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Functional and anatomical profile of visual motion impairments in stroke patients correlate with fMRI in normal subjects

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We used six psychophysical tasks to measure sensitivity to different types of global motion in 45 healthy adults and in 57 stroke patients who had recovered from the initial results of the stroke, but a large subset of them had enduring deficits on selective visual motion perception tasks. The patients were divided into four groups on the basis of the location of their cortical lesion: occipito-temporal, occipito-parietal, rostro-dorsal parietal, or frontal–prefrontal. The six tasks were: direction discrimination, speed discrimination, motion coherence, motion discontinuity, two-dimensional form-from-motion, and motion coherence – radial. We found both qualitative and quantitative differences among the motion impairments in the four groups: patients with frontal lesions or occipito-temporal lesions were not impaired on any task. The other two groups had substantial impairments, most severe in the group with occipito-parietal damage. We also tested eight healthy control subjects on the same tasks while they were scanned by functional magnetic resonance imaging. The BOLD signal provoked by the different tasks correlated well with the locus of the lesions that led to impairments among the different tasks. The results highlight the advantage of using psychophysical

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techniques and a variety of visual tasks with neurological patients to tease apart the contribution of different cortical areas to motion processing.

Visual motion processing is widespread in the cerebral cortex of primates. The last 30 years have provided abundant evidence from single-cell recordings in behaving monkeys that several cortical areas in the occipital, temporal, parietal, and the frontal lobes contribute to processing different aspects of visual motion. Most of this evidence in macaque monkeys concerns either the middle temporal area (MT) and its adjacent satellites middle superior temporal area (MST) and fundus of superior temporal sulcus (for reviews: Albright & Stoner, 1995; Andersen, 1997; Britten, 2008; Maunsell & Newsome, 1987; Movshon, Adelson, Gizzi, & Newsome, 1985; Newsome, Britten, Salzman, & Movshon, 1990; Wurtz, Yamasaki, Duffy, & Roy, 1990) or regions within the intraparietal sulcus, namely areas LIP, MIP, AIP, and VIP, i.e., lateral, medial, anterior, and ventral intraparietal sulcus, respectively, (Berman, Heiser, Dunn, Saunders, & Colby, 2007; Bisley & Goldberg, 2003; Colby, Duhamel, & Goldberg, 1996; Huk & Shadlen, 2005) or regions V3, V3A, and PO (Galletti, Gamberini, Kutz, Baldinotti, & Fattori, 2005). Furthermore, the frontal eye-fields (including Brodmann's area 8) are also involved in motion processing and selective attention to motion (Bruce & Goldberg, 1985; Mohler, Goldberg, & Wurtz, 1973; Xiao, Barborica, & Ferrera, 2007). Yet there are surprisingly few complementary studies of the effects of removing or neurochemically disabling cortical motion responsive areas in monkeys (Cowey & Marcar, 1992; Deng, Goldberg, Segraves, Ungerleider, & Mishkin, 1986; Marcar & Cowey, 1992; Newsome & Pare, 1988; Rudolph & Pasternak, 1999) even though ablation studies provide additional important information which physiology alone cannot. For example, even total neurochemical destruction of neurons of area MT, widely considered to be a pivotal cortical motion area, does not render monkeys motion blind, and does not even permanently impair the perception of the direction of motion (Newsome & Pare, 1988). The investigations on monkeys show that visual motion is processed in various cortical areas, and that these areas are specialized for different types of motion but they do not reveal whether these areas are indispensable for different aspects of motion processing or for motion discrimination.

Perhaps functional neuroimaging provides the key to the contribution each of these areas makes to the perception of visual motion. However, although functional magnetic resonance imaging (fMRI) shows that we, like monkeys, process motion in a variety of cortical areas (e.g., Kovacs, Raabe, & Greenlee, 2008; Moutoussis & Zeki, 2008; Peuskens, Sunaert, Dupont, Van Hecke, & Orban, 2001; Rutschmann, Schrauf, & Greenlee, 2000; Shipp, de Jong, Zihl, Frackowiak, & Zeki, 1994; Singh, Smith, & Greenlee, 2000; Smith, Wall, Williams, & Singh, 2006; Sunaert, Van Hecke, Marchal, & Orban, 1999; Tootell *et al.*, 1997; Vaina & Soloviev, 2004; Wall, Lingnau, Ashida, & Smith, 2008; Zeki, 1990, 1991) there is still too little evidence for the functional specialization of all these different regions. Studies of motion perception in individual patients with selective and highly localized brain damage provide the clearest direct evidence for regional functional specialization but they cannot reveal whether the region concerned is the only one involved in a particular motion task (Barton, Sharpe, & Raymond, 1995; Battelli *et al.*, 2001; Beardsley & Vaina, 2005, 2006; Billino, Braun, Bohm, Bremmer, & Gegenfurtner, 2009; Royden & Vaina, 2004; Vaina, LeMay, Bienfang, Choi, & Nakayama, 1990; Vaina & Rushton, 2000; Vaina & Soloviev, 2004; Zihl, von Cramon, & Mai, 1983). Studies on larger groups of patients with different cortical lesions help to clarify this issue (Rizzo, Nawrot, Sparks, & Dawson, 2008; Vaina, Cowey, Eskew, LeMay, & Kemper, 2001) for a small number of quantitative, well controlled, psychophysical motion tests.

When extended to a broader selection of motion tasks, which are commonly used with neurologically intact subjects to study regional specialization by means of functional neuroimaging, studies of large group patients should provide particularly important insight into the cortical mechanisms of visual motion mechanisms.

The present study addresses this issue in 57 patients with unilateral ischemic, occasionally haemorrhagic, stroke involving cortical areas grouped in four broadly defined regions (Vaina *et al.*, 2001) and by correlating the quantitatively assessed motion impairments with the functional activations produced by a subset of the same tasks in eight normal control subjects in an fMRI study. In addition, we correlate the impairments on different tasks with activations in regions of interest (ROIs) within the three large cortical areas of the groups that showed a deficit in one or more of the motion tasks. ROIs were defined and chosen on the basis of published fMRI studies of healthy subjects, and the sites of cortical activity elicited by the present psychophysical tasks in the fMRI study and by using localizer stimuli, which identified the retinotopic areas and the motion responsive area hMT/V5.

Given the widespread interest in cortical parcellation of structure and function it might seem strange to study a large group of patients whose lesions are rarely if ever confined to a small region of cortex of the kind that cyto- or myelo-architecture or functional activations suggest is important for a particular aspect of behaviour. However, there are several reasons why group studies like the present one continue to be informative and important. First, brain damage is capricious with respect to location and extent. Even with respect only to motion perception, neurological patients present with a variety of deficits which may impact their everyday lives in many different ways, and specific motion tests can diagnose which motion mechanisms are impaired, thus providing the basis for programs targeted to rehabilitate visual motion deficits. Second, given that much of the visually responsive cortex contains populations of neurons, which code visual motion, it would be informative to determine whether lesions to broadly defined brain regions selectively spare or impair, to various degrees, visual motion perception. Third, we expect that the study of groups of patients with damage to large but different cortical regions would reveal different patterns of motion deficits which subsequently can be correlated with selective impairments in activities of daily living, which is clinically useful.

Methods

Patients and healthy control subjects

We tested 57 patients, aged between 35 and 80 (mean age: 53.77, standard deviation: 12.38, 20 females and 37 males), with unilateral damage in the cortex and the underlying white matter resulting from a first stroke, and 45 healthy control subjects (mean age: 48.73, standard deviation: 18.47, 21 females and 24 males). Patients were referred from several rehabilitation hospitals in the Boston area and were seen at the Boston University NeuroVisual Clinic. Any patients with mental retardation, a history of neurological or psychiatric disease, ethanol or drug abuse, anosognosia, denial of illness, and visual spatial neglect, were excluded. Only patients with neuroradiological evidence of a unilateral cerebral single brain lesion due to infarct or haemorrhage that occurred between 4 and 6 weeks prior to our first meeting them, and who were able to cooperate in computerized tests (i.e., maintain fixation and attend sufficiently long to undertake psychophysical tests), and who were right handed for writing, were included.

The patients were broadly divided by lesion location, as revealed by brain scans, into four groups: (1) occipito-temporal, (2) occipito-parietal, (3) rostro-dorsal parietal, and (4) frontal–prefrontal. The corresponding cortical locations of the four lesion groups are illustrated by the coarsely defined outlines in Figure 3. We chose this coarse lesion localization since our interest was to document motion deficits that might be of diagnostic and direct clinical relevance. Accordingly, all patients underwent neurological examination and were evaluated with classical neuropsychological perceptual tests to determine their broad perceptual profile and their suitability for inclusion. Patients' demographic characteristics and performance on standardized neuropsychological tests are summarized in Table 1. The neuropsychological tests are described in the Supplemental material.

The four groups of patients were compared with two groups of healthy control subjects. One group, consisting of 45 subjects naïve to visual testing in general, provided comparisons with the performance of the four groups of stroke patients on a set of motion psychophysical tasks. The other group consisted of eight subjects, similarly naïve, who participated in an fMRI study designed to provide a finer grain localization of the specific cortical areas that provide the underlying neural substrate for a subset of the motion tasks. Collectively, the controls and patients should indicate whether the cortical activation elicited by a specific motion task could be predictive of the behavioural results associated with a coarse, clinically driven, parcellation of the patients into four lesion groups.

The first group of 45 controls consisted of two subgroups as follows: 35 young (age $\leq$ 65, mean age: 41.80, standard deviation: 14.64, 18 females and 17 males), and 10 old controls (age $>$ 65, mean age: 73.00, standard deviation: 4.40, 3 females and 7 males).

To determine at a finer spatial scale the neuronal substrate of the same psychophysical motion tasks, an additional eight healthy control subjects underwent fMRI on a subset of the motion tests administered to the patients. They were younger than the patients, aged between 24 and 55 (mean age: 27.75, standard deviation: 11.37, 4 females and 4 males) but not more experienced at visual tests. Prior to this study all subjects (patients and controls) practised with computerized psychophysical visual tests different from those reported here in order to minimize the common initial fluctuations in performance.

All subjects had no history of psychiatric or neurological disorders (other than a first-ever stroke in the case of the patients) and had normal or corrected-to-normal visual acuity. All participants gave written informed consent to participate in the studies, which were approved by the ethics committees of Boston University and of the Martinos Center for Biomedical Imaging for the fMRI studies.

Psychophysics and fMRI

Psychophysics: Materials and methods

The tests were chosen on the basis of the results previously published in several investigations of a small number of stroke patients, as described in Introduction. Here, we were interested to determine the generalizability of these results in a much larger number of patients. Testing occurred in a dimly lit room, where the major illumination was from the computer screen display. The subjects were seated with the head in a chin-rest facing the computer monitor at a viewing distance of 54 cm. Stimuli consisted of dynamic random dot displays (RDKs) containing 158 white dots (79.2 cd/m^2, subtending 4 arcmin), on a dark background (9.3 cd/m^2) and uniformly distributed

Table 1. Demographic and neuropsychological characteristics of the stroke patients, listed by lesion group

			Lesion		Neuropsychological tests of visual perception					
Patient	Sex	Age (years)	Side	Site	Raven	Position discrimination	Number localization	Dot counting	Bells	Stereo
Group 1										
1	F	49	R	Posterior temporal parietal	33.23	17	8	10	15	Absent
2	F	54	L	Temporal occipital	35.67	16	10	10	14	Normal
3	F	49	R	Occipital temporal	35.06	18	10	10	15	Normal
4	M	38	L	Occipital temporal	32.17	17	8	10	15	Normal
5	F	58	L	Occipital temporal	36.96	16	10	9	14	Normal
6	F	35	R	Occipital temporal	31.05	17	10	10	15	Normal
7	F	59	L	Occipital temporal	33.78	17	8	10	15	Normal
8	M	38	L	Temporal occipital	29.26	16	8	8	14	Absent
9	M	57	L	Occipital	32.08	17	7	8	13	Normal
10	M	57	L	Occipital temporal	31.54	18	8	7	15	Normal
11	M	49	L	Occipital temporal	30.42	18	10	10	15	Absent
12	F	42	L	Occipital	30.73	16	8	10	14	Normal
13	F	60	L	Occipital temporal	34.39	17	8	10	15	Absent
Group 2										
14	M	72	L	Occipital parietal	28.79	15	7	6	14	Absent
15	F	66	L	Parietal	28.28	15	6	9	14	Absent
16	M	65	R	Occipital parietal	26.83	14	6	9	13	Absent
17	M	68	R	Occipital parietal	27.42	14	6	8	13	Normal
18	F	48	R	Posterior parietal	31.79	15	7	7	13	Normal
19	M	65	R	Occipital parietal	29.66	15	7	7	12	Absent
20	M	55	L	Occipital posterior parietal	21.40	12	6	7	13	Absent
21	M	66	R	Occipital	21.82	13	6	8	12	Absent
22	M	45	R	Occipital parietal	25.39	13	5	7	13	Absent
23	M	52	R	Parietal	30.27	14	5	7	13	Normal
24	M	55	R	Occipital parietal temporal	29.02	13	5	7	14	Absent
25	M	56	R	Posterior parietal	29.27	13	7	8	14	Absent

Table 1. (*Continued*)

			Lesion		Neuropsychological tests of visual perception					
Patient	Sex	Age (years)	Side	Site	Raven	Position discrimination	Number localization	Dot counting	Bells	Stereo
26	M	67	L	Parietal	30.15	12		8	13	Absent
27	M	62	R	Occipital	23.16	15	8	8	15	Normal
28	F	49	L	Occipital parietal	37.86	19	10	10	15	Normal
29	M	62	R	Posterior parietal	31.61	17	7	6	14	Absent
30	M	39	L	Parietal	36.05	17	8	8	13	Normal
31	M	65	R	Parietal	34.92	16	7	7	14	Normal
32	M	66	R	Occipital	29.07	16	8	8	15	Impaired
33	M	62	L	Occipital	30.99	17	8	7	15	Impaired
34	M	71	R	Occipital	28.37	17	9	10	15	Absent
35	F	29	L	Occipital posterior parietal	32.70	17	8	10	15	Impaied
36	M	60	R	Occipital	31.58	19	10	10	15	Normal
Group 3										
37	M	36	R	Frontal parietal	34.20	17	8	8	15	Normal
38	F	39	L	Posterior and anterior temporal	32.34	16	8	9	15	Normal
39	M	65	R	Middle temporal	30.92	15	7	8	13	Normal
40	M	55	R	Superior temporal	30.20	15	6	7	11	Absent
41	M	47	R	Parietal	29.99	14	6	6	13	Absent
42	F	58	R	Parietal temporal	29.96	14	6	6	12	Absent
43	F	37	R	Parietal temporal	24.37	13	6	6	12	Absent
44	F	70	R	Parietal	31.45	16	8	7	13	Normal
45	F	68	R	Parietal	36.22	17	7	7	13	Normal
46	F	51	L	Temporal	28.09	15	6	8	13	Normal
47	M	49	R	Frontal parietal	30.65	17	8	9	15	Normal
48	F	52	L	Parietal	35.07	19	8	10	14	
49	M	52	L	Parietal	33.18		10	10	15	Normal

Table 1. (*Continued*)

			Lesion		Neuropsychological tests of visual perception					
Patient	Sex	Age (years)	Side	Site	Raven	Position discrimination	Number localization	Dot counting	Bells	Stereo
Group 4										
50	M	80	R	Frontal parietal	22.62	17	7	7	14	Absent
51	M	48	R	Frontal	23.35	19	7	8	14	Normal
52	M	70	L	Frontal	25.28	18	7	8	13	Normal
53	M	25	R	Frontal parietal	31.41	19	9	10	15	Normal
54	F	56	R	Frontal parietal	34.65	19	9	10	15	Normal
55	M	46	R	Frontal parietal	33.01	17	7	8	15	Normal
56	M	23	R	Frontal parietal	31.10	19	10	10	15	Normal
57	M	48	R	Frontal	32.24	16	7	8	13	Absent

within a circular 10° aperture displayed at the centre of the display. All stimuli were computer generated and displayed on a 17 inch screen with resolution and refresh rate of 832 × 624 pixels and 75 Hz, respectively. Each motion sequence lasted 880 ms (22 frames; 40 ms per frame). Dot speed was 3°/s and dot density was 2 dots/deg^2. Experiments 3–6 contained a variable proportion of signal dots and of masking motion noise (defined in the description of Expt 3).

Task difficulty was systematically varied across trials until subjects achieved a performance level of 79% correct (threshold) by means of an adaptive staircase (Vaina *et al.*, 2003). The test procedure was explained to the subjects while they became dim-adapted. Following practise trials and when it was clear that they understood the task, psychophysical testing began. Viewing was binocular. On each trial subjects fixated a white cross placed 2° to the left or right of the imaginary circular aperture of the stimulus, at midline level. The experimenter started each trial and the subject's eyes were watched throughout the period that the display was present. Any saccadic eye movements were easily detected and such trials were cancelled and a stimulus of the same difficulty was repeated. The patient responded verbally and the experimenter entered the response on the computer keyboard. Each task was administered 2–3 times in the left and right visual hemifield, alternating between fields. Means and standard deviations of the thresholds on each particular test were calculated for each hemifield.

Experiment 1: Direction discrimination. All the dots in the stimulus moved upwards and at a variable angle to the left or right of true vertical (Figure 1a), which was indicated by a short clearly visible line placed 0.5° above the display aperture. In a two alternative forced choice (2AFC) procedure, subjects reported whether the dot-field moved to the right or to the left of the vertical line. Threshold was the angle at which performance was 79% correct.

Experiment 2: Speed discrimination. This task measured the perception of relative speed of two RDKs (shown schematically in Figure 1c) displayed sequentially, with a 500 ms inter-stimulus interval. In each interval, every dot's trajectory changed randomly from frame to frame, but the speed was the same for all the dots. The variable was the ratio of speed difference between the two intervals. The standard speed, presented first or second at random, was 3°/s and the speed in the other interval varied from trial to trial, starting from a maximum of 6°/s (ratio = 2). In a two temporal alternative forced choice procedure, subjects reported in which interval (the first or the second) the dots moved faster. Threshold was the speed ratio at which performance was 79% correct.

Experiment 3: Motion coherence. This stimulus display, adapted from Newsome and Pare (1988), was designed to isolate motion-sensitive mechanisms by using a controlled motion signal whose strength did not alter the average spatial and temporal structure of the stimulus (as adapted by Vaina *et al.* (2001) from Newsome and Pare (1988)). The display (schematized in Figure 1e) consisted of stochastic RDKs in which a specifiable percentage of the dots had a constant velocity and correlated motion signal while the remainder moved in random directions at random speeds, providing masking motion noise. The strength of the motion signal was varied by changing the percentage of dots moving coherently between 0 (just noise) and 100 (all dots are signal and move in the same direction). In each frame, the position of the noise dots was random, and at

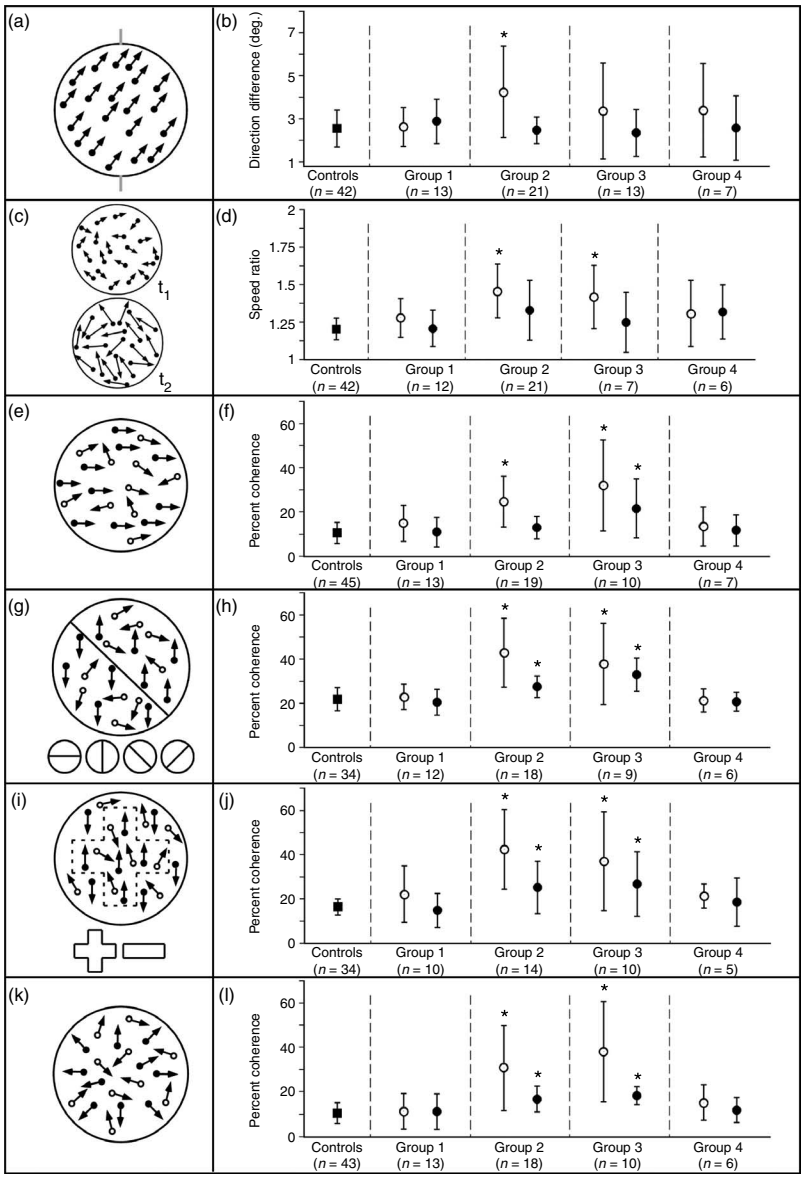

Figure 1. The visual motion tests and results from the stroke patients and healthy controls. The left column of panels represents schematic views of the visual motion displays. (a) DDT; (c) local SDT; (e) MCT (translation); (g) MDT; (i) 2D-FFM; (k) MCT-radial. In all the tests, each dot is represented as a vector indicating the magnitude and direction of motion. The filled circles represent signal dots (moving in the same direction) and the open circles represent noise dots. The second column of panels (b, d, f, h, j, l) represents the behavioural results for each test for the control subjects and each group of patients. Each data point represents the group mean $\pm$ *SD* of the thresholds obtained for the particular test. The open circles indicate the contralesional visual field and the filled circles indicate the ipsilesional visual field. The '*' symbols illustrate instances where the patients performed significantly worse than control subjects. As there was no statistically significant difference between performance in the right and left visual fields of the controls, the results were combined.

0% coherence the display appeared as a fluctuating pattern of spatiotemporal noise. The motion content of the display (direction) could be extracted only by integrating brief local motion signals over time and space (Downing & Movshon, 1989; Newsome *et al.*, 1990). In a four alternative forced choice task, subjects reported whether the overall direction of the RDK was up, down, left, or right. Threshold was the percentage of signal dots at which direction discrimination (DDT) was 79% correct.

Experiment 4: Motion discontinuity. The display was an RDK with identical statistical properties to that described in Expt 3 except that in half of the trials (discontinuous) an illusory line divided the display into two equal fields of dynamic random dots (Figure 1g) and the other half the trials (homogeneous) contained no such division. The signal dots moved upwards or downwards. The illusory line arose from the opposite direction of motion of the 'signal' dots within the two halves of the stimulus aperture. To prevent any use of spatial local cues, the illusory line had four possible orientations and the centre of the line was slightly (less than 0.5°) and randomly offset from the centre of the stimulus aperture. In a 2AFC task, subjects reported whether the display was discontinuous or homogeneous. Threshold was the percentage of signal dots at which subjects could discriminate between the homogeneous and discontinuous displays at 79% correct.

Experiment 5: Two-dimensional form-from-motion. As in Expts 3 and 4, the stimulus was an RDK of variable proportion of signal dots embedded in masking motion noise. A two-dimensional form, defined solely by the relative motion of two oppositely moving fields of signal dots and resulting in an illusory line outlining a two-dimensional form (either a 'plus' or a 'minus', of equal areas (schematized in Figure 1i) appeared in the centre of the stimulus aperture. In a 2AFC task, subjects reported whether the two-dimensional form was a 'plus' or a 'minus'. Task difficulty was titrated by varying the proportion of signal dots and threshold was the percentage of coherently moving dots where performance was 79% correct.

Experiment 6: Motion coherence – radial. This task is similar to that of Expt 3 except that the signal dots move radially in the frontal plane from centre to periphery (expansion) or the reverse (contraction), illustrated in Figure 1k. To ensure that subjects perceived planar motion, all dots had an equal displacement at all distances from the centre, preventing the depth illusion that radial motion stimuli can produce. The proportion of dots moving coherently and radially was titrated as above and the subject reported whether the pattern was expanding or contracting. Threshold was the percentage of signal dots at which performance was 79% correct.

Psychophysics: Analysis

Statistical analyses were carried out using SAS version 8.2 (SAS Institute, Inc., Cary, NC, USA). The correlation between the performance of the patients on the neuropsychological tests and the psychophysical motion tasks was done using standard Pearson correlation. To compare the performance of the two healthy control groups and their performances for stimuli displayed in the right or left visual fields, we used the student *t* test. On each test, for the four patient groups, comparisons of thresholds in the

contralesional and ipsilesional fields were made with *t* tests, taking into account unknown and unequal variances (Behrens–Fisher problem) and Satterthwaite approximations were reported for degrees of freedom and probability level measurements. Nonparametric one-way analysis of variance (Kruskal–Wallis test) was used to assess any significant difference in performance across different lesion groups and controls. Significantly different results between pairs of lesion groups were determined by Tukey–Kramer's multiple comparison tests.

Functional magnetic resonance imaging: Materials and methods

The eight volunteers were scanned with fMRI while they performed a subset of the tests described above (DDT; speed discrimination, SDT; motion discontinuity, MDT; two-dimensional form-from-motion, 2D-FFM) to probe the extent to which cortical activity is specific to each of these visual motion tasks or to a subset of them. The tasks were adapted for use in an fMRI block-design study, using the method of constant stimuli. All stimulus properties (aperture size, dot size, luminance, dot density, and speed) were identical to those already described in psychophysical methods. Prior to the scanning session, thresholds were first obtained by the staircase procedure, and subsequently three suprathreshold constant stimulus levels were chosen. Thus for all subjects, the stimuli used in the fMRI acquisition were of similar difficulty, at roughly 85% correct. The stimuli were presented in the centre of the screen to avoid having to test the two hemifields separately, which would double the scan time. In a blocked design paradigm, during each run six epochs of moving dots lasting for 30 s (task-condition) alternated with 15 s (baseline) presentation of fixation on the blank screen at mean luminance. Each run started and ended with the presentation of the baseline (off period) for 15 s and was repeated in pseudo-random order three times during a session. The onset of the stimulus was synchronized with the beginning of the image acquisition. In all the runs of the psychophysical tasks, subjects performed one of the motion discrimination tasks during the 'on' condition and a fixation discrimination (see below) during the 'off' condition.

Localizers. The motion coherence – radial (MCT-radial) task was used in pseudo-passive mode to functionally localize the motion-selective areas (hMT/V5). The coherence level varied randomly between 35 and 50% (which was suprathreshold for all subjects). Localization was done by comparing activations evoked by the radially moving random dot stimuli with the baseline fixation condition and by the invariant anatomical position of hMT/V5 at the junction of the ascending limb of the inferior temporal sulcus and the lateral occipital sulcus (Dumoulin *et al.*, 2000). In addition, all subjects underwent retinotopic mapping, using established procedures (Engel *et al.*, 1994; Tootell, Hadjikhani, Mendola, Marret, & Dale, 1998).

Subjects were familiarized with the stimuli before the fMRI experiment. A central red fixation cross whose colour intensity changed randomly, was shown at the centre of the image in all tests. Subjects were instructed to continually fixate the red central cross, which was visible throughout the run. In the hMT/V5 localizer, retinotopic mapping, and the 'off' conditions of the experimental psychophysical tasks subjects had to press a key each time the luminance of the fixation-mark changed. Runs in which this brightness discrimination was less than 95% correct were discarded, and repeated. This ensured that subjects maintained fixation on the cross and did not

significantly move their eyes. During the on-periods of the DDT, SDT, MDT, and 2D-FFM runs, subjects were asked to actively perform the task while fixating the central fixation mark. They entered their responses by pressing predetermined keys on a magnet compatible keypad.

Although the subjects in the fMRI study were younger than the patients, there is no known evidence that their gross brain regions concerned with motion perception are any different from those of older normal subjects and the psychophysical titration procedure ensured that their performance was the same as that of the patients.

Image acquisition. Data were acquired at Massachusetts General Hospital – Martinos Center for Biomedical Imaging using a 3-Tesla whole-body scanner (Siemens, Trio, Erlangen, Germany) and standard head coil. Functional images were obtained with a gradient echo, echoplanar (EPI) sequence (repetition time TR = 2, 500 ms, echo time TE = 70 ms, flip angle = 90°, field of view 200 mm) for measurement of BOLD contrast. Twenty-two axial, 5 mm thick slices, 1 mm gap, at $3.13 \times 3.13 \times 6\,\text{mm}^3$ resolution, parallel to the AC–PC plane (anterior comissure - posterior comissure plane), were acquired over the entire cortex and most of the cerebellum. All functional data were registered to the subject's structurally imaged brain. For the latter we acquired two T1-weighted MR (magnetic resonance) images, magnetization-prepared rapid-acquisition gradient echo (MPRAGE; TR = 2.53 s, TE = 3.28 ms, flip angle = 7°, T1 = 1, 100 ms, 256×256 matrix; voxel size $1.00 \times 1.00 \times 1.33\,\text{mm}^3$). Head motion was minimized by a forehead strap and tightly packed foam pads.

Throughout scanning, the room was darkened. Subjects, fitted with earplugs and when necessary with magnet-compatible correction spectacles or contact lenses, lay supine within the magnet while visual stimuli were rear-projected on to a translucent $40 \times 25\,\text{deg}^2$ acrylic screen (DaTex, Da-Lite Corp.) using a colour LCD projector (Notevision6) and collimating lens (Buhl Optical). Luminance of the display and the LCD projector was calibrated using a PhotoResearch Spectroradiometer. Luminance contrast was expressed as $(L_{\max} - L_{\min}/L_{\max} + L_{\min})$. Because stimulus contrast was not varied within a scan and because previous investigators (Tootell *et al.*, 1997) have shown that steady-state differences in mean luminance do not produce significant variations in MR signal level over a range even broader than ours, we considered this specification of contrast as adequate in the case of high contrast stimuli (e.g., localizers), permitting experimental replication and comparison with results from other imaging centres.

Functional magnetic resonance imaging: Data analysis

Data were analysed with MEDx 3.42 software (Sensor Systems, Inc., Sterling, VA, USA) and complementary scripts in MEDx TCL, MATLAB (The Mathworks, Inc., Natick, MA, USA), