

RESEARCH ARTICLE

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Three-dimensional covert attentional functions in Parkinson's disease subjects

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Abstract This study assessed the ability of mildly affected Parkinson's disease (PD) subjects ($n=16$) to perform attentional cognitive tasks within a three-dimensional object. A hollow cube was displayed on a computer screen and the subject was required to respond as quickly as possible to the highlighting of one of the cube angles by pressing the spacebar of the keyboard. Prior to the appearance of this imperative stimulus, the same ("valid" trials) or an alternative ("invalid" trials) angle was highlighted. For the invalid trials this meant that the subject oriented attention to the cued angle but, on imperative stimulus appearance, was unexpectedly required to redirect attention to another angle, which could be on a different cube face to that which had been cued. For one experimental session the cube was stationary, that is, object-centred and viewer-centred coordinates of a cube angle corresponded. For another session, the cube rotated such that the viewer-centred coordinates of an angle changed between appearance of the cue and appearance of the stimulus, but the angle's object-centred coordinates remained constant. The finding of lower reaction times for the valid than for the invalid trials, even when the cube was rotating, indicated that PD subjects could operate attention using an object-centred coordinate system. However, PD subjects showed exaggerated reaction times when the stimulus appeared in a cube face that was opposite to, rather than the same as, that of the invalidly cued angle. It is suggested that this reflects a dysfunction in the grouping of the structural components of the whole object at an attentional level.

Key words Parkinson's disease · Attention · Three-dimensional object · Coordinate systems · Human

Introduction

There is increasing evidence to suggest that Parkinson's disease (PD) subjects have dysfunctions with particular covert, visuospatial attentional mechanisms (Sharpe 1990; Wright et al. 1990; Yamada et al. 1990; Bennett et al. 1995; M. Mari, K. M. B. Bennett, M. Scarpa, G. Brighetti, U. Castiello, unpublished work). Most commonly, the Posner (Posner 1980; Posner et al. 1980) paradigm, or a modification of this paradigm, has been used to reveal such dysfunction. This assesses the ability of subjects to orient and reorient attention to stimuli presented in expected and unexpected positions of the visual field without eye movements. To date, however, there appears to be no clear consensus as to the exact visuospatial dysfunctions displayed by this heterogeneous subject group. Some studies have reported that PD subjects, despite showing generally longer reaction times (RTs), display the same cost-benefit pattern of longer RTs to stimuli in unexpected locations ("costs") than to stimuli in expected locations ("benefits") as non-brain-damaged subjects (Bennett et al. 1995). Other studies have reported no dysfunction to the RT benefits of attending to the expected location (e.g. Rafal et al. 1984), but reduced RT costs when required to reorient attention to an unexpected location (e.g. Sharpe 1990; Wright et al. 1990). This latter finding has been interpreted as reflecting a dysfunction in the maintenance of attention upon a specific visuospatial location, such that attention is more readily released to an alternative location (Sharpe 1990; Wright et al. 1990). A study that assessed a number of other visuospatial functions, such as the splitting and focusing of attention, reported that PD subjects show subtle dysfunctions which become more apparent when more than one attentional operation is required, suggesting time efficiency limits upon the amount of cognitive operations that can be performed at any given moment in this disorder (Bennett et al. 1995).

The common factor in all of the above-mentioned studies is the use of two-dimensional (2D) displays and the requirement for subjects to manipulate attention be-

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tween the left and right sides of a computer screen. Practically nothing is known, or at least reported, about the ability of these subjects to shift attention in three-dimensional (3D) space; for example, to shift from the front to the back of a cube. For that matter, despite the obvious fact that humans usually allocate attention within 3D coordinate systems and despite empirical evidence pointing to a role for attention in the construction of depth and 3D structure (Epstein and Lovitts 1985; Epstein and Broota 1986; Peterson 1986; Hochberg and Peterson 1987; Nawrot and Blake 1989; Shulman 1991), only a few studies have addressed the 3D allocation of attention in non-brain-damaged subject groups.

A recent study by Umiltà et al. (1995) with non-brain-damaged young subjects looked at the distribution of attention in relation to a 3D hollow cube displayed on a computer screen. This research received its theoretical inspiration from a number of current issues relating to the manner in which attention is distributed in space. One issue, relevant to any visual scene that includes an object, is related to whether or not subjects direct attention to only the object (object-based model; Prinzmetal 1981; Duncan 1984; Driver and Baylis 1989) or to a region of the visual field which may or may not include the object (space-based model; Eriksen and Yeh 1985; Posner 1980; Posner et al. 1980). Perhaps not unexpectedly, recent research suggests that both models are probably used (Duncan 1984; Vecera and Farah 1994), but that the left-hemisphere may be more specialized for the object-based allocation of attention and the right hemisphere for space-based allocation (Egley et al. 1994).

Given that attention is allocated to both the object and the space it occupies, a second issue relates to the coordinate system used for this allocation; that is, whether or not the reference system is based upon object-centred coordinates (Marr 1982; Biederman 1985) or upon viewer-centred coordinates (Braunstein et al. 1988; Andersen 1990). For the former, the spatial coordinates are computed with respect to the object. As such, an angle of a cube is an object-centred reference point which remains constant even if the cube rotates or moves in space. In contrast, if the coordinate system is viewer-centred, the coordinates of the angle change as the cube moves within the visual field. Although, both systems are probably used (Gibson and Egeth 1994), results from studies of patients with left neglect indicate that the object-coordinate system plays an important part (Driver and Halligan 1991; Driver et al. 1992; Caramazza and Hillis 1990; Behrmann and Tipper 1995). For example, stimuli on the left side of an object may continue to be neglected even if the object is rotated so that its left side lies to the right side of the subject or within the right visual field (Driver and Halligan 1991; Behrmann and Tipper 1995).

Using a Posner-type paradigm with cue and imperative stimuli, Umiltà et al. (1995) were able to demonstrate that the normal cost-benefit function to stimuli in expected and unexpected object-centred locations applied when attention was allocated within a 3D object, but that it did not apply when the reference frame of the

moving object disappeared. This was interpreted as indicating that attention can operate within a 3D object-centred coordinate system. Other studies have investigated the distribution of attention in viewer-centred 3D space. For example, Downing and Pinker (1985) required subjects to respond to valid and invalid stimuli presented in two rows in depth. They reported greater costs when subjects shifted attention in depth (particularly if this shift was from near to far) than when they shifted attention across the visual field (left-right; right-left; see also Gawryszewski et al. 1987). More recent studies have further defined the spatial characteristics of attention in 3D space and have suggested that the attentional focus shows 3D elliptical gradients between regions of greater and lesser processing efficiency (Andersen and Kramer 1993).

