory strategy adopted to prevent falling, and to compensate for reduced movement times (of the head, trunk etc.), as the eyes contributed more than other segments in PD subjects during turning (Anastasopoulos et al., 2011). However, similar outcomes have been found in older adults who fixate on stepping targets significantly earlier than younger subjects (Chapman and Hollands, 2006a, Di Fabio et al., 2003), with increased cognitive (visuomotor) processing time required (Chapman and Hollands, 2010, Chapman and Hollands, 2006b). Another study stated that PD subjects reduced saccadic impairment during real-world activities or used saccadic activity to compensate for motor deficiencies (Marx et al., 2012). It is unclear if these compensatory strategies exist due to incomprehensive reporting of VS outcomes, small sample sizes and methodological variations (such as not controlling for cognitive or visual dysfunctions).

4.3 Interpretation of outcomes

Five studies (Galna et al., 2012, Heremans et al., 2012, Sacrey et al., 2009, Sacrey et al., 2011, Uc et al., 2006) assessed or controlled for visual or cognitive function. Cognitive processes underpin VS during real-world activities, as reflexive activity

which is not governed by top-down cognitive control is rare during such situations (Anderson and MacAskill, 2013). Cognitive deficits (visuospatial, attentional and memory domains) influence VS in PD and older adults (van Stockum et al., 2008, van Stockum et al., 2012, van Stockum et al., 2011, van Stockum et al., 2013). These cognitive and visual impairments influence real-world activity performance resulting in visuocognitive deficits, such as increased visuomotor processing time (Chapman and Hollands, 2010, Chapman and Hollands, 2006b, Antal et al., 2008), perceptual deficits (Young et al., 2010, Bodis-Wollner, 2003) and abnormal environment scanning (Matsumoto et al., 2011, Matsumoto et al., 2012). Similarly, basic visual function impairments, such as visual acuity and contrast sensitivity are common in ageing, but are further implicated in PD due to dopamine depletion within retinal and primary visual structures (Archibald et al., 2009, Bodis-Wollner, 2013, Bodis-Wollner et al., 2013). Such visual deficits have been linked to functional impairments during real-world activities and falls in older adults (Moes and Lombardi, 2009, Archibald et al., 2009, Owsley, 2011). Although, visual acuity impairment is variable in PD (Geldmacher, 2003), as it can be corrected with prescription glasses (Antal et al., 2008). Conversely, contrast sensitivity has been related to everyday task impairment in PD and older adults (Moes and Lombardi, 2009, Owsley, 2011, Geldmacher, 2003). Therefore, we were surprised that most of the reviewed studies either excluded subjects with cognitive or visual deficits, or did not test for them. The exclusion of these subjects limits the generalisability of the findings and may obscure the underlying mechanisms of VS impairment in PD.

Visual and cognitive impairments in PD were associated with reduced VS (Galna et al., 2012, Heremans et al., 2012, Uc et al., 2006) and increased fixation durations (Sacrey et al., 2009, Sacrey et al., 2011) during real-world activities. Although similar impairment is seen during static tests of VS (Clark et al., 2010, Matsumoto et al., 2011, Matsumoto et al., 2012, Archibald et al., 2013), it is likely that VS was influenced by the increased cognitive demand of a real-world activity (Ho et al., 2001). Age, disease progression, and disease-specific motor characteristics (e.g. FOG) have also been implicated in cognitive and visual processing time (Chapman and Hollands, 2006a, Di Fabio et al., 2003, Chapman and Hollands, 2010, Sacrey et al., 2009, Lord et al., 2012). Therefore, measurement of not only motor but also cognitive and visual impairment is required when investigating VS in PD and older

adult subjects, due to the aforementioned internal and external influences (Ho et al., 2001, Maltz and Shinar, 1999, Archibald et al., 2013).

4.4 Test Protocols

Pelz and Canosa (2001) acknowledged that many previous studies investigating VS have incorporated simple tasks involving stationary observers, with subjects interacting with their environment via button presses or mouse clicks. These experiments provide valuable information concerning specific mechanisms behind VS and allow for experimental manipulation. However, they lack ecological validity because movements during real-world activities commonly involve multiple motor, cognitive and visual processes. In contrast, fifteen studies included in this review examine real-world activities under dynamic conditions providing insight into visual behaviour and the interplay between motor function, cognition and vision. Previous investigations of vision during real-world activities, neglect the quantitative objective measurement of VS (i.e. measurement of eye-movements). For example, previous studies manipulated visual input during real-world activities by testing under conditions where vision was present (light or no occlusion) or restricted (dark or occluded) (Adamovich et al., 2001, Almeida et al., 2005, Azulay et al., 1999, Klockgether and Dichgans, 1994, Rand et al., 2010, Schettino et al., 2006, Vaillancourt et al., 2001b, Vaillancourt et al., 2001a). These studies provide global information on the contribution of vision compared to proprioception (Ghez et al., 1994), but unlike studies involving eye-tracking technology they do not assess specific VS outcomes during real-world activities.

5 Conclusions

The functional implications of VS during real-world activities remain unclear, but research in this area is emerging. Precise quantitative measures of VS during real-world activities are essential for characterising the VS impairments involved in PD. However, no single measure or combination of outcomes has been established as the most informative indicator of these processes. Although mobile infra-red eye–trackers are the most comprehensive method available to date, the validity and

reliability of such devices during real-world activities in people with PD or older adults are yet to be determined.

Variations in VS during different real-world activities infer not only an impairment of eye-movements in PD, but a task-specific alteration influenced by a combination of motor, cognitive and visual deficits. Further quantification of VS is needed to determine the effect of PD-specific impairments on real world activities.

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Appendix

Data extraction form

Study

General information	
Date of extraction, name of reviewer	
Title	
Study characteristics	
Verification of study eligibility	The paper met all inclusion criteria stated including study design, participants, instrumentation and outcomes.
Population characteristics and care setting	
population source or setting,	
study inclusion/exclusion criteria	
recruitment	
Characteristics; age, sex,	
Numbers in each group	
Methodological quality	
Blinding	
Allocation Concealment	
Methodology	
Focus of protocol	
Number of groups	
Test protocol	
Durations, delivery, staff	
Outcomes	
What was measured at baseline; during and after testing; by whom?	
What was the measurement tool, was it validated?	
What were the time intervals	

between measurements?

Analysis

Statistical techniques used; unit of analysis

Attrition rate, how dealt with?

Numbers followed up from each group.

Results

For each main variable, pre-test, post-test, difference

Effect on other mediating variables

Qualitative results

Outcomes - able to use

Adverse effects

Outcomes - unable to use

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KEY TERMS

Parkinson's disease: "parkinson*" TITLE-ABS-KEY

Visual sampling: ("vision" OR "visuomotor" OR "gaze" OR "visuospatial" OR "eye movement" OR "ocular motor" OR "ocular movement" OR "oculomotor" OR "sensorimotor" OR "visual movement" OR "visual behaviour" OR "visual behavior" OR "orientat*" OR "attention" OR "saccad*" OR "eye track*" OR "visual sampling" OR "visual search" OR "visual field" OR "visual exploration" OR "oculo motor" OR "ocularmotor") TITLE-ABS-KEY

Motor task: ("gait" OR "locomot*" OR "abulat*" OR "walk*" OR "move*" OR "motor*" OR "hand" OR "reach*" OR "grasp" OR "turn*" OR "leg" OR "arm" OR "motor control" OR "motor co-ordination" OR "driv*" OR "prehension" OR "motor activity" OR "motor performance" OR "mobilization") TITLE-ABS-KEY

NOT ("sleep*" OR "monkey*" OR "rat*" OR "hallucination") TITLE

('*' indicates a wildcard and 'TITLE-ABS-KEY' indicates a title, abstract and keyword search).

Figure 1. Search strategy used to screen for relevant articles included in this review. This illustrates the three key terms used for this review and the synonyms used for each.

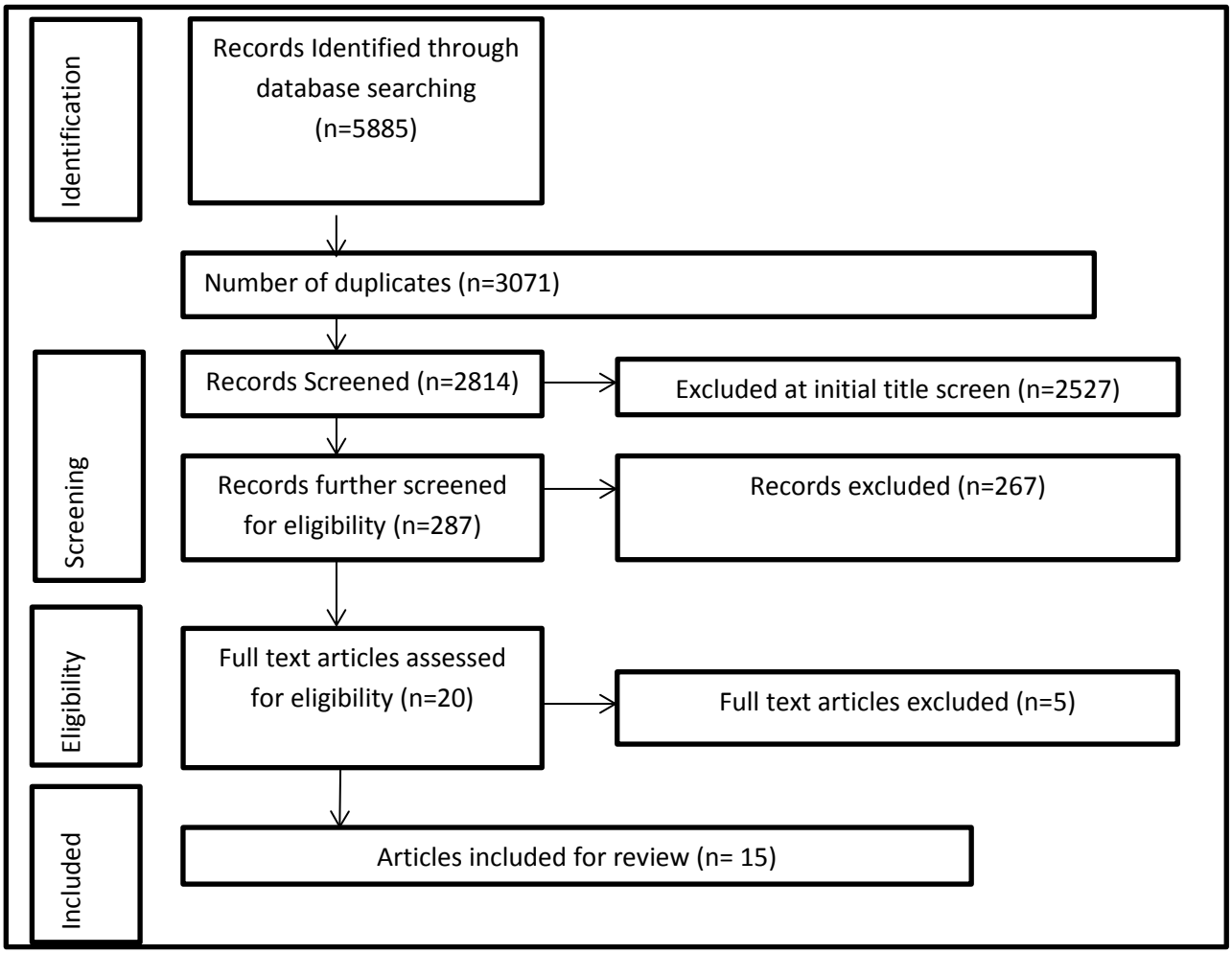

Figure 2. PRISMA flow chart of study design. This illustrates the yield of the search strategy at each stage of the study selection process.

Table 1. Participant characteristics, PD diagnosis, motor task, visual sampling instrument and motor task instrument of the reviewed studies

Author	Participants	PD Diagnosis	Motor Task	Visual Sampling Instrument	Motor task Instrument
(Anastasopoulos et al., 2011)	10 idiopathic PD (aged 58.3 ± 11 years) 6 males, 4 females 10 HC (aged 52 ± 2.6 years) (from a previous study)	H & Y I n = 4, H & Y II n = 6 Disease duration: range 1-9 years	Turning in place	EOG sampling at 240 Hz	3D motion analysis
(Desmurget et al., 2004)	*Study 1* - 7 PD (aged 56 ± 11 years) 3 males, 4 females 7 HC (aged 53 ± 7 years) 4 males, 3 females *Study 2* - 5 PD (aged 46 ± 8 years) 2 males, 3 females 5 HC (aged 55 ± 10 years) 2 males, 3 females	*Study 1 and 2 combined* H & Y II n=5*, H & Y III n=4, H & Y IV n=3 * One patient was classified as H & Y 2.5 Disease duration: range 6-17 years	Seated reaching task	EOG sampling at 1000 Hz	Finger movements were recorded using a magnetic tracking system
(Galna et al., 2012)	21 idiopathic PD (aged 67.6 ± 9.9 years) 14 males, 7 females 12 HC (aged 67.4 ± 8.7 years) 5 males, 7 females	H & Y I n = 1, H & Y II n = 13, H & Y III n = 7 Disease duration: 46.3 ± 50.9 months	Walking and turning (through a doorway)	EOG sampling at 1000 Hz	3D motion analysis
(Heremans et al., 2012)	14 PD (aged 59.1 ± 9.6 years) 9 males, 5 females. 14 HC (aged 61.1 ± 6.6 years) 8 males, 6 females.	H & Y I n = 5*, H & Y II n = 5, H & Y III n= 4 * One patient was classified as H & Y 1.5 Disease duration: range 0.5-17 years	Upper limb tasks	EOG sampling at 1024 Hz A chin rest restricted head movements	EMG of the forearm sampling at 1024Hz
(Lee et al., 2012)	2 PD (aged 56 and 59 years, driving history of 37 and 40 years, respectively) and 6 HC (aged 49.8 ± years)	56 year old PD: H & Y: 1.7, Disease duration: 4 years 59 year old PD: H & Y: 1.9, Disease duration: 6 years	Driving task (simulator)	Mobile infra-red eye tracker sampling at 60 Hz	NR
(Lohnes and Earhart, 2011)	23 idiopathic PD; 90 degree turn: n = 22 (aged 68.7 ± 10.2 years), 14 males, 8 females * 180 degree turn: n = 20 (aged 68.6 ± 10.8 years), 13 males, 7 females * Freezers (n=8), Non-freezers (n=12) 19 HC (68.8 ± 11.4) 11 males, 8 females * Data for the 90 degree turn (n = 1) and 180 degree turn (n = 2) was omitted due to poor oculomotor data quality	Numbers represent those for 90(180) degree turns H & Y I n = 1(1), H & Y II n = 19(17)*, H & Y III n = 2(2) * 10 of the participants in H & Y II were classified as H & Y 2.5 Disease duration: 90 degree turn: 7.4 ± 5.8 years 180 degree turn: 6.8 ± 5.6 years	Turning in place	Mobile eye tracker sampling at 360 Hz EOG sampling at 1000 Hz used as a secondary measure if unable to get data from eye tracker	3D motion analysis
(Marx et al., 2012)	11 PD (aged 65.5 ± 12.7 years) 8 males, 3 females (2 PD were wheelchair-bound) 10 HC (aged 68.3 ± 9.1 years) 4 males, 6 females	H & Y I n = 2, H & Y II n = 3, H & Y III n = 6 Disease duration: 6.2 ± 4.7 years	Walking	Mobile video oculography, gaze and head videos were sampled at 25 Hz and eye movements at 300 Hz	Head movements extracted via a fixed head camera and two high-speed cameras
(Muilwijk et al., 2013)	15 early stage PD (aged 61.1 ± 8.4 years) 10 males, 5 females 15 age-matched HC (aged 56.0 ± 6.4 years) 6 males, 9 females	H&Y ranged between I and II Disease duration: 3.7 ± 2.4 years	Eye-hand co-ordination during a computer based task	Static infra-red eye tracker sampling at 200 Hz	3D motion analysis of upper limbs sampling at 200 Hz Touch screen sampling at 60 Hz
(Sacrey et al., 2009)	8 mild PD (≤ 2.5 H&Y) (aged 63.9 ± 8.3 years) 2 males, 6 females 7 advanced PD (≥ 2.5 H&Y) (aged 75.0 ± 6.7 years) 4 males, 3 females 15 older adults HC (aged 62.8 ± 7.52 to 81.7 ± 5.0) 7 males, 8 females 11 young adult HC (aged 22.3 ± 3.9) 7 males, 4 females	H & Y I n = 2*, H & Y II n = 9**, H & Y III n = 1, H & Y IV n = 2 * One patient was classified as H & Y 1.5 ** Three patients were classified as H & Y 2.5 Disease duration: NS	Seated reaching task	Mobile infra-red eye tracker sampling at 60 Hz	Digital video camera recorded sagittal plane motion at 500 Hz. Data were digitised using Peak Motus
(Sacrey et al., 2011)	8 PD (aged 70.3 ± 6.8 years) 6 males, 2 females	H & Y I n = 4*, H & Y II n = 2**, H & Y III, n = 2	Seated reaching task	Mobile infra-red eye tracker	Digital video camera recorded

	8 HC (aged 69.0 ± 5.78 years) 3 males, 5 females	* Three patients were classified as H & Y 1.5 ** One patient was classified as H & Y 2.5 Disease duration: NS		sampling at 30 Hz	sagittal plane motion at 30 Hz. Data were digitised using Peak Motus
(Uc et al., 2006)	79 PD (aged 66.0 ± 8.6) 64 males, 15 females 151 HC (aged 65.3 ± 11.5 years), 75 males, 76 females	Mean H & Y: 2.1 ± 0.7 Disease duration: 5.6 ± 5.0 years	Driving task	Landmark and traffic sign identification test (LTIT)	ARGOS (Automobile for Research in Ergonomics and Safety) instrumented vehicle composed of hidden instrumentation and motion sensors. Miniature cameras mounted inside the vehicle sampling at 30 Hz
(Ventre-Dominey et al., 2001)	6 PD (aged 55.0 ± 10 years) 3 males, 3 females 9 HC (aged 53.5 ± 8.4 years) 5 males, 4 females	H & Y I n = 4*, H & Y II n = 2 * All four patients were classified as H & Y 1.5 Disease duration: 4.8 ± 2.1 years	Repetitive pointing task	EOG: Signals were filtered at 40 Hz and then digitised using a sampling frequency of 250 Hz	Touch-sensitive screen sampling at 1 kHz
(Ventre-Dominey et al., 2002)	9 PD (aged 54.9 ± 10.5 years) 6 males, 3 females A subgroup of 6 PD participants were assessed for both separate and coupled eye and hand movement: 6 PD (aged 55.0 ± 10 years) 3 males, 3 females 9 HC (aged 53.5 ± 8.4 years) 5 males, 4 females	PD cohort (n = 9) H & Y I n = 7*, H & Y II n = 2 * Six patients were classified as H & Y 1.5 Disease duration: PD cohort (n = 9) – 4.1 ± 2.1 years Sub-group (n = 6) – 4.8 ± 2.1 years	Repetitive pointing task	EOG: Signals were filtered at 40 Hz and then digitised using a sampling frequency of 250 Hz	Touch-sensitive screen sampling at 1 kHz
(Vitório et al., 2012)	12 idiopathic PD (aged 69.8 ± 5.72 years), 8 males, 4 females12 HC (aged 69.6 ± 6.04 years), gender not stated for control cohort	H & Y I n = 10*, H & Y II, n = 2** *5 were classed as H & Y 1.5, **1 was classed as H & Y 2.5 Disease duration: NS	Self-paced walking under 3 visual conditions: (i) dynamic (normal lighting), (ii) static (static visual samples), (iii) voluntary VS	Liquid crystal glasses for manipulation of vision Camcorder sampling at 60 Hz	3D referencing system and a force plate sampling at 200 Hz
(Vitorio et al., 2013)	12 idiopathic PD (aged 69.8 ± 5.72 years), 8 males, 4 females 12 HC (aged 69.6 ± 6.04 years) , gender not stated for control cohort	H & Y I n = 10*, H & Y II n = 2** *5 were classed as H & Y 1.5, **1 was classed as H & Y 2.5, Disease duration: NS	Walking and obstacle crossing	Camcorder sampling at 60 Hz	Two digital camcorders with 3D referencing system.

[NR: Not Reported, EOG: Electro-oculography, H&Y: Hoehn and Yahr, PD: Parkinson's disease, HC: Healthy control, Data are presented as means ± standard deviation unless otherwise stated]

Table 2. Inclusion and exclusion criteria, study aims, research design and outcome measures

Author	Inclusion Criteria	Exclusion Criteria	Design and Aims	Test Protocol	Visual outcome definition
(Anastasopoulos et al., 2011)	- 'ON' medication (2hrs prior) - All were right side dominant - Cohort were physically fit	- None of the cohort wore spectacles	**Experimental -** To assess whether hypometric saccades are secondary to low head movement velocity in PD	Turns-in-place from standing to visual (LED) cues placed at 45, 90, 135 and 180 degrees.	NR
(Desmurget et al., 2004)	All participants were: - Right handed - Absence of dementia and any other neurological disorders (other than PD for the PD cohort) - No signs of tremor - PD's were tested 'OFF' medication (12hr withdrawal)	NR	**Experimental -** To investigate the process of on-line motor correction in PD patients.	2 conditions: Relevant to this review was a seated upper-limb task	A single saccade was defined as an eye movement occurring >50°/sec
(Galna et al., 2012)	- Able to walk independently without an aid - Adequate vision, hearing and language skills to comply with testing and provide a fully informed consent	- Dementia (MOCA <17) - Dyskinesia, vision or hearing impairment - Moderate or severe tremor - No confounding co-morbidity (cardiovascular disease)	**Exploratory -** To compare saccade frequency and timing in PD and HC while walking through environments of differing complexity under single and dual task.	4 walking conditions - Straight walk single task - Straight walk dual task - Turn single task - Turn dual task	NR
(Heremans et al., 2012)	- PD diagnosed by a neurologist using the Brain Bank Criteria - PD participants were assessed 'ON' medication	- MMSE <24 - Severe tremor - Any neurological comorbidity - Unpredictable motor fluctuations - Eye movement abnormalities - Severe orthopedic problems of the upper limb - Receiving treatment with deep brain stimulation (PD only)	**Experimental -** To investigate whether cues (visual, auditory) positively affect mental imagery performance in PD patients.	Relevant to this review was a seated upper limb task PD subjects performed the tasks with their most affected side. HC did it side-matched. Head movement restricted with a chin rest.	Fixations were defined as stable gaze maintained for >100ms. Eye movements included 1 single primary saccade and 1 or more corrective saccades.
(Lee et al., 2012)	All participants wore corrective spectacles	NR	**Experimental -** To assess the reliability of driving assessments made from the back seat by two occupational therapists	Subjects drove a fixed route in a computer-based driving simulator.	
(Lohnes and Earhart, 2011)	*Common criteria* - Aged 30 years or older - Normal central and peripheral neurological function (excluding PD participants) - Able to stand independently for at least 30mins Walk independently without assistive device - No history of vestibular disease - No evidence of dementia *PD only* - 'OFF' dopaminergic medication - Diagnosis of definite PD by neurologist	- Any serious medical condition other than PD - Use of neuroleptic or other dopamine-blocking drugs - Use of medication known to affect balance (eg. benzodiazepines) - Evidence of abnormality on brain imaging - Other neurological deficits (stroke or muscle disease) - Surgical management of PD (DBS or pallidotomy)	**Experimental -** To determine whether saccadic activity is impaired whilst turning in PD.	Turns-in-place from standing to 90 and 180 degrees, right and left. No visual or auditory cues were provided.	A single saccade was defined as an eye movement occurring >30°/sec

