

Impact of optic flow perception and egocentric coordinates on veering in Parkinson's disease

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Spatial navigation is a complex process requiring integration of visuoperceptual information. The present study examined how visuospatial function relates to navigational veering in Parkinson's disease, a movement disorder in which visuospatial cognition is affected by the degeneration of the basal ganglia and resulting dysfunction of the parietal lobes. We hypothesized that patients whose initial motor symptoms start on the left versus right side of the body (LPD, predominant right-hemisphere dysfunction; RPD, predominant left-hemisphere dysfunction) would display distinct patterns of navigational veering associated with the groups' dissimilar visuospatial profiles. Of particular interest was to examine the association of navigational veering (lateral deviation along the medio-lateral axis) with perception of egocentric coordinates and of radial optic flow patterns, both of which are mediated by the parietal lobes. Thirty-one non-demented Parkinson's disease patients (16 LPD, 15 RPD) and 18 healthy control (HC) adults received visuospatial tests, of whom 23 Parkinson's disease patients and 17 HC also underwent veering assessment. The participants were examined on three visual-feedback navigation conditions: none (eyes closed), natural, and optic flow supplied by a virtual-reality headset. All groups veered to the left when walking with eyes closed, women with Parkinson's disease more so than the other participants. On the navigation assessments with visual feedback, only LPD patients deviated right of centre. On tests of visuospatial function, the perceived midline was shifted rightward in LPD (men and women), increasingly so with the addition of visual input. In contrast, men with RPD showed leftward deviation. RPD patients and HC perceived optic flow in the left hemifield as faster than in the right hemifield, with a trend for the opposite pattern for LPD. Navigational veering in LPD was associated with deviation of the perceived egocentric midline and not with perception of optic flow speed asymmetries, and in RPD it was also associated with visual dependence, though in fact LPD subjects were more visually dependent than those with RPD. Our results indicate that (i) parietal-mediated perception of visual space is affected in Parkinson's disease, with both side of motor symptom onset and gender affecting spatial performance, and (ii) visual input affects veering.

Keywords: Parkinson's disease; navigation; optic flow; visuospatial

Abbreviations: cpd = cycles per degree; ECRP = egocentric reference point; HC = healthy control; LPD = Left-onset Parkinson's disease; NVF = natural visual feedback; PSE = point of subjective equality; RPD = Right-onset Parkinson's disease; VR = virtual reality

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Introduction

Spatial navigation is a complex set of behaviours that includes the processing of incoming sensory information and the continuous updating of one's position relative to spatial landmarks. Systematic biases in processing of incoming perceptual information may contribute to

abnormalities in spatial navigation, including lateral drift, or veering. The present study examined how vision and visuospatial function relates to navigational veering in Parkinson's disease, a movement disorder that is increasingly recognized as causing alterations in cognition and perception. Impairments in basic vision as well as in

higher-order visuospatial function are well documented in Parkinson's disease (Bodis-Wollner *et al.*, 1987; Cronin-Golomb and Braun, 1997; Lee *et al.*, 1998, 2001*a, b*; Amick *et al.*, 2003, 2006; Davidsdottir *et al.*, 2005; Schendan *et al.*, in press), and may well underlie patients' difficulty with spatial navigation beyond the effects of motoric dysfunction.

Information about heading during navigation may be gained from either perception of optic flow patterns or perceived location of a goal (Harris and Carre, 2001; Warren *et al.*, 2001; Kearns *et al.*, 2002; Fajen and Warren, 2004; Turano *et al.*, 2005). Asymmetries in optic flow bias the perceived heading towards the hemifield in which there is slower flow speed (Dyre and Andersen, 1996); a strategy for steering down a corridor is to equalize the speed of optic flow across the left and right hemifields (Srinivasan *et al.*, 1991; Duchon and Warren, 2002). Besides optic flow, the perceived location of a goal may influence one's path of movement (Rushton *et al.*, 1998; Harris and Bonas, 2002). The egocentric reference point (ECRP) divides space into two lateral hemifields with respect to the midline of the trunk (Karnath *et al.*, 1991), providing a framework for spatial orientation and goal-directed actions, including walking (Hasselbach-Heitzeg and Reuter-Lorenz, 2002). Functional neuroimaging has demonstrated that parietal areas are recruited both in perception of optic flow patterns (Peuskens *et al.*, 2001) and computation of the midline (Vallar *et al.*, 1999). Shifting of the perception of the egocentric midline may be seen in patients with spatial neglect associated with extensive right parietal lesions (Karnath, 1994; Hasselbach and Butter, 1997), together with shifting in extrapersonal (allocentric) midpoint estimates, such as is observed on line bisection tests (e.g. Rorden *et al.*, 2006). While shifting in extrapersonal midpoint estimates has been reported in Parkinson's disease, consistent with a neglect-like pattern (Lee *et al.*, 2001*a*), neither egocentric midline shifting nor optic flow perception has been examined in this disorder. Impairments in these functions may be expected because of dysfunction of basal ganglia-thalamocortical circuitry that extends to the parietal lobe (Middleton and Strick, 2000*a*; Clower *et al.*, 2005; Bartels *et al.*, 2006).

A factor of potential importance in investigating the association between deficits in visuospatial perception and veering in Parkinson's disease is the hemispheric side of disease onset. Parkinson's disease patients who initially experience motor symptoms on the left side of their body (LPD), reflecting predominantly right-hemisphere dysfunction, generally present with more pronounced disturbance on tests of spatial perception than do patients whose motor symptoms start on the right side of their body (RPD, predominantly left-hemisphere dysfunction) (Blonder *et al.*, 1989; Lee *et al.*, 2001*a, b*; Harris *et al.*, 2003). There is evidence that the representation of external space (particularly left hemispace) in LPD patients is compressed (Lee *et al.*, 2001*a, b*). These findings are consistent with LPD

having a shift of midline perception to the right. It is also relevant that parietal activation in the perception of optic flow patterns is predominantly in the right hemisphere (Peuskens *et al.*, 2001) and therefore optic flow perception as well as egocentric midline alignment may be particularly deficient in LPD patients.