Given these above-mentioned descriptions of 3D attentional functioning, of further theoretical importance is the part played by the basal ganglia in this 3D allocation system. Anatomically the basal ganglia is well placed to influence both the posterior "spatial orienting" and the anterior "volitional control and awareness" attentional networks, described by Posner and Peterson (1990; for review see Jackson and Houghton 1992), and cortical forebrain systems, which are thought to be concerned with object-based spatial encoding (Schlag and Schlag-Rey 1983; Tipper et al. 1994). Output pathways from the substantia nigra pars reticulata and the medial segment of the globus pallidus project to the thalamic reticular nucleus. This latter nucleus sends projections to the pulvinar (Crick 1984; Pare et al. 1990; Hazrati and Parent 1991), which in turn sends afferents to both the posterior parietal cortex (posterior network) and the anterior cingulate/dorsolateral prefrontal regions (anterior network). To complete the "loops", the basal ganglia receives input from all the cortical visuospatial attentional regions proposed by Posner and Peterson (1990). Such an anatomical structure indicates a potential for the basal ganglia to mediate changes to various stages/processes of the visuospatial attentional system. Presumably such stages/processes would include those for the distribution of attention within 3D objects located in 3D space.

A primary aim of the current experiment was to assess the performance of PD subjects in a task requiring the orienting of attention in 3D space. For this purpose, a modified version of the Posner reaction-time paradigm (Posner 1980; Posner et al. 1980) was employed, and, instead of 2D figures, the subject was presented with a screen display of a hollow cube. To test the orienting of attention to an expected location, an angle of the cube was highlighted prior to the appearance of the imperative stimulus at that same angle; that is, the subject was given a valid cue. To test the orienting of attention to an unexpected location, one angle was cued but the imperative stimulus appeared in another angle; that is, the subject was given an invalid cue. In the study by Umiltà et al. (1995), described previously, it was demonstrated that RTs for valid trials were lower than RTs for invalid trials, indicating that the benefits from valid cueing and the

costs from invalid cueing, as described by Posner (1980), also operate within a space that is perceived as 3D. Based upon previous results from 2D studies (Bennett et al. 1995), it is predicted that the PD subjects of the current study, all at early stages of the disease, should demonstrate longer RTs than control subjects, but normal patterning of the benefits and costs from valid and invalid cuing, at least when the cue and imperative stimulus appear within the same 2D plane. The expected results for operating across planes cannot be predicted, as no previous studies have addressed this issue in this subject group.

Another aim of the current study was to assess the ability of PD subjects to allocate attention in relation to object-centred coordinates. For this purpose, the experiment consisted of two sessions; one in which the cube was stationary and one in which it rotated. Under the stationary condition, the object-centred and viewer-centred coordinates of the object corresponded. Under the moving condition, the object-centred coordinates were constant but their viewer-centred coordinates were changing. In this experiment, subjects were given two types of cues, brief or sustained. With the brief cue, the cue was displayed for a short period of time, then extinguished for a period prior to appearance of the imperative stimulus. With the sustained cue, the cue remained immediately up until appearance of the stimulus. For this latter cue type, subjects were thus given continuous information about the more likely position of the subsequent imperative stimulus, while, for the brief cue type, this information was withdrawn for a period prior to stimulus presentation. Under the stationary condition with this latter cue type, this meant that the subject was required to maintain attention to a cube angle which did not change in either object- or viewer-centred coordinates; for validly cued trials, the cue and the stimulus would appear at the same reference point of both sys-

tems. It is difficult to predict results given the discordance in the literature. If the theory holds that PD subjects have difficulties in maintaining attention, it could be proposed that a "brief" cue would be less likely to "capture" the attentional focus, and that costs for the invalid trials in this condition should be reduced. If, in contrast, it can be proposed that PD subjects in early disease states do not have difficulties with the maintenance of attention, it could be proposed that the cost-benefit relationship should hold. For the validly cued trials under the rotating condition, the cue and the stimulus could appear at the same reference point of the object-centred coordinate system, but, since the cube moves between presentation of the cue and presentation of the stimulus (Gibson and Egeth 1994; Umiltà et al. 1995), the cue and the stimulus would appear at different reference points of the viewer-centred coordinate system. The subject would thus be required to track the moving cube angle during the period of cue extinction. As the performance of PD subjects in "tracking" covert attention has not yet been investigated, it is difficult to predict the results under this condition. If benefits and costs remain under the rotating cube condition and particularly when a brief cue has been presented, this would indicate that PD subjects can allocate and maintain attention upon fixed object-centred coordinates, even when viewer-centred coordinates are changing.

Materials and methods

Subjects

Details of the subjects who were assessed are shown in Table 1. The PD subjects ($n=16$) were classified as being at stages I or II of the Hoehn and Yahr scale (1967), and all showed bilateral signs. The number of years from initial diagnosis of idiopathic PD ranged from two to five. Medication was most commonly Sinemet

Table 1 Characteristics of the Parkinson's disease (PD) and control subjects (H&Y Hoehn and Yahr (1967), MMSE mini-mental state examination, see Folstein et al. 1975)

No.	PD subjects						Controls		
	Sex	Age (years)	H & Y scale	MMSE score	Diagnosis (years)	Medication	Sex	Age (years)	MMSE score
1	M	57	2	30	4	Sinemet	M	55	30
2	M	51	1	30	3	Sinemet	M	48	30
3	M	50	2	28	5	Sinemet	M	50	30
4	F	46	1	28	4	Sinemet	F	45	29
5	F	47	1	30	3	Sinemet	F	46	30
6	F	53	1	27	3	Madopar	F	51	30
7	M	52	2	30	4	Eldepryl	M	51	30
8	M	49	1	30	3	Sinemet	M	49	30
9	M	49	1	30	2	Sinemet	M	49	30
10	F	50	1	30	4	Sinemet	F	50	29
11	F	46	1	28	2	Sinemet	F	47	30
12	M	54	1	28	3	Madopar	M	51	28
13	F	48	1	30	2	Sinemet	F	48	30
14	F	56	1	29	4	Sinemet	F	55	30
15	F	49	2	30	4	Eldepryl	F	48	28
16	M	50	1	28	3	Sinemet	M	49	29