(Marx et al., 2012)	- Clinically probable PD - No history of alcohol or substance abuse - Free from neurologic, systemic, or psychiatric disorder (other than PD for those participants) - PD participants were tested 'ON' medication	- Neurological disorders - Dementia (MMSE <24) - Any presently active psychiatric disorder - Any structural brain lesion, cataracts or other neuro-ophthalmological disorder - Visual correction by glasses as glasses cannot be worn with the eye tracker	**Experimental -** To establish mobile eye tracker usage in PD, HC and Progressive supra-nuclear palsy cases and validate its power to discriminate eye movements between these groups	2 tasks: Relevant to this study was a walking condition.	A single saccade was defined as an eye movement occurring >60°/sec
(Muilwijk et al., 2013)	- >45 years old - had normal cognitive function - were classified as having mild PD (PD cohort only; < 2.5 H&Y) - PD patients were tested 'ON' medication	- Dyskinesia - Coexistence of other neurological or psychiatric disorder - History of ocular pathology	**Experimental -** To quantify visuomotor coordination in early-stage PD patients	4 seated upper-limb tasks. Head movement restricted via chin rest.	A single saccade was defined as an eye movement occurring >50°/sec
(Sacrey et al., 2009)	All were required to have normal or corrected to normal (contact lens) vision HC's self-reported good health and had no history of neurological disorder PD's were required to be 'ON' medications	NR	**Experimental –** To investigate the effect of music (auditory cue) on sensory and motor impairments (during reaching task)	3 seated upper-limb conditions	NR
(Sacrey et al., 2011)	*Common criteria:* Normal or corrected to normal (contact lens) vision *HC only:* No history of neurological disorder *PD only:* Diagnosis of PD by experienced neurologist	NR	**Experimental -** To investigate the effects of music and medication on sensory control in PD (sensory monitoring and shifts during reach to eat task)	A seated upper-limb task PD participants were tested both 'ON' (1.5hr prior) and 'OFF' (12hr withdrawal) medication	NR
(Uc et al., 2006)	- Independently living and held a full and valid driver's license *PD only:* - Driving experience of at least 10years	- Cessation of driving before assessment - Acute illness or confounding medical conditions (vestibular disease) - Alcoholism or other substance abuse - Other neurological disease leading to dementia - Concomitant treatments - Treatment with investigational medication - Major psychiatric disorder - Ocular disease with normal or corrected visual acuity less than 20/50	**Experimental -** 1. To assess visual search using the landmark and traffic sign identification task (LTIT) while driving 2. To assess whether PD drivers make more safety errors as a result of the increased cognitive load imposed by the LTIT 3. To determine whether performance on the LTIT and safety errors could be accurately estimated by the measures (visual, cognitive and motor) known to decline in PD	A driving assessment in a car on the road PD participants were tested whilst 'ON' medication. All participants underwent a visual and cognitive testing battery that incorporated tests of basic visual sensory functions (contrast sensitivity and both near and far visual acuity) and visual perception.	No specific saccadic or fixation outcomes were assessed
(Ventre-Dominey et al., 2001)	- All participants were right handed PD's were tested 'ON' medication and displayed asymmetric akinetic-rigid syndrome HC's had no history of neurological or ophthalmological disorders	NR	**Experimental -** To investigate the role of the basal ganglia in eye-hand co-ordination (repetitive pointing)	A seated upper-limb task. Head movements were restricted via chin rest.	NR

(Ventre-Dominey et al., 2002)	*PD only:* - Tested 'ON' levodopa medication - Asymmetric akinetic-rigid syndrome - Diagnosis of PD (UK Brain Bank Criteria) HC's had no history of neurological or ophthalmological disorder	NR	**Experimental -** To investigate predictive saccades without hand pointing. Then investigate predictive saccade and pointing performance in an eye–hand coordination condition	A seated upper-limb task (same as that described in (Ventre-Dominey et al., 2001)) under two conditions: with and without visual stimulus. Head movements were restricted via chin rest	NR
(Vitório et al., 2012)	- Walk independently - Cognitively intact - No history of neurological, musculoskeletal or cardiorespiratory disease (other than PD for the PD cohort) PD's were tested 'ON' medication.	No PD participants experienced freezing of gait	**Experimental -** To investigate the role of visual information and locomotor control in people with PD.	2 walking conditions Participants wore liquid crystal glasses that manipulated visual input. Glasses were either opaque or transparent.	No specific saccadic or fixation outcomes were assessed.
(Vitorio et al., 2013)	PD and HC cohorts were matched for age, body height, body mass and gender - Walk independently - No cognitive, neurological, musculoskeletal or cardiorespiratory impairments PD participants were assessed 'ON' medication (1hr prior)	NR	**Experimental -** To investigate the role of visual information on locomotor control in PD as they negotiated obstacles	3 walking conditions (under static and voluntary VS) Participants wore liquid crystal glasses that manipulated visual input. Glasses were either opaque or transparent.	No specific saccadic or fixation outcomes were assessed.

[NR denotes not reported]

Table 3. Summary of the reported visual sampling outcomes and PD impairments during complex motor tasks

	Saccade						Fixation		Visual sampling	
Visual Outcome / Motor Task	Velocity	Direction	Duration	Frequency	Latency	Amplitude	Duration	Frequency	Saccades and Fixations	
									Frequency	Duration
Walking	✓ (↑)	✓ (-)	✓ (↑)	✓ (↓)	NR	✓ (↑)	NR	NR	✓ (↓)	✓ (↓)
Obstacle crossing	NR	NR	NR	NR	NR	NR	NR	NR	✓ (↓)	✓ (↓)
Turning in place	✓ (↓)	NR	NR	✓ (↑)	✓ (↓)	✓ (↓)	NR	NR	NR	NR
Upper-limb tasks	✓ (↓)	NR	✓ (↑)	NR	✓ (↑)	✓ (↓)	NR	NR	NR	NR
Driving	NR	NR	NR	NR	NR	NR	NR	✓ (↓)	✓ (↓)	NR

[✓= Reported outcome for both PD and HC, NR denotes not reported, '↓' indicates PD subjects less than HC, '↑' indicates PD subjects more than HC, '-' indicates no difference between PD and HC]

Table 4. Recommendations for future research.

• Use task-appropriate instrumentation to measure VS with temporal resolution ≥50Hz for saccade detection • If measuring saccade durations use a temporal resolution of ≥200Hz, which may involve combining devices • Report the reliability and validity of any instrument used to monitor VS • Use an adequately powered sample size • Define all visual outcomes and measure using a task-dependent or adaptable algorithm • Routinely assess and control for basic visual function and cognition

Supplementary Data 1. Reason for exclusion of studies (n = 47)

NON MOTOR TASK			MOTOR TASK				No age-matched controls
Computer based task	Visual function	**Visual task**	**Simple motor Task**	**Bulletin/ review/ conference**	**Unrelated VS & motor task**	**No measure of visual sampling**	
(Archibald, Hutton, Clarke, Mosimann, & Burn, 2013)	(Corin, Elizan, & Bender, 1972)	(de Hemptinne, Ivanoiu, Lefevre, & Missal, 2013)	(Shimizu, Naito, & Yoshida, 1981)	(Baziyan, Chigaleichik, Teslenko, & Lachinova, 2007)	(Bekkering et al., 2001)	(Tropini, Chiang, Wang, Ty, & McKeown, 2011)	(Lohnes & Earhart, 2012a)
(Cameron, 2011)	(Harris, Atkinson, Lee, Nithi, & Fowler, 2003)	(Economou & Stefanis, 1978)	(Weinrich & Bhatia, 1986)	(Naushahi et al., 2012)	(Crawford, Goodrich, Henderson, & Kennard, 1989)		(Temel, Visser-Vandewalle, & Carpenter, 2008)
(Cools, Rogers, Barker, & Robbins, 2010)	(Duval & Beuter, 1998)	(Flowers & Downing, 1978)	(Yoshida, Warabi, Kato, Kiriyama, & Yanagisawa, 2005)		(Lohnes & Earhart, 2012b)		(Temel, Visser-Vandewalle, & Carpenter, 2009)
(Fielding, Georgiou-Karistianis, Millist, & White, 2006) **(Fielding, Georgiou-Karistianis, & White, 2006)**		(Gibson, Pimlott, & Kennard, 1987) (Hansen, Gibson, Zangemeister, & Kennard, 1990)			(Lord, Archibald, Mosimann, Burn, & Rochester, 2012)		(Velasques et al., 2007)
(Gurvich, Georgiou-Karistianis, Fitzgerald, Millist, & White, 2007)		(Highstein, Cohen, & Mones, 1969)					
(Hodgson, Tiesman, Owen, & Kennard, 2002)		(Hochstadt, 2009)					
(Inzelberg, Schechtman, & Hocherman, 2008)		(Horowitz, Choi, Horvitz, Cote, & Mangels, 2006)					
(Joti, Kulashekhar, Behari, & Murthy, 2007)		(MacHner et al., 2010)					
(Kimmig, Haußmann, Mergner, & Lücking, 2002)		(Marino et al., 2007)					
(Kuechenmeister, Linton, Mueller, & White, 1977)		(Pinnock, McGivern, Forbes, & Gibson, 2010)					
(Mannan, Hodgson, Husain, & Kennard, 2008)		(Poujois et al., 2007)					
(van Stockum, MacAskill, Anderson, & Dalrymple-Alford, 2008)		(Praamstra, Stegeman, Cools, & Horstink, 1998)					
(van Stockum, Macaskill, Myall, & Anderson, 2011)		(Sampaio et al., 2011)					
(van Stockum, MacAskill, & Anderson, 2012)		(Shibasaki, Tsuji, & Kuroiwa, 1979)					
(van Stockum, MacAskill, Myall, & Anderson, 2013)		(Terao et al., 2011)					
		(van Koningsbruggen, Pender, Machado, & Rafal, 2009)					
		(von Noorden & Preziosi, 1966)					

Supplementary Data 2. Detailed visual outcome measures and key findings

Author	Visual Outcome Measures	Key Findings
(Anastasopoulos, Ziavra, Savvidou, Bain, & Bronstein, 2011)	Initial saccade: Velocity Amplitude Frequency Latency	1. PD participants made more eye movements than HC ($P < .0001$) with reduced contribution from the trunk and head during turning (Eye movements were observed first followed by head/trunk movement). 2. Reduced initial saccade velocity was recorded in PD participants compared to HC (non-significant) 3. PD participants demonstrated smaller initial saccade amplitudes than HC (non-significant) 4. Significantly decreased single-step saccade frequency ($P = .0006$) was observed in PD patients. As well as no significant group difference in latencies.
(Desmurget et al., 2004)	Eye position (mm) Initial saccade: Latency Peak velocity Duration Amplitude	1. PD participants demonstrated longer saccadic reaction times compared to HC (Statistical trends were observed) 2. On-line (in vision) movement corrections are impaired in PD subjects compared to HC due to an inability to adjust force control with changing requirements. 3. Initial saccade peak velocity and amplitude are all reduced in PD compared to HC 4. Initial saccade duration and latency were increased in PD compared to HC None of the vision contrasts between PD and HC were statistically significant
(Galna et al., 2012)	Frequency of early and late saccades (under single and dual task conditions)	1. People with PD explored their environment less than HC, particularly when approaching a turn or when distracted (dual tasking) 2. Under single task conditions, PD participants made 30% less saccades than HC (non-significant) 3. PD participants made less saccades than HC under dual task conditions ($p < .04$)
(Heremans et al., 2012)	Eye movement: Time between fixations Frequency Amplitude	Goal-directed aiming task (GDAT) and Box and block task (BBT) 1. No differences were found between the number of eye movements or amplitudes observed during the physical execution and mental imagery tasks, but no significant differences were noted between cohorts.
(Lee, Yanting Chee, Selander, & Falkmer, 2012)	Visual fixations were monitored with respect to seven AOI's. Analyses of fixations were relative to seven predefined AOI in the car (i.e. mirrors, speedometer etc.)	1. PD subjects kept their head still and made reduced eye movements in comparison to the HC group 2. PD subjects reportedly made fewer fixations on AOI's compared with that observed in HC subjects for all testing parameters
(Lohnes & Earhart, 2011)	Number of saccades Initial saccade: Velocity Amplitude Total frequency	1. Saccades were impaired during turning in people with PD 2. PD participants made the initial saccade earlier compared to HC. The earlier saccade was accompanied by reduced initial saccade velocity ($p < .01$) and amplitude ($p < .01$, only for 180 degree turn) compared to that of HC 3. PD participants demonstrated increased saccade frequency than HC ($p < .01$)

(Marx et al., 2012)	Saccades: Peak velocity Amplitude Duration Direction	1. PD subjects demonstrated reduced saccade duration compared to HC ($p < .05$) 2. PD subjects 'compensate' for saccade activity impairments when walking 3. Saccade peak velocity, amplitude and duration are all increased in PD compared to HC when walking (non-significant) 4. There was no difference between the groups for saccade direction
(Muilwijk, Verheij, Pel, Boon, & van der Steen, 2013)	Saccade latency	1. Initiation of saccades in goal directed tasks was not affected. 2. Eye movements (during tasks ii and iii) were initiated faster by PD participants. The authors attributed this to a difficulty suppressing reflexive saccades in early stage PD 3. Hand movements were delayed in PD participants (tasks i and ii) 4. Saccade latency of PD participants was equal to or less than HC in 3 of the 4 tasks (pro, anti-tapping and dual planning). PD subject saccade latency was increased compared to HC in the spatial memory task.
(L. A. Sacrey, Clark, & Whishaw, 2009)	Saccadic activity: Latency Fixation duration	1. Visual activity during reaching in mild PD is similar to HC subjects (both young and old), but was impaired in advanced PD compared to HC. 2. The time from visual engagement to the grasping of the food item and the time from grasping the food item to visual disengagement was significantly longer in the advanced PD cohort compared to the three other groups (mild PD, young adults and older adults; $p < .0001$)
(L. A. R. Sacrey, Travis, & Whishaw, 2011)	Saccadic activity: Latency Fixation duration	1. When listening to music, PD participants (both medicated and un-medicated) took longer to initiate a reaching movement after a visual fixation compared with HC ($p > .05$). They exhibited an impaired switching of visual attention and somatosensory guidance 2. Medicated PD subjects have to fixate for a similar duration as HC participants, whereas un-medicated PD fixated significantly longer ($p < .05$) 3. Saccade latencies were significantly increased in both medicated and non-medicated PD compared to HC participants ($p < .05$)
(Uc et al., 2006)	LTIT: Visual search score which included the per cent of landmarks and traffic signs identified and the number of at fault safety errors	Visual search was quantified by the score derived from the LTIT. The findings indicated that: 1. Visual search was impaired in PD compared to HC participants (total identification of landmarks and traffic signals was significantly less and the number of at-fault errors was significantly greater; $p < .001$. These differences persisted even when accounting for familiarity of the location/ region, far and near visual acuity, gender, driving exposure and level of education) 2. Cognitive (visuospatial and attention), visual (visual acuity and contrast sensitivity), and balance deficits were observed in PD participants
(Ventre-Dominey, Ford Dominey, & Broussolle, 2001)	Saccades: Latency	1. Eye-hand coupling is preserved in PD participants 2. PD subjects demonstrated longer saccade latencies for both hands compared to HC ($p < .0001$) 3. Differences in saccade latencies were even more pronounced when PD participants pointed with the 'affected hand'.
(Ventre-Dominey, Dominey, & Broussolle, 2002)	Initial saccade: Amplitude Latency Frequency	1. Pointing reduced saccade frequencies in PD subjects compared to HC's but increased frequencies when using PD affected limb. 2. Saccade latencies were longer in PD subjects than HC (non-significant)
(Vitório et al., 2012)	Voluntary visual samples: Frequency Duration	1. No significant differences were found between PD and HC participants in terms of their visual activity during walking. 2. Under single task PD made 25% less visual samples than HC (non-significant) 3. Duration of VS was less in PD subjects than HC (non-significant)
(Vitorio et al., 2013)	Voluntary visual samples: Frequency Duration	1. People with PD are more dependent on dynamic visual information than HC 2. PD subjects made significantly less visual samples than HC subjects 3. Reduced duration of VS in PD compared with HC (non-significant)