When the integrity of optic flow perception is compromised, such that optic flow speed perception is asymmetrically affected, or the midline is misaligned, systematic heading errors in navigation (veering) may be expected. The aim of the present study was to examine navigational veering in Parkinson's disease and the contributions of disturbances in the perception of optic flow and the egocentric midline to biases in this behaviour. It was predicted that persons with Parkinson's disease, who have impairments in multiple visuospatial domains, would experience an imbalanced optic flow pattern, in which motion in the non-compressed side of space is perceived to be faster than in the compressed space, wherein points of texture appear to travel a shorter distance in the same amount of time. Such inaccuracy in visual perception during navigation would result in a biased path of locomotion. In the case of LPD, with greater right than left parietal dysfunction, perceived compression of the left hemispace would translate into the perception of slowed optic flow speed on that side. Because individuals move away from the side of faster-moving flow, LPD should veer to the left. In contrast to the results predicted for optic flow perception, if LPD have a rightward shift of the egocentric midline, one would expect rightward veering. Predictions in both cases are less clear for RPD, for whom there is less evidence of spatial distortion. As Lee and colleagues (2001*b*) provided some evidence that spatial perception is expanded rather than compressed in RPD, one might expect these individuals to show a pattern of veering opposite that of LPD. Investigation of the direction of veering would provide evidence of the preferential use of optic flow perception or midline reference to update position during spatial navigation in Parkinson's disease. To this purpose we manipulated optic flow speed during an open-field test of spatial navigation and assessed the role of midline estimation as well as vision and other visuospatial function in veering.

Methods

Participants

There were 49 individuals in the study: 31 patients with idiopathic Parkinson's disease (15 men, 16 women) and 18 healthy control (HC) adults (nine men, nine women). Consent was obtained according to the Declaration of Helsinki. The study protocol was approved by the Institute Review Board of Boston University. All participants were native speakers of English. Exclusion criteria included co-existing serious chronic medical illnesses (including psychiatric or neurological), use of psychoactive medications besides antidepressants and anxiolytics in the Parkinson's disease

group, use of any psychoactive medications in the HC group, history of intracranial surgery, traumatic brain injury, alcoholism or other drug abuse, or eye disease or abnormalities as noted on a neuro-ophthalmological examination. Individuals who had a physical disability that prevented them from moving freely in the open-field spatial navigation task (such as past knee or hip surgeries or lower back pain) were excluded from the study. Participants were not demented as indicated by scores of 26 or above on the Mini-Mental State Examination (MMSE; Folstein *et al.*, 1975) and 135 or above on the Mattis Dementia Rating Scale (DRS; Mattis, 1976, 1988).

The Parkinson's disease patients included 16 with LPD (nine men, seven women) and 15 with RPD (six men, nine women). Only Parkinson's disease patients with clear asymmetric onset of motor symptoms were enrolled in the study. Initial side of motor symptom onset was affirmed with a review of neurology records. Although most individuals were experiencing motor symptoms on both sides of their body at the time of the study, this was acceptable because hemispheric brain disease asymmetry is maintained after motor symptoms have progressed from unilateral to bilateral (Rinne *et al.*, 1993). Motor disability as indexed by Hoehn and Yahr stage (H & Y; Hoehn and Yahr, 1967) was similar for the LPD and RPD groups, Kolmogorov-Smith (K-S) $Z=0.51$, $P=0.96$. The median stage of H&Y was 2 (off medications). Only one patient was stage 1.5 (unilateral), 25 were stage 2 (mild bilateral), four were stage 3 (moderate bilateral with postural instability) and one was stage 4 (considerable disability but able to walk independently). Age and education were matched for LPD, RPD and HC, $F(2, 46)=0.43$, $P=0.65$ and $F(2, 46)=0.34$, $P=0.72$, respectively. Mean age in years for LPD was 60.0 (SD=8.6); RPD 62.8 (SD=7.8); HC 61.2 (SD=8.8). Mean education in years for LPD was 16.6 (SD=2.6); RPD 17.0 (SD=2.9); HC 16.2 (SD=2.6). The three groups performed similarly on the MMSE and the DRS, $F(2, 46)=0.38$, $P=0.69$ and $F(2, 46)=0.74$, $P=0.48$, respectively. All participants were right-handed except for one LPD and one HC. Mean Parkinson's disease duration was 5.9 years (SD=3.4, range 1–15) with no difference between LPD and RPD, $t(29)=1.51$, $P=0.14$ (LPD: $M=6.8$ years; SD=3.6, range: 1–15; RPD: $M=4.9$ years, SD=3.1, range 1–11).

Mood functioning was assessed with the Beck Depression Inventory-2 (BDI-2; Beck, 1987). A one-way analysis of variance (ANOVA) demonstrated that there were significant group differences, $F(2, 46)=8.44$, $P=0.001$. *Post hoc* Scheffé *t*-tests showed that LPD and RPD scored higher on the BDI-2 than did HC ($P=0.002$ and $P=0.009$, respectively) and that LPD and RPD did not differ ($P=0.91$). Thirty-seven participants scored within the normal range on the BDI-2 (range 0–9), including all HC and 19 Parkinson's disease patients. Depression scores were used as a covariate in the main experimental analyses. There was no difference in the level of Parkinson's disease-related disability for LPD and RPD as measured with the Parkinson's Disease Quality of Life Inventory-39 (Jenkinson and Fitzpatrick, 2003), $t(29)=1.34$, $P=0.19$.

The majority of patients reported using dopamine agonists (24, or 77%) and/or levodopa (27, or 87%). Six (19%) used monoamine oxidase inhibitors and catechol-*O*-methyltransferase inhibitors and ten (32%) used amantadine or anticholinergic agents. Nine (29%) reported using antidepressant or anti-anxiety

medications. LPD and RPD did not differ significantly in medication usage.

Characteristics of participants who completed the walking assessment

Of the 31 Parkinson's disease patients and 18 HC who volunteered to participate in the study, 23 Parkinson's disease patients and 17 HC completed the assessment of veering during walking. There were eight individuals for whom we were unable to schedule the walking assessment within a short enough time of the visuospatial testing, or who declined the opportunity to schedule a session to walk in the optic flow virtual reality (VR) condition after introduction to the optic flow environment on a perceptual measure. The majority of these individuals were RPD (seven of eight). Demographics, disease variables (duration and motor disability) and basic visual functioning were similar between Parkinson's disease patients who did and who did not complete the walking session. Additionally, veering data from the two left-handed individuals (1 LPD, 1 HC) were not included in the analyses, because both individuals demonstrated an exaggerated degree of veering compared with their group counterparts, consistent with reports that handedness affects lateralized motor preference (Mohr *et al.*, 2003). This was a conservative decision, as it is likely that failure to exclude the LPD patient would have produced larger statistical effects for the deviation of the LPD group. Both of these individuals demonstrated rightwards veering; the left-handed LPD veered 202 mm rightward (12 times that of right-handed LPDs) and the left-handed HC veered 106 mm rightward, which is a shift both in magnitude and direction of veering compared to other HC. In sum, veering data from 14 LPD, 8 RPD and 16 HC are reported, with groups matched for age and education, $F(2, 38)=0.20$, $P=0.82$ and $F(2, 38)=0.38$, $P=0.69$, respectively, and with equal numbers of men and women in each group. There were no significant differences between LPD and RPD for disease duration, $t(20)=1.58$, $P=0.13$; extent of motor disability as measured by the H&Y scale, K-S $Z=0.48$, $P=0.97$, or for participant characteristics or vision assessments (described in the Results section).

Procedures

Assessment of veering in an open-field environment

Navigation with natural visual feedback and eyes closed. Prior to data collection, participants were trained to walk a 15 m long pathway with eyes open at 0.8 ± 0.1 m/s and to maintain this walking speed throughout the session. There were five trials conducted with eyes open, then five with eyes closed. The participant was then fitted with a headset (head-mounted display), which was connected to a VR system. Five additional training trials were conducted in which the participant wore the head-mounted display and was instructed to walk at the target speed with eyes open. Three-dimensional kinematic data were collected through an Optotrak/3020 System (Northern Digital Inc., Waterloo, ON, Canada). An Optotrak bank was placed on each side of the walkway and a third bank was located at the end of the walkway in order to capture bilateral movements for at least eight strides. Calibrations among the three banks were accepted when the mean error was 1.5 mm or less. Infrared light emitting diodes (LEDs) were placed bilaterally on ankles, knees (patella), hips

(anterior superior iliac spine), wrists (radiocarpal joint), shoulders (humeral head), cheeks (2 cm below zygomatic arch) and chin. Small adjustments from these positions were made to increase LED visibility when necessary. The instantaneous position of each LED was sampled at a rate of 100 Hz and stored to disk for further analysis. The average between left and right hip position data in the Z-axis (medio-lateral axis) was used to estimate heading drift during walking. The measure of drift was the signed distance between Z_1 and Z_n ($\text{Drift} = Z_n - Z_1$). Z_n was the maximum positive value in the Z-direction of the last stride cycle and Z_1 was the maximum positive medio-lateral deviation of the first stride cycle.

Navigation in a VR corridor with symmetrical optic flow. The procedure was similar to the open-field natural visual feedback (NVF) condition, except that VR input was applied. The VR input consisted of a virtual hallway, which was composed of two sidewalls of white random dots on a black background, with a black floor and ceiling devoid of texture. There was one condition in which the white dots on the black backgrounds were stationary (0.0 m/s), and four in which optic flow speed was symmetric across hemifields (0.4, 0.8, 1.2 and 1.6 m/s). This perceived scene was consistent with self-motion through a three-dimensional corridor. Across VR trials, participants always walked down the hallway at a speed of 0.8 m/s while optic flow speed was varied. There were five training trials followed by the experimental conditions, each of which consisted of five walking trials.

The virtual hallway was created using World ToolKit Release 9 (Sense8, San Francisco, CA, USA) on an Onyx2 Reality graphics work station (Silicon Graphics Inc., Mountain View, CA, USA). The scene was displayed on a ProView 60 head mounted display (Kaiser Opto-Electronics Inc, Mountain View, CA, USA) weighing 1.75 lbs. This display contained two active LCD panels (640 × 480 resolution, true color, 60 Hz) and had a 60° field of view (diagonal) with 100% overlap to allow for true stereo viewing. Field of view was restricted to the VR environment by an additional mask that occluded vision outside the LCD panels. Head coordinates (except for the anterior-posterior axis) were tracked in real time, using an IS 900 LAT system (InterSense, Burlington, MA, USA) and the information was used to update the visual scene. The dots disappeared off the edges of the LCD panels and reappeared at the open end of the hallway. The depth of the hallway ahead of the participants remained constant regardless of the position of the participants—that is, an infinite hallway was created in which the participants could not move closer to the end of the hallway, but they were still able to experience motion parallax and move closer to the right or left wall.

Visual functioning

We assessed acuity, contrast sensitivity and planar motion perception. Participants used their own refractive correction. Most participants (24/31 Parkinson's disease and 13/18 HC) underwent a neuro-ophthalmological examination to ensure eye integrity, ruling out any ocular disease or other abnormalities; the rest experienced scheduling difficulties. There was no significant difference in the basic visual functioning of individuals who underwent this exam and those who did not (e.g. letter-identification contrast sensitivity, $t(6.47) = -0.65$, $P = 0.54$).

Acuity. Snellen eye charts (Lighthouse Company, New York, NY, USA) were used to measure near binocular visual acuity at 16 in.

Contrast sensitivity. was assessed binocularly with near (16 in.) and far (10 ft) Functional Acuity Contrast Test charts (FACT: Stereo Optical, Chicago, IL, USA) and a computer-based letter-identification measure. The FACT determined contrast sensitivity level for five spatial frequencies: 1.5, 3, 6, 12 and 18 cycles per degree (cpd). The computer-based letter-identification measure is a genuine threshold test, similar to one used to demonstrate contrast sensitivity deficits in Parkinson's disease (Amick *et al.*, 2003). This task uses a ZEST procedure that permits the reliable determination of a threshold in relatively few trials. Further details of both contrast sensitivity tests are available in Gilmore *et al.* (2005).

Planar motion perception. Participants viewed a single centrally presented field in which coherent motion appeared to move either up or down. The task was to state the direction of coherent dot motion (up or down). The window of motion was 200 × 200 pixels subtending 6.9° of visual angle. Each dot subtended ~0.069° of visual angle and was displayed for 24 ms. Noise dots were randomly replotted. Coherent dot motion varied from 0% to 100%. Responses were recorded on computer by the examiner. Threshold was determined using a staircase procedure with a stopping criterion of 25% standard error of the estimate. Further details of this test are available in Amick *et al.* (2003).

Visuospatial functioning

We assessed visual dependence and line bisection, the latter of which is sensitive to spatial neglect, in addition to optic flow perception and egocentric reference.

Visual dependence. We used large-screen presentation of a 1.5 m horizontal line (53.1° of visual angle) that was tilted at the outset of each trial (initial tilt ranging from 9° to 12°). Azulay *et al.* (2002) reported increased visual dependence in Parkinson's disease using a similar test. Participants indicated when the rod was horizontal. There were 10 trials, with equal number of trials in which the left end of the line was initially tilted upwards and downwards. The angle of the line was gradually altered to become more horizontal by 1° increments. Mean deviation from horizontal reflected the level of visual dependence.

Line bisection. The Landmark test of line bisection has been used to demonstrate lateral biases in allocentric spatial perception in Parkinson's disease (Lee *et al.*, 2001a). This version of the test did not require use of motor skills and did not have time limits. Participants sat in front of a projection screen, trunk aligned with a predetermined midpoint. A 2.2 m horizontal line and a vertical cursor were projected on the screen (72.5° of visual angle). The cursor was initially presented on the left or the right of the line's true center, at a starting point of 8–12% deviation (of the total length of the horizontal line). Cursor adjustments were made in increments of 0.5% of the total line length. There were 10 trials, with equal number of trials in which the cursor initially appeared on right and left. The examiner moved the cursor towards the line's center and the task was to state when the cursor fell in the center of the horizontal line. Lateral deviation of the judgment of the center of the horizontal line was analysed.

Optic flow perception. Perception of expansive optic flow patterns was measured by manipulating optic flow speeds in the two hemifields. Participants sat in front of a large projection screen using a headrest to align them with a predetermined

midpoint. Two mirror-symmetrical stimulus fields were presented simultaneously on both sides of fixation, each extending 41° to the periphery. The symmetrical fields resembled the hallway in the VR walking trials, in that they were composed of two sidewalls of white random dots on a black background with a black floor and ceiling devoid of texture. On the optic flow task, differences in motion speed for the dots were introduced by gradually varying the temporal frequency in one of the two stimulus fields, starting from either a very slow (0.0–0.15 m/s) or fast (1.45–1.60 m/s) speed compared to the fixed-speed visual field for that set of trials (0.80 m/s). Speed adjustments were made in increments or decrements of 0.05 m/s. This perceived scene was consistent with self-motion through a three-dimensional corridor. On trials in which one hemifield speed was held constant, the participant was asked to determine whether movement in the other hemifield was faster, slower or the same speed as in the first hemifield. There were 20 trial sets, 10 for each fixed-speed visual field, for a total of 636 judgments about the relative hemifield speeds. The point of subjective equality (PSE) was obtained when the participant judged the speed of optic flow in the two hemifields as equal. The PSE indicated whether there was a hemifield imbalance that distorted the perceived symmetry of the optic flow.

Egocentric reference point. ECRP, which divides space into two hemifields by way of perception of the spatial midline, was measured by means of a pointing task (Heilman *et al.*, 1983). Participants sat with the sternum aligned to a predetermined point, using a headrest. They placed the index finger on the sternum for a reference, then pointed straight ahead, then lowered the arm to place the index finger on the desk. There were two conditions for this test, one with eyes open (five trials each with right and left hands) and one with eyes closed (five trials each with right and left hands). There was a large sheet on the desk, on which the experimenter marked the placement of the index finger. Responses were analysed for lateral deviation in estimates of the perceived straight-ahead.

Notes on statistical analyses

Analyses were corrected for multiple comparisons (Bonferroni method). Analysis of covariance was used to account for variables that could affect the dependent measures (e.g. age disease onset; disease duration). In all cases, gender was examined as a variable but is mentioned in results only if there was a significant effect.

Results

Veering during open-field spatial navigation

Statistical results of the veering assessments appear in Table 1.

Eyes-closed condition. All groups veered leftward. While women demonstrated greater leftward veering than men in the Parkinson's disease group, there was no significant difference between men and women in the HC group (Fig. 1).

Natural visual feedback condition (eyes open). Veering was affected by group but not by gender or trial order. The LPD group veered rightward, and differed significantly from the other two groups, whereas RPD and HD veered leftward

Table 1 Results of ANOVA for veering and sources of variance for eyes-closed, NVF and VR conditions

	d.f.	F	P
Eyes-closed condition			
Group	2	1.57	0.21
Gender	1	5.18	0.02
Group \times gender	2	3.99	0.02
Group \times condition	1	2.86	0.09
Gender \times condition	1	0.19	0.67
Group \times gender \times condition	1	2.83	0.09
Error	184		
NVF condition (eyes open)			
Group	2	11.60	<0.001
Trial order	1	0.93	0.34
Gender	1	0.72	0.39
Error	368		
VR condition			
Group	2	29.83	<0.001
Gender	1	3.61	0.06
Optic flow speed	1	1.88	0.11
Error	918		

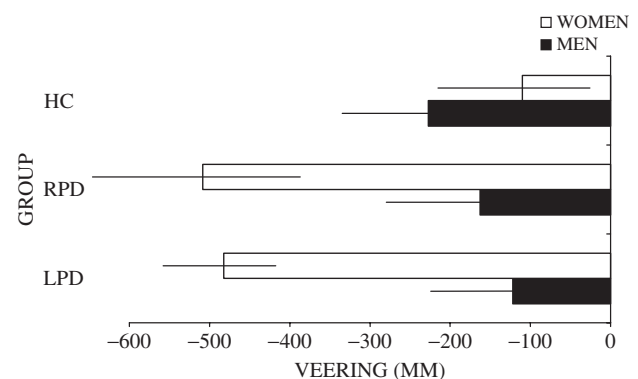


Fig. 1 Veering during a walking trial without visual feedback (eyes closed). HC: eight women, eight men, LPD: seven women, seven men, RPD: four women, four men. Negative signs represent leftward deviation from the true centre. Horizontal lines represent standard error of the mean.

and did not differ from each other ($P=0.61$) (Tukey *post hoc* tests) (Fig. 2).

Virtual reality condition. As in the NVF condition, LPD veered rightward and RPD and HC veered leftward. LPD differed significantly from RPD and HC, and HC and RPD differed significantly from each other (Games-Howell *post hoc* tests).

Figure 3 compares veering on the three walking conditions (eyes-closed, NVF and VR visual feedback). Because there was no effect of optic flow speed, veering on VR walking trials was averaged across the five speed conditions. Whereas all participants veered leftward in the absence of visual information, decreased leftward deviation was observed upon walking with visual feedback, independent of whether the feedback was natural or synthetic (VR),

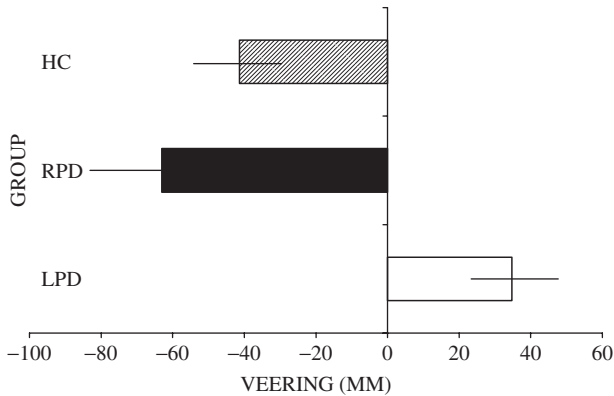


Fig. 2 Veering during a walking trial with NVF condition (eyes open). HC: N = 16, LPD: N = 14, RPD: N = 8. Negative signs represent leftward deviation from the true center. Positive signs represent rightward deviation from the true center. Horizontal lines represent standard error of the mean.

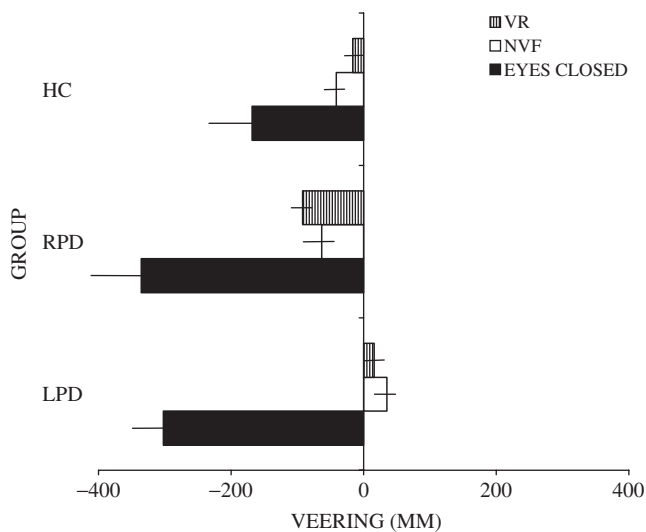


Fig. 3 Comparison of veering on three walking conditions: eyes closed, NVF, VR. HC: N = 16, LPD: N = 14, RPD: N = 8. Negative signs represent leftward deviation from the true center. Positive signs represent rightward deviation from the true center. Horizontal lines represent standard error of the mean.

with LPD demonstrating absolute rightward deviation (343.7 mm shift), and RPD and HC remaining left of center (RPD = 171.4 mm shift, HC 77.2 mm shift). Paired *t*-tests demonstrated that veering of LPD and RPD was significantly altered by visual input ($P < 0.001$, $P = 0.01$, respectively), and that veering of HC did not change across conditions ($P = 0.10$).

Statistical findings are presented in Table 1. As there were no significant interaction effects for the various conditions ($P > 0.10$ in each case), those *P*-values are not shown.

Visual functioning

Acuity and contrast sensitivity. Median near acuity for each group was 20/16 (−0.1 LogMar). The groups (LPD,

Table 2 Performance by group on tests of visual functioning, mean (SD)

	LPD	RPD	HC
FACT log contrast sensitivity: far			
1.5 cpd	1.9 (0.19)	1.8 (0.14)	1.9 (0.07)
3.0 cpd	2.1 (0.14)	2.0 (0.21)	2.0 (0.16)
6.0 cpd	2.1 (0.26)	1.9 (0.25)	2.0 (0.19)
12.0 cpd	1.6 (0.37)	1.6 (0.39)	1.7 (0.26)
18.0 cpd	1.2 (0.43)	1.1 (0.34)	1.3 (0.32)
FACT log contrast sensitivity: near			
1.5 cpd	1.9 (0.07)	1.9 (0.05)	1.9 (0.10)
3.0 cpd	2.1 (0.20)	2.1 (0.18)	2.1 (0.19)
6.0 cpd	2.0 (0.21)	2.0 (0.18)	1.9 (0.26)
12.0 cpd	1.5 (0.34)	1.5 (0.35)	1.5 (0.31)
18.0 cpd	1.2 (0.39)	1.1 (0.40)	1.1 (0.40)
Letter-identification contrast sensitivity: Michelson contrast at criterion error rate of 20%	46.5 (20.7)	52.8 (20.7)	30.9 (12.6)
Planar motion perception: percent coherent dot motion at threshold.	W: 9.3 (3.9) M: 5.7 (2.8)	W: 9.1 (3.0) M: 5.6 (2.8)	W: 5.0 (2.8) M: 7.2 (3.6)

RPD and HC) performed similarly on the FACT charts. The computerized test that identified contrast threshold for letter identification elicited performance differences between the groups. HC required less contrast than RPD in order to perform at an 80% accuracy level, there was a trend for LPD to perform more poorly than HC and there was no significant difference between RPD and LPD performance on this test ($P = 0.004$, 0.05 and 1.00 , respectively) (Bonferroni *post hoc* tests). These findings are in accord with Amick *et al.* (2003) who found normal Parkinson's disease performance on the FACT but impaired contrast sensitivity using the more sensitive letter-identification test. Accordingly, data from the latter test only are included in subsequent correlational analyses.

Planar motion perception. Whereas men with Parkinson's disease performed better than women with Parkinson's disease, the opposite occurred for HC participants, as HC women outperformed HC men. There was no difference between men and women (such as age or corrected visual acuity) that explained this finding. The results for the Parkinson's disease groups were similar in Amick *et al.* (2003), but in that study, the HC men outperformed HC women.

Descriptive performance statistics for the contrast sensitivity and motion perception measures appear in Table 2. The statistical findings appear in Table 3.

Visuospatial function

Statistical findings for the visuospatial tests are provided in Table 4.

Table 3 Results of ANOVA of tests of visual functioning

	d.f.	F	P
FACT contrast sensitivity			
Group	2	29.83	<0.001
Spatial frequency	1	3.61	0.06
Distance	1	1.88	0.11
Error	445		
Letter-identification contrast sensitivity			
Group	2	6.20	0.004
Error	45		
Planar motion perception			
Group	2	1.02	0.37
Gender	1	2.94	0.09
Group × gender	2	4.30	0.02
Error	37		

Sources of variance for fact contrast sensitivity, letter-identification contrast sensitivity and planar motion perception.

Table 4 Results of ANOVA on tests of visuospatial function

	d.f.	F	P
Visual dependence			
Group	2	34.31	<0.001
Error	487		
Landmark test (line bisection)			
Group	2	14.33	<0.001
Gender	1	6.67	0.01
Initial location of the bisection cursor	1	89.93	<0.001
Group × gender	2	21.92	<0.001
Error	478		
Optic flow			
Group	2	5.16	0.006
Constant side	1	27.96	0.001
Group × constant side	2	2.76	0.064
Error	906		
ECRP			
Group	1	3.12	0.08
Gender	1	2.30	0.13
Condition	1	1.38	0.24
Hand	1	52.62	<0.001
Group × gender	1	7.03	0.008
Group × condition	1	2.86	0.09
Gender × condition	1	0.19	0.67
Group × gender × condition	1	2.83	0.09
Error	542		

Sources of variance for visual dependence, Landmark test (line bisection), optic flow and ECRP. Constant side: Hemisphere side in which optic flow speed was held constant.

Visual dependence. The three groups performed differently on this task. LPD were more visually dependent than either RPD or HC, and RPD were more visually dependent than HC (Games-Howell *post hoc* tests).

Line bisection: Landmark test. Whereas men in the LPD group deviated towards the right, men in the HC group estimated the midline to be close to its true midpoint and men in the RPD group demonstrated a relatively large

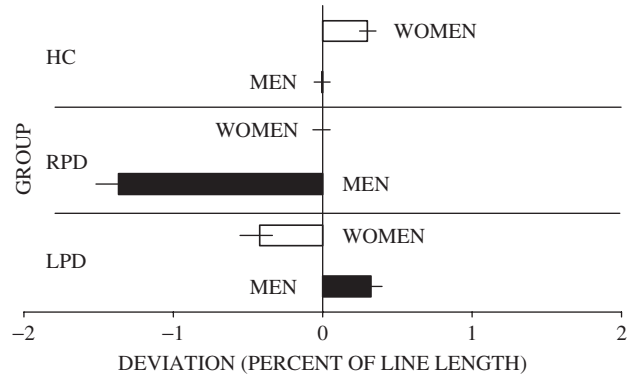


Fig. 4 Performance by group and gender on the Landmark test. Horizontal lines represent standard error of the mean. HC men and RPD women estimated the midpoint to be close to the true midpoint.

leftward deviation. In contrast, women in the LPD group deviated towards the left, women in the HC group deviated to the right, and performance of women in the RPD group was close to the true midpoint. These findings are depicted in Fig. 4.

Optic flow: perception of hemispheric speed asymmetries. LPD performed differently on this test than either HC or RPD ($P=0.016$ and 0.024), but there was no significant difference between HC and RPD ($P=0.096$). Paired *t*-tests were used to assess the perception of the two hemifields for PSEs for each group. When optic flow speeds were equal in the two hemifields, RPD and HC perceived the optic flow speed in the left hemifield as faster than in the right hemifield ($P=0.007$ and 0.005 , respectively). On average, RPD estimated optic flow speed in the left hemifield as 0.024 m/s faster, and HC estimated it as 0.020 m/s faster. There was an opposite trend for LPD to evaluate the left hemifield optic flow speed as slower than optic flow speed in the right hemifield, on average by 0.013 m/s, $P=0.093$.

Egocentric reference point estimation. The HC participants (who were tested first) did not use a headrest; Parkinson’s disease patients required that support to maintain their position during this test. Because the groups differed on this procedure, performance of Parkinson’s disease patients only was analysed. Across visual input conditions, on average, women with LPD exhibited a relatively large deviation toward the right side but men with LPD deviated minimally leftward. A different pattern was observed for RPD, with women displaying a small leftward and men a small rightward deviation (Fig. 5).

There was a trend for an interaction between group, gender and condition. On average, women with LPD showed rightward bias with eyes closed that was exaggerated with visual input. Men with LPD showed leftward bias with eyes closed that changed to rightward bias with visual input. Women with RPD, like men with LPD, moved from leftward bias with eyes closed to rightward bias with visual input. Hence, in these three groups, addition of visual input

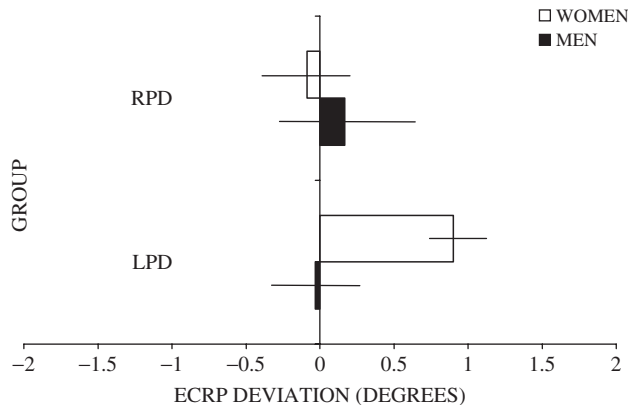


Fig. 5 Performance by group and gender on the ECRP task. Horizontal lines represent standard error of the mean.

resulted in rightward bias, which constituted a change of direction from leftward deviation or an exaggeration of a preexisting rightward deviation. Men with RPD performed opposite the other groups, moving from rightward bias with eyes closed to leftward bias with visual input.

Correlation analyses

Correlations between tests of vision and visuospatial function, and between tests of visuospatial function. There was a significant correlation between visual dependence and contrast sensitivity impairment on the letter-identification measure, $r=0.54$, $P=0.001$ for the Parkinson's disease participants. There was no correlation between motion perception and any of the other visuospatial function tests in any of the experimental groups.

We also examined correlation of performance on tests of visuospatial function pertaining to asymmetries in perception of the two hemispaces. Analyses were split across group and gender, with Bonferroni corrections for multiple comparisons ($\alpha 0.05/6=0.0083$). There were no significant correlations between performance on the Landmark test, ECRP deviation or optic flow asymmetries for men or women in any of the groups.

Correlations between perceptual variables and veering without visual feedback and with NVF. There were no significant correlations for any group between veering under these conditions and any participant characteristic or measure of vision or visuospatial ability including optic flow PSE, deviation on the Landmark test, or deviation on the ECRP estimate test.

Correlations between visual and visuospatial variables and veering under VR condition. Visual dependence was correlated with VR veering for RPD ($P=0.004$), with RPD who were more visually dependent veering to a greater extent to their left. For RPD, there was a significant correlation between VR veering (at 0.0 m/s, stationary walls) and ECRP deviation (on the eyes-closed trial), such that they veered in the direction of the ECRP shift ($r=0.91$, $P<0.01$). For

LPD, there was a significant correlation between VR veering (at 1.6 m/s) and ECRP deviation (on the eyes-open trial) such that patients veered in the direction of shifted ECRP ($r=0.67$, $P=0.01$). There were no other correlations between VR veering and performance on measures of basic visual or visuospatial function, including optic flow PSE and the Landmark Test.

Discussion

The present study provides evidence for the existence of distinct patterns of veering in Parkinson's disease that are associated with side of motor symptom onset, gender and the level of visual input available. It further documents impairments in optic flow perception and the perception of the egocentric midline that vary with side of disease onset and gender.

Veering

When participants were instructed to walk straight ahead with eyes closed, all groups veered leftward (women with Parkinson's disease more so than other participants). Upon addition of visual feedback (either natural or virtual-reality input), LPD demonstrated a rightward shift in veering (across the medio-lateral axis), whereas HC participants and RPD continued to veer leftward (RPD more than HC).

In healthy individuals, veering, or direction of heading, may be influenced by optic flow asymmetries (e.g. Duchon and Warren, 2002), by information gained from the egocentric reference system (Rushton *et al.*, 1998; Harris and Bonas, 2002), or by both types of information (Warren *et al.*, 2001). In Parkinson's disease patients, we expected that reliance on information provided by optic flow asymmetries would be perturbed by abnormal perception of the size of the visual hemifields. Specifically, use of optic flow equalization strategies to maintain heading would lead to leftward deviation in LPD (on the basis of the prediction of perceived spatial compression of the left visual hemifield) and possibly rightward deviation in RPD (on the basis of the prediction of perceived spatial expansion). In contrast, based on the findings of Rushton and colleagues (1998), who reported that a lateral shift of the perceived egocentric midline is associated with veering toward the corresponding side, and on the study by Bracha *et al.* (1987), who found spontaneous whole-body rotational behavior towards the ipsilesional hemisphere in patients with Parkinson's disease, one might predict that navigation based on egocentric midline perception would follow a pattern opposite to that predicted by optic-flow reliance. That is, patients with LPD would veer rightward and patients with RPD would veer leftward. Our data mainly bore out the latter prediction. We found that veering corresponded to the shifting of the perceived midline rather than to optic flow perception (PSE of speed in the two hemifields) and, for the RPD group, also corresponded to increased visual dependence.

Leftward navigational bias under visual feedback in the HC group is consistent with the findings of Mohr *et al.* (2004), who reported leftward rotational bias. These investigators suggested that visually directed left-sided rotational preference arises from greater activation of the right- than the left-hemispheric dopaminergic system, a consequence of relatively great right-hemisphere processing of visuospatial information. In our HC group, leftward bias occurred under the eyes-closed as well as the visual feedback (natural and virtual-reality) conditions. In our sample, there were two left-handed individuals, one in the LPD group and one in the HC group, who exhibited veering patterns that were shifted both in magnitude and direction. This finding underscores the importance of controlling for handedness in studies of veering.

The LPD results are consistent with the overall effects of increased visual feedback on walking in Parkinson's disease patients that was reported by Almeida *et al.* (2005) as well as with the idea of Mohr *et al.* (2004) that in LPD, there would be decreased dopamine available to the right-hemisphere system during visuospatial processing and therefore there would be no 'normal' leftward bias. In the present study, the extent of veering in the RPD group correlated with the extent of visual dependence and shifting of the egocentric midline. In contrast, veering in the LPD group was primarily associated with ECRP deviation and not with visual dependence. This result suggests that visual dependence in the LPD group (which was larger in extent than was that of the RPD group) may have already exerted its maximal influence. Because the veering pattern for Parkinson's disease patients changed with visual feedback, the results of these experiments cannot be attributed simply to directional hypokinesia.

In regard to visual dependence, Parkinson's disease patients rely more than healthy adults on visual guidance or feedback on tasks of simple perception and postural manipulations, and when walking (Cooke *et al.*, 1978; Bronstein *et al.*, 1990; Azulay *et al.*, 1999, 2002; Morris *et al.*, 2005). Our new finding is that the extent of visual dependence varies as a function of laterality of motor symptom onset. Patients with LPD were more visually dependent than were patients with RPD, and those with RPD were more visually dependent than were HC. Only for RPD was visual dependence associated with veering, suggesting that in the LPD group there were more salient influences on veering, correlated with associated shifting of the ECRP.

Optic flow

This is the first study to present evidence for impaired optic flow perception in Parkinson's disease, although there are studies on the effects of modulation of speed of artificial optic flow on gait parameters in Parkinson's disease (Schubert *et al.*, 2004; van Wegen *et al.*, 2006). As predicted, we found that RPD and HC perceived flow in their left hemifield as moving faster than the right

hemifield, as indicated by their PSE of flow speed in the two hemifields, whereas an opposite trend was observed in LPD, in which there is evidence for compressed perception of left hemispace (e.g. Harris *et al.*, 2003). The evidence that parietal-mediated optic flow perception is impaired in Parkinson's disease lends support to the notion of parietal-lobe dysfunction in Parkinson's disease (Cronin-Golomb and Braun, 1997; Amick *et al.*, 2006; Schendan *et al.*, in press). It appears likely that parietal areas that are recruited in optic flow perception may be functionally affected in Parkinson's disease through disruption of the basal ganglia-thalamocortical loops (Clower *et al.*, 2005).

Egocentric reference

While disruption of egocentric midpoint estimation may certainly be seen in patients with spatial neglect (Hasselback and Butter, 1997; Karnath, 1994), not all researchers have found a correlation between shifting of ECRP and traditional neglect measures (e.g. allocentric line bisection tasks) (Chokron and Bartolomeo, 1997; Hasselbach and Butter, 1997; Pizzamiglio *et al.*, 2000; Chokron *et al.*, 2002; Pisella *et al.*, 2002), and accordingly the possibility has been raised that these phenomena are causally unrelated (Chokron, 2003). In light of this possibility, we used a traditional line bisection measure (the Landmark test) in addition to the egocentric midline estimation task. On both tasks, patients' gender, as well as which hemisphere was predominantly affected, played a role in determining the direction of the shift. Overall, on the egocentric midline estimation task, patients showed shifts in opposite directions depending on which hemisphere was predominantly affected (LPD: rightward, RPD: leftward). On the Landmark measure, men with Parkinson's disease showed a similar pattern, but not women; LPD women showed a slight leftward deviation and RPD women remained close to the center in their estimates. In the overall direction of effect, the results are primarily in accord with findings from neglect patients who demonstrate shifting of the midline towards the ipsilesional hemispace (Karnath *et al.*, 1991; Chokron and Bartolomeo, 1997; Karnath, 1997; Richard *et al.*, 2004), though the intertask correlations were not significant in our study. As we expected, the observed Parkinson's disease deviations were small (largest $<2^\circ$) compared to those reported in neglect patients (commonly $10\text{--}15^\circ$). We interpret our findings as suggestive that Parkinson's disease affects the integrity of the ability to estimate the midline.

On the egocentric midpoint estimation task, there was a trend for LPD to demonstrate an increased deviation towards the right side when they performed the task with eyes open compared to eyes closed. RPD patients showed less deviation upon performing the task with their eyes open, and their estimates approached the true reference point. The finding that Parkinson's disease patients' midline deviation was dependent on visual input provides evidence

for the impact of visuoperceptual biases on the perception of the ECRP in Parkinson's disease, with deviation increasing for LPD and decreasing for RPD. Richard *et al.* (2005) reported that neglect patients demonstrated greater deviation of the ECRP when they had access to visual input. Because the midline deviation of LPD patients became more pronounced with added visual feedback, it appears that behavioural biases in these individuals reflect genuine visuoperceptual biases rather than being due solely to motor biases (hemispacial akinesia), as has in the past been suggested for Parkinson's disease (e.g. Brown and Marsden, 1986; Garcia-Larrea *et al.*, 1996; Heilman *et al.*, 2002).

Despite some gender differences in group performances, there was an overall similarity in direction of deviation on the egocentric and allocentric midpoint measures, possibly reflecting to some extent a common neural substrate. This common substrate likely involves parietal areas, as functional neuroimaging studies on healthy individuals have shown increased activation in the right posterior parietal lobe with line bisection (Fink *et al.*, 2000) and with computation of the mid-sagittal egocentric reference plane (Vallar *et al.*, 1999). As technology develops, more fine-grained analysis of the within-parietal substrates may be possible, accounting for behavioral evidence of a distinction between egocentric and allocentric task performance (Chokron, 2003). Lesion studies have demonstrated that shifting of the egocentric midline is predominantly seen in patients with spatial neglect due to extensive right parietal lesions (Hasselbach and Butter, 1997; Karnath, 1994). Deviation of this type has also, however, been documented in idiopathic cervical dystonia (Muller *et al.*, 2005), which is associated with gray matter increase in the putamen (Black *et al.*, 1998) and in the globus pallidus in addition to changes in the metabolism of cortical areas of the basal ganglia-thalamocortical circuit (e.g. right supplemental motor area, dorsolateral prefrontal and visual cortex) (Dragansky *et al.*, 2003). These observations, together with those of the present study of Parkinson's disease, suggest a central role of the basal ganglia-thalamocortical system, which includes the parietal lobes, for maintaining the integrity of egocentric midline perception.

Gender effects

Gender effects in the Parkinson's disease group were noted on several tasks, including the navigation assessment, motion perception, ECRP deviation and the Landmark test. This is an area that clearly requires more investigation, with larger samples, in light of Parkinson's disease gender differences in self-reports of visuospatial problems (Davidsdottir *et al.*, 2005), disease prevalence rate (Van den Eeden *et al.*, 2003) and constellation of motor symptoms (Bordelon and Fahn, 2006).

Conclusions

The present study provided evidence that parietal-mediated perception of visual space is affected in Parkinson's disease, including perception of optic flow speed and egocentric midline coordinates. Side of motor-symptom onset and gender affected spatial performance. The walking assessment demonstrated that visual input affects veering, that veering corresponds to the shifting of the egocentric midline rather than to abnormal perception of optic flow speed in the two hemifields and, although LPD were more visually dependent than RPD, only in RPD was visual dependence associated with veering.

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