or Madopar, and none of the PD subjects showed motor complications owing to medication. Testing sessions were always conducted during a period of least signs and symptoms, 1–2 h after medication, when rigidity and tremor were minimal. The 16 age- and gender-matched controls reported no neurological or skeletomotor dysfunctions. The age of the PD subjects ranged from 46 to 57 years (mean 50.25 years, SD 3.38) and that of the control subjects, from 45 to 55 years (mean 49.5 years, SD 2.76). All PD and control subjects showed right-handed dominance (Oldfield 1971). The Mini-mental State Examination (MMSE) was used to provide an index of the global cognitive state (Folstein et al. 1975). The mean score for PD subjects (29.13, SD 1.08) was not significantly different from that for control subjects (29.56, SD 0.73; non-parametric Mann-Whitney *U*-test). With visual acuity testing, all PD and control subjects scored 10/10. Subjects were naive as to the experimental design and purpose and gave informed consent for participation. The PD subjects were part of a larger group of subjects who had previously participated in a 2D attentional study (Bennett et al. 1995).

Apparatus and procedure

The subject was positioned comfortably and seated upright to face a computer screen driven by a Compaq 486 personal computer. The head was positioned in an adjustable head-and-chin rest, so that the distance between the eyes and the screen was approximately 50 cm. Experiments were conducted under normal room-lit conditions. Eye movements were recorded with two Ag/AgCl electrodes (Ver Med; diameter 6 mm) positioned on the inner and outer canthi of the right orbit. The recorded signals were subjected to high-gain amplification (10^4), filtered using a Butterworth filter (cut-off frequency 30 Hz), and digitized using a sampling frequency of 100 Hz. Prior to commencement of the experiment, the mean signal amplitude was determined for a 10-s period of static gaze fixation upon the fixation stimulus. During the experiment, an algorithm determined the number of sample points whereby the electro-oculogram (EOG) signal exceeded a voltage which was greater than 2 SEs above this mean. If this number exceeded 20, eye movement was assumed to have occurred and the trial was rejected.

The principal component of the display was a line drawing of a hollow cube (see Fig. 1), the sides of which were 24 mm. The cube was white against a black background and was shown in the centre of the screen. For one experimental session the cube was stationary. The angle of presentation was such that the front face of the cube was directed approximately 25° to the left edge and

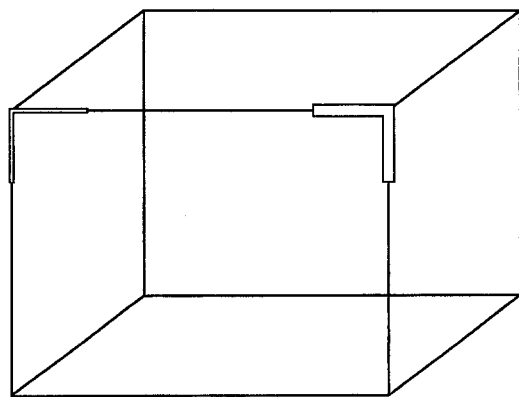


Fig. 1 Schematic representation of the hollow-cube screen display. Note, however, that the cube was white on a black background for the actual experiment. The *whitened-out corners* on the front face of this cube represent the cue and the imperative stimulus. However, in the actual experiment the cue was heavy white lines, and it appeared 600 ms before the imperative stimulus, which was heavy red lines

approximately 10° to the lower edge of the screen. For the other experimental session, the cube rotated about either its horizontal *x*-axis or its vertical *y*-axis, at a rate of $45^\circ/\text{s}$. Presentation order according to the angle from which rotation commenced and according to the axis of rotation was randomized.

For the purposes of gaze fixation, a white dot (diameter 2.5 mm) was shown in the geometrical centre of the cube. To direct covert attention to a particular location of the cube, a cue was displayed. This was a highlighting of one right angle of the cube with heavy white lines (length 5 mm). To signal the requirement for response emission, an imperative stimulus was displayed. This was a highlighting of one right angle of the cube with heavy red lines (length 5 mm). Given that there are three right angles at each of the eight corners of the cube, the cue or imperative stimulus could indicate any one of 24 right angles. (The graphic portrayal of a "real" 3D cube meant that the distance between cue and imperative was not constant; however, both subject groups were exposed to this confound. This distance effect can be seen, for example, by noting that the distance between the front right upper corner to the back right upper corner is less than that from the front right upper to the front left upper corner). The response to the imperative stimulus was emitted by pressing the space bar of the computer keyboard. RT, measured in milliseconds, was taken as the time from the onset of imperative stimulus display to the time of response emission. Accuracy of RT measurements (approximately 55/65536 ms) was ensured by performing suitable software adaptations.

The beginning of each trial was signalled by the screen display of the cube and the fixation dot (this display remained until the end of the trial). The cue was then displayed after an interval of 100, 250, 350, or 600 ms. This variability was introduced in order to reduce expectancy effects. Two types of cue conditions were used: (1) brief cue – cue displayed for 300 ms and then extinguished for 300 ms; and (2) sustained cue – cue displayed for 600 ms. In both cases the imperative stimulus was then presented for 100 ms. (Note: the time from onset of cue to onset of imperative stimulus was always 600 ms.) As explained previously, these different cue conditions were introduced to test the ability of PD subjects to maintain attention upon a particular region. The end of the trial was taken as the time of keyboard response. If no response was emitted, the end of the trial was taken as being 3000 ms after presentation of the imperative stimulus or, in the case of "catch" trials, 4000 ms after presentation of the cue. After the end of each trial, the subject was given feedback display about speed and accuracy. The cube for the next trial was then displayed 2 s later.

The following types of trials were delivered: (1) catch trials (10%), whereby no imperative stimulus was presented; (2) valid trials (70%), whereby the imperative stimulus was presented at the same right angle indicated by the cue; and (3) invalid trials (20%), whereby the imperative stimulus was presented at 1 of the 21 right angles that had not been indicated by the cue, and that was not part of the corner where the cue had occurred. The trial presentation order according to trial type, type of cue, angle of cue, and angle of imperative stimulus in non-cued locations, was randomized.

Prior to each session, the experimental paradigm was explained. The subject was instructed to maintain gaze upon the central fixation dot for the entire trial period and, upon appearance of the cue, to direct (covert) attention to this cue, even if it was moving. It was explained that when the cue was no longer visible (brief cue condition), the subject should continue to maintain attention upon the right angle which had been cued, because the imperative stimulus would most likely appear at this same right angle. In the sustained cue condition, the most probable location of the stimulus was always clearly indicated. Upon presentation of the imperative stimulus, the subject was required to press the space bar of the computer keyboard as quickly as possible. It was warned that sometimes no imperative stimulus would be presented and that, in this case, no response should be given.

Each subject performed two experimental sessions (stationary cube; rotating cube), the session presentation order being counter-balanced across subjects. A practice session and each of the exper-

imental sessions were conducted on different days, but all were at the same time of day. Each session consisted of two blocks of 120 trials, the blocks being separated by a 5-min rest period. Typically a block lasted less than 20 min. The following types of trials were rejected on-line, but later analysed: (1) "error" trials, whereby the RT was less than 150 ms or greater than 2500 ms; (2) catch trials, whereby a response had been given; and (3) trials whereby eye movement had occurred. Experimentation continued until 120 non-rejected trials had been performed for each block. Of a total of 480 trials per session, 336 were of the valid type, 96 were of the invalid type, and 48 were catch trials.

Results

The mean RTs from non-rejected trials (see Table 1) were entered into a mixed-design analysis of variance (ANOVA). The between-subjects factor was Group (PD, control). The within-subjects factors were Cube Presentation (stationary, rotating), Trial Type (valid, invalid) and Cue Duration (brief, sustained). Post hoc comparisons between means of interest were performed using the Newman-Keuls procedure (α -level 0.05). Intertrial variability was assessed with the O'Brien method (1971). Two further ANOVAs, with Block (1st, 2nd) as the within-subjects factor, were performed for the Stationary and for the Rotating Cube Presentation sessions. Neither ANOVA showed a significant effect (respectively, $F_{1,1}=1.03$, $P>0.05$ and $F_{1,1}=0.87$, $P>0.05$). It was thus concluded that neither group showed signs of fatigue. Neither group showed more than 3% of responses to catch trials. Both groups also showed a low percentage of eye movements (PD subjects 7%; controls 5%). Because the number of responses to catch trials and the number of trials with eye movements were so low, they were not analysed.

Not unexpectedly, the mean RT for PD subjects (588 ms) was greater than that for control subjects (479 ms; Group effect $F_{1,24}=68.13$, $P<0.0001$). Of interest for the purposes of this study, however, was the functioning of covert visuo-spatial attentional tasks under the different experimental conditions. Turning first to the question of how attention is oriented following cueing within a 3D object, the results indicated similar performance patterns for both groups. RTs for valid trials (PD 564 ms; control 464 ms) were less than those for invalid trials (PD 611 ms, an 8.3% difference; control 494 ms, 6.5%; Trial Type effect $F_{1,24}=27.04$, $P<0.0001$). This difference between valid and invalid trials, referred to as the "validity effect", gives an indication of the extent to which the subject's covert attention is maintained upon the cube angle that had been cued. In the case of an invalid trial, attention must be disengaged from this cued location and then redirected and re-engaged upon an alternative and unexpected angle (Posner 1980; Posner et al. 1980). The validity effect thus gives a measure of the RT costs of these latter cognitive processes.

The results for both subject groups indicated that the validity effect was present under both Cube Presentation conditions. For the Stationary Cube, a subtraction of the valid from the invalid trial RT (i.e., the validity effect) gave values of 60 ms for PD subjects (a difference of

6.64%) and 26 ms (7.2%) for control subjects. For the Rotating Cube, the validity effect was 35 ms (9.99%) for PD subjects and 17 ms (5.37%) for control subjects. These results thus indicated that RT benefits and costs could be demonstrated despite manipulation of the relationship between viewer-centred and object-centred coordinate systems. In particular, the finding of a validity effect even when the cube was moving suggested that PD subjects, like controls, could attend to a moving object-based reference point.

The cognitive processes underlying the ability to attend to specific points of a moving object took more time than those related to a stationary object. This was indicated by the result for both groups of generally longer RTs for the rotating than for the stationary cube (PD: 631 ms and 545 ms, respectively; controls: 497 ms and 460 ms, respectively; Cube Presentation effect $F_{1,24}=32.21$, $P<0.0001$), and greater intertrial variability for the rotating cube (O'Brien's test, 1971; $P_s<0.05$). However further analysis of the interaction between Group and Cube Presentation ($F_{1,24}=17.03$, $P<0.001$) demonstrated that the cognitive demands of the rotating cube bore more heavily on PD than on control subjects. For example, the difference of RTs between the rotating and stationary Cube Presentation conditions for PD subjects (86 ms; 15.8%) was around twice as much as that of control subjects (36.5 ms; 8%). Further, the PD subjects showed a greater increase in variability with the rotating cube than the control subjects (see SD values of Tables 2, 3).

Both groups showed changes of RT according to Cue Duration; however, the performance pattern of the PD subjects was different from that of the control subjects. This was indicated by the significant interactions between Group, Cue Duration and Trial Type ($F_{1,24}=5.18$, $P<0.05$), Group, Cube Presentation and Cue Duration ($F_{1,24}=9.07$, $P<0.001$) and Group, Cube Presentation, Cue Duration, and Trial Type ($F_{1,24}=5.24$, $P<0.05$). For the stationary cube, PD subjects showed no difference of validity effect across the two Cue Duration conditions. As can be seen from Table 2, this contrasted to the control subjects' result of a greater validity effect for the sustained than for the brief cue, and to the PD subjects' result for the rotating cube. Overall these results suggested that, although PD subjects were able to track attention to a moving cue, they showed a reduced capacity to respond appropriately to different stationary cue displays.

A further means of investigating 3D mechanisms of attention was to compare the RTs from same- and opposite-face invalid trials. For same-face trials, the cue was presented on one cube face and the stimulus appeared on the same face but at a different angle. For opposite-face trials, the stimulus appeared in the cube face which was opposite to the face in which the cue appeared. To address this issue, three ANOVAs with Group as the between-subjects factor and Cube Presentation, Cue Duration and Face (Same, Opposite) as the within-subjects factors were performed on the appropriate mean invalid RTs. For one analysis, the comparison was between the front and the back faces; that is, Same Face invalid trials

Table 2 Mean reaction times (RTs; with SDs) for the different trial types with stationary and rotating cubes. All values are in milliseconds. *Brief* and *Sustained* refer to the two different cue conditions. $\leftarrow n.s. \rightarrow$ and $\leftarrow s. \rightarrow$ indicate, respectively, non-significant and significant differences between the numbers indicated by the arrows. *Validity effect*: RT invalid trials minus RT valid trials.

	PD subjects		Control subjects	
	Brief	Sustained	Brief	Sustained
Stationary cube				
Valid trials	521 (79)	533 (97)	451 (48)	438 (50)
Invalid trials	561 (91)	563 (121)	468 (52)	485 (51)
Validity effect	40 $\leftarrow n.s. \rightarrow$	30	17 $\leftarrow s. \rightarrow$	47
	7.68%	5.63%	3.78%	10.73%
Rotating cube				
Valid trials	580 (100)	621 (128)	483 (49)	485 (50)
Invalid trials	630 (136)	691 (158)	500 (47)	520 (54)
Validity effect	50 $\leftarrow s. \rightarrow$	70	17 $\leftarrow s. \rightarrow$	35
	8.62%	11.27%	3.52%	7.22%

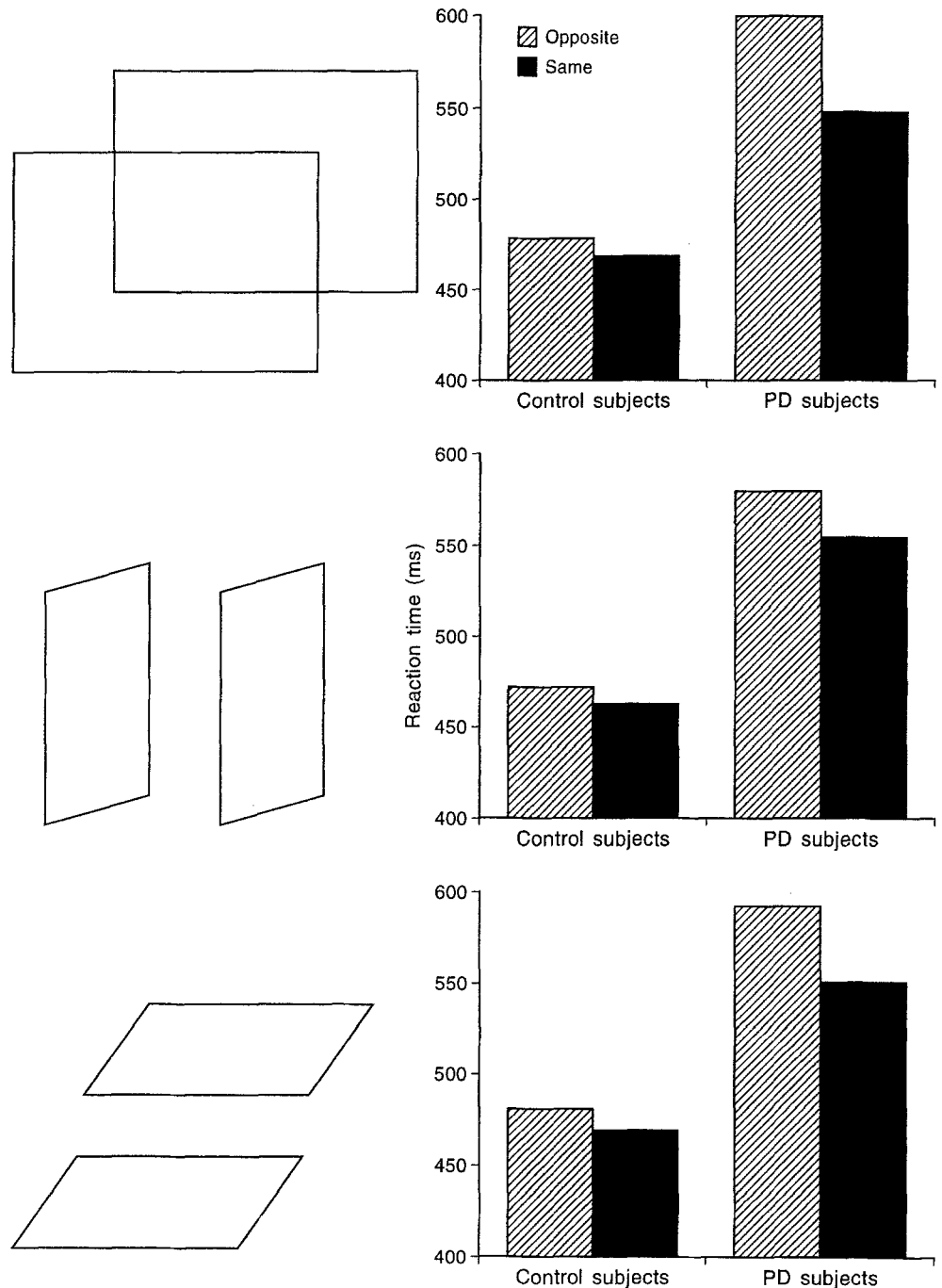
Table 3 Mean reaction times for invalid trials (*B* brief cue, *S* sustained cue, *Same* cue and imperative stimulus occur on the same cube face, *Opposite* cue appears on the cube face which is opposite to that of the imperative stimulus, *Difference* RT Opposite minus RT Same; *Front*, *Back*, *Left*, *Right*, *Top* and *Bottom* refer to the cube faces)

	Stationary cube				Rotating cube			
	PDs		Controls		PDs		Controls	
	B	S	B	S	B	S	B	S
Front/Back								
Same	542 (76)	548 (78)	468 (47)	477 (50)	623 (100)	642 (118)	500 (58)	510 (55)
Opposite	560 (90)	600 (98)	478 (51)	486 (49)	659 (147)	722 (168)	510 (60)	521 (56)
Difference	18	52	10	9	36	80	10	11
	3.32%	9.49%	2.14%	1.89%	5.78%	12.46%	2%	2.16%
Left/Right								
Same	547 (63)	557 (65)	464 (46)	476 (48)	630 (83)	638 (90)	500 (47)	513 (51)
Opposite	558 (75)	582 (75)	473 (45)	488 (45)	648 (84)	680 (87)	512 (50)	525 (54)
Difference	11	25	9	12	18	42	12	12
	2.01%	4.49%	1.94%	2.52%	2.86%	7.94%	2.4%	2.35%
Upper/Lower								
Same	550 (80)	551 (78)	470 (51)	481 (47)	621 (98)	650 (100)	491 (50)	507 (49)
Opposite	566 (88)	592 (91)	481 (51)	491 (50)	658 (111)	703 (132)	510 (55)	519 (52)
Difference	16	41	11	10	37	53	9	12
	2.91%	7.44%	2.34%	2.08%	5.96%	8.15%	3.87%	2.37%

were those where both the cue and the imperative stimulus appeared on either the front or the back face. Opposite Face invalid trials were those where the cue appeared on either the front or the back face, but the stimulus appeared on the opposite face. For the two further analyses, comparisons were between left and right faces, and between upper and lower faces. (Note that for the rotating cube, the front face was taken as that facing the subject at the time of the onset of the cue display. Given that the cube rotated as $45^\circ/s$, in the 600-ms interval between cue and stimulus onset the cube rotated 27° – this meant that opposing faces held the same front-back, left-right or upper-lower relationship.) The results are shown in Table 3. Analyses were also performed on the number of delayed error trials (i.e., those trials where the subject took more than 2500 ms to respond to the imperative stimulus).

All three analyses revealed a significant main effect for Face (front/back $F_{1,24}=11.03$, $P<0.001$; left/right $F_{1,24}=21.14$, $P<0.001$; upper/lower $F_{1,24}=23.12$, $P<0.001$). For both subject groups, RTs for Same Face invalid trials were lower than RTs for Opposite Face invalid trials; the difference between the Same and Opposite Face RTs is shown as “Difference” in Table 3. All three analyses also revealed a significant interaction between Group, Cube Presentation, Cue Duration and Face (front/back $F_{1,24}=10.05$, $P<0.001$; left/right $F_{1,24}=5.14$, $P<0.05$; upper/lower $F_{1,24}=9.07$, $P<0.001$). As can be seen from Table 3, the most obvious post hoc analysis finding was that the difference of RTs between Same and Opposite faces was greater for the PD than for the control subjects (see Fig. 2). For example, this difference value ranged from 11 to 80 ms for the PD subjects, but from 9

Fig. 2 Comparison between the reaction times obtained from the same-face (*striped columns*) "invalid" trials and the reaction times obtained from the opposite face (*black columns*) invalid trials for the control (*left*) and the Parkinson's disease (PD) subjects (*right*). The examples shown here are for the stationary cube presentation, where the imperative stimulus was preceded by a sustained cue. The *top diagram* is for the front face/back face comparison. The *middle diagram* is for the left face/right face comparison. The *lower diagram* is for the top face/bottom face comparison



to 12 ms for the control subjects. In fact, the only condition where the two groups showed similar Same/Opposite difference values was for the comparison of left/right invalid trials following a brief cue. These results demonstrated that the costs of disengaging/shifting/re-engaging attention (Posner 1980; Posner et al. 1980) within one cube face were less than the costs of disengaging attention from one cube face and shifting and re-engaging attention to a geometrically opposing face. This latter time penalty for the invalid opposite trials was much greater for the PD than the control subjects.

A further, striking finding was the task-related sensitivity of PD subjects to cue type. In particular, and unlike

control subjects, PD subjects showed greater RTs for the opposite invalid trials which were preceded by a sustained, as opposed to a brief cue. Referring to Table 3, it can be seen that the absolute and relative difference between same-face and opposite-face invalid trials was consistently greater for the PD subjects when a sustained cue was presented. That is, when required to execute attentional functions in the cube face geometrically opposing that which was cued, PD subjects show time-processing sensitivity to cue duration. In contrast, such sensitivity was not observed for the same-face invalid trials – PD subjects, like controls, showed no or little difference in RTs when comparing brief and sustained cue condi-

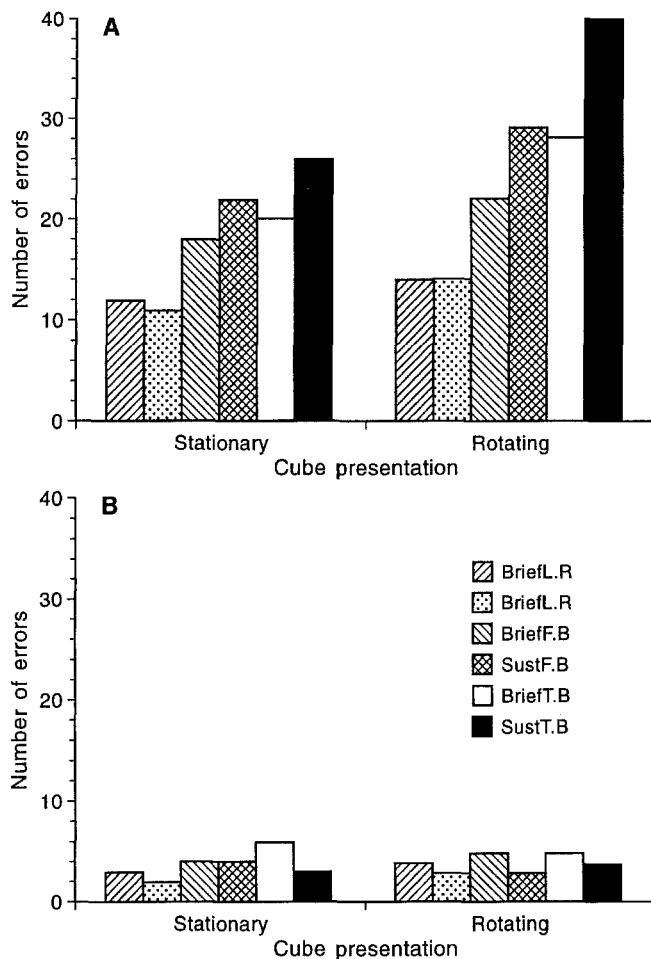


Fig. 3 Number of delayed errors for the opposite-face invalid trials of the PD (A) and control (B) subjects. Results for the stationary cube presentation are shown on the left. Results for the rotating cube presentation are shown on the right (*BriefL.R.* brief cue, left-right face trials; *Sust.L.R.* sustained cue, left-right face trials; *BriefF.B.* brief cue, front-back face trials; *SustF.B.* sustained cue, front-back face trials; *BriefT.B.* brief cue, top-bottom face trials; *SustT.B.* sustained cue, top-bottom face trials)

tions. As can be seen in Table 3, this PD subject sensitivity of cognitive processes to cue duration for opposite invalid trials was irrespective of whether the cube was moving or stationary. RTs for the invalidly cued opposite trials that had been preceded by a sustained cue were always greater than the RTs for those trials that had been preceded by a brief cue.

Delayed-error opposite invalid trials were entered into an ANOVA with Group as the between-subjects factor and Cube Presentation and Cue Duration as the within-subject factors. Post hoc analyses of the significant interaction between Group, Cube Presentation and Cue Duration ($F_{1,24}=18.21$, $P<0.001$) indicated that PD subjects showed a higher and significant incidence of delayed responses (more than 2500 ms). For the PD subjects the number of delayed trials was greater for the rotating than for the stationary cube and, in some instances, was greater for the sustained than for the brief cue. The number of delayed-error trials are shown graphically in Fig. 3.

Overall the results from these latter three analyses indicated that PD subjects were disabled in shifting attention within a 3D object, and that this disability was dependent upon task constraints. It was more evident following a sustained, rather than a briefly presented, "misleading" cue. It was also more evident when the 3D object was moving about its axis, rather than when it was stationary.

Previous investigators, studying non-brain-damaged subjects, have found differences in results according to the direction of the attentional movement in depth. Unfortunately, this could not be validly assessed in the current study because of an insufficient number of invalid trials for acceptable means. However, for all of the values obtained, the pattern was the same as that previously reported in studies that have assessed the allocation in viewer-centred rather than object-centred coordinates (Downing and Pinker 1985; Gawryszewski et al. 1987). All subjects showed greater RTs for the shift from front to back face than for that from back to front face – this result applied for both cue durations and whether the cube was stationary or rotating. In light of the results reported by Andersen and Kramer (1993), it was also interesting to note that RTs for the shift from upper to lower face appeared to be greater than those from lower to upper face.

Discussion

This study compares control subjects and mildly affected PD subjects in the performance of attentional operations upon a 3D object displayed on a computer screen. The experimental procedure incorporates a modified version of Posner's (1980; Posner et al. 1980) valid/invalid, RT paradigm. The display consists of a hollow cube which is moving or stationary. A cue highlights one angle of this cube and, shortly after, the subject is required to give a keyboard response immediately upon detecting a highlighting of the cued (valid trial) or of a non-cued (invalid trial) angle. Despite generally greater RTs, PD subjects, like controls, show shorter RTs for the valid than for the invalid trials, indicating that benefits to cognitive processing times are gained from attending in advance to the cued cube angle, and that costs accrue from being given misleading information. The validity effects (RT of invalid trials minus RT of valid trials) remain even when the cube is moving, suggesting that PD subjects can track the attentional focus. These effects are also present despite variations in the amount of time that the cue is displayed. For example, when the cue is on for 300 ms but then off for 300 ms, validity effects for the moving cube are still evident. This implies that PD subjects are able to attend to a moving reference point which is no longer being obviously indicated.

These results suggest that PD subjects can operate attentional processes within an object-centred reference system. As demonstrated by the valid trial benefits, the attentional focus can be directed to an angle of a cube.

As demonstrated by the invalid trial costs, attentional processes such as maintenance upon a cube angle, disengagement from this angle, and reorientation to and re-engagement upon another cube angle, are intact. The reason for proposing that primarily an object-centred, rather than a viewer-centred, reference frame is utilized in this paradigm, can be partly inferred from the maintained ability of these subjects to track an angle which is no longer being indicated. However, this result alone is insufficient to clarify whether the attentional focus is tracking a constant, object-centred reference point that moves or whether the focus is being directed along the series of viewer-centred points covered by the path of the cube angle. Obviously this needs further testing, but based on a previous study with healthy young subjects (Umiltà et al. 1995), the former view is more feasible. In addition to the paradigm of the current study, the subjects of the Umiltà et al. study (1995) were required to respond to valid and invalid trials in which the cube was not displayed. In other words, subjects were shown neither a 3D object nor geometric "closure" information (Caelli et al. 1978; Treisman and Paterson 1984). For both the stationary and the moving cubes, validity effects were absent for the brief cueing (300 ms on, 300 ms off) condition. This result suggested that the subjects could neither hold attention upon a specific viewer-centred coordinate which was not related to a visible 3D object, nor could they track attention along an imagined viewer-centred trajectory. Indirectly, this suggests that the PD subjects of the current study also use an object-centred reference system.

At a general level, mildly affected PD subjects can thus be described as having slower cognitive responses but maintained 3D attentional resources. However, the results indicate two dysfunctions at a more specific level. One dysfunction relates to the ability to interpret cueing information, particularly under stationary object conditions. The other, to the ability to shift attention across the volume of the cube.

Dealing with the first dysfunction, the results showed that PD subjects showed no difference of validity effect between the sustained and the brief cue under stationary cube conditions. This contrasted to the results for the control subjects of this study (see also results from Umiltà et al. 1995), who demonstrated greater validity effects for sustained than for brief cues, suggesting differences in the ability of the cue to capture and hold attention to a particular location of the visual field. Longer precues and, more precisely, the absence of a no-cue period, facilitate the maintenance of attention upon the cued site to such a degree that costs are greater when attention must be allocated unexpectedly to another uncued location. A brief cue coupled with a no-cue period prior to stimulus presentation could be said to have a lower capturing or holding effect upon visuospatial attention. The results for the PD subjects show quite large costs irrespective of cue type and irrespective of whether or not the cube is stationary or moving. Such findings counter the idea that PD subjects, at least in the early

disease stages, show dysfunctions with the maintenance of attention, but indicate that there is some problem in differentiating between cue types. An interesting finding is that the PD subjects show a greater validity effect for the long cue than for the brief cue when the cube is moving. Under this condition, the capturing or holding ability of the long cue appears to be slightly stronger than that of the stationary cube, probably because of the added component of movement. Hence it could be proposed that the ability of PD subjects to maintain sustained attention upon an object-centred coordinate varies according to whether or not the object-centred coordinate moves in viewer-centred coordinates. Tentatively, it could also be suggested that there are probably a host of other factors associated with the characteristics of the cue, in terms of its duration, luminance, etc., which might add to the variability of attentional maintenance in PD.

With regards to the second dysfunction, the results indicated that, for both subject groups, RTs are greater when attention is shifted unexpectedly from one to another cube face than when it is shifted within the same face (i.e. from one to another angle of the face). For control subjects, the face-transfer RT is about 10 ms greater than the same-face RT. However, for the PD subjects this difference can be as great as 80 ms. These results are probably best interpreted by considering the geometric organization of the cube. The RT difference between face-transfer and same-face trials for both subject groups suggests that attention can be directed or focused upon a unit of the 3D object – in this case a cube face – and that time efficiency of attentional operations within that unit is promoted. This idea would be consistent with several theories of object identification and feature integration, which proposed that the elements of object perception are 3D solids that are represented according to geometric features (Marr 1982; Biederman 1985; Humphreys and Riddoch 1993). With such theories, the face of a cube can be defined as a "geon" (Biederman 1985) or as a "texton" (Julesz 1981), that is, a basic structural component of the cube. The results of the current study indicate that, also at the attentional processing level, the cube is probably represented in terms of these basic units such that the main operational attentional focus can be within a cued cube face. This is not to suggest an equal distribution of attention within that unit – the greater RTs for invalid over valid same-face trials support the well-established idea of gradients or highlighting (La Berge and Brown 1989) within the area of attentional focus – but rather an overall promotion of cognitive functions within that particular unit, in contrast to other units.

The face-transfer task of shifting attention to the cube face opposite to that which was cued is clearly more demanding for PD than for control subjects. This result raises interesting questions about how PD subjects allocate attention within a 3D object. It could indicate, for example, that object representation is not well bound at the attentional level. Thus, rather than attending to the object as a whole, PD subjects may divide the 3D screen

representation into individual planes, being unable to distribute attention in a time-efficient parallel manner upon a logical grouping of geons or textons or upon a stored structural description (Marr 1982; Biederman 1987; Humphreys and Riddoch 1993). In other words, control subjects can operate attention within the main attentional zone of the cube face while distributing attention about the whole object so that its various structural components are grouped together. This latter "attentional grouping" would allow the subject to rapidly transfer the operational attentional zone to an alternative structural unit. PD subjects appear to have a dysfunction in the parallel management of the operational attentional zone and the attentional grouping.

As was found for the comparison between valid and invalid RTs under moving and stationary conditions, the comparison of same-face and opposite-face invalid RTs gives results that differ according to the characteristics of the cue: RTs for invalid opposite trials preceded by a sustained cue are greater than those preceded by a brief cue, and this difference is irrespective of whether or not the cube is rotating. Confirming the results outlined previously, there is little difference in brief/sustained cue RTs for the same-face invalid trials when the cue is stationary, but differences when the cube is rotating about its axis. Such results would suggest that, despite the inability to interpret and use the differences in given cue information within a stationary planar attentional operational zone, a sustained cue is better at holding the attentional focus within that operational zone than a brief cue, so that PD subjects have difficulty in releasing to another planar surface of the 3D object. Consistent with the idea that PD subjects have an attentional grouping dysfunction, the temporal characteristics of the cue become an important task factor when attention must be unexpectedly allocated to an alternative operational zone.

Despite showing a deficit in transferring attention from one to another plane, PD subjects appear to show a distribution of attention that has similar directional and "preferential" zones to those of control subjects. The reason for using the words "appear to show" is that insufficient values were available for a valid statistical analysis, hence the observed trends must await more thorough study. Nevertheless, both subject groups showed greater RTs when transferring attention unexpectedly from the front to the back face than for the converse transfer, and greater RTs for a top-to-bottom than for a bottom-to-top transfer. These observations suggest that attention may be more readily held about the front upper part of the cube than about the back lower segments. Such trends in the data fit in with the results of previous studies that have assessed the distribution of attention according to viewer-centred coordinates. Andersen and Kramer (1993) demonstrated that the attentional focus could be described as a 3D ellipse with more efficient processing towards the centre of this ellipse and a gradual but directional decrease in processing efficiency towards its boundaries. In particular, the gradient from high to low

processing efficiency is steeper in the up/down and near/far dimensions than in the left/right dimensions of this ellipse. Given the similar results for both the stationary and the moving cube in the current experiment, it can be proposed that attentional gradients and preferential zones can also apply within an object-centred coordinate system. If attention were distributed only in a viewer-centred fashion, it would be expected that the results for the rotating cube where, for example, the back face is changing its viewer-centred coordinates and moving more towards the subject, should show differences from those of the stationary cube where the viewer-centred coordinates remain constant.

In effect, this study has employed a version of the Necker cube, an ambiguous 2D representation of a 3D object. Thus subjects may perceive the cuboidal pattern in one form for some periods during the experiment, but switch spontaneously to an alternative form for other periods. For example, the same face can appear to be near or far from the viewer. Spontaneous reversal rates were not measured, so we have no information about the frequency of Necker cube-perceived alternations, and thus cannot speculate about how such alternations would influence the data. Interpretations that cannot be excluded, but that must await more specific study, include (a) that PD subjects may show a different rate of spontaneous reversal and that this somehow affects the distribution of attention within the cube, particularly in the depth dimension about which the reversal occurs, and (b) that spontaneous reversals may interfere with the process of shifting attention within the object's space and thus increase the chances of error. However, the pattern of results whereby invalid trial RTs for same face were consistently less than those for opposite face would tend to suggest that all subjects grouped the cue and imperative stimulus into one (same face) or two (opposite face) planes, at least during the cue-stimulus interval. This argument is valid if one considers that the front-back perceptual relationships may alternate, but that the top-bottom and left-right do not change.

It is concluded that mildly affected PD subjects are able to perform attentional operations within a 3D object, and, most probably, that they use an object-centred reference system. Like control subjects, PD subjects show operational attentional zones that correspond to geometrical structural units of the 3D object. In the case of a hollow cube displayed on a computer screen, these zones are the cube faces. The main dysfunctions for PD subjects are (a) variabilities in the interpretation and use of cue information according to movement of object-centred coordinates, and (b) in the transferring of the operational attentional zone from one to its opposite cube face. It appears that the object is divided into structural units to which attention is allocated in a serial rather than in a parallel manner. This dysfunction in the parallel processing of different geometric components, and thus in the attentional grouping or binding of the object as a whole, would contribute to difficulties in performing time-efficient transfers of attention within a 3D object.

Overall these results point to a role for the basal ganglia in the modulation of 3D visuospatial attention; a role which is probably mediated via the thalamic projections to the cortical attentional systems. In particular, it could be suggested that the basal ganglia assist in maximising the time efficiency of attentional binding or grouping within the entire framework of a 3D object. With dysfunction to the basal ganglia, attentional operations tend to operate within divided structural regions of the object with reduced temporal cohesiveness between these regions. Intuitively, it seems appropriate that the basal ganglia, a centre traditionally associated with motor systems, should also influence 3D attentional operations that contribute to the selection and sequencing of motor actions which operate upon 3D objects and/or within 3D space. However, the degree to which the parallel "motor circuits" and "attentional circuits" interact and the site of this interaction remains to be elucidated.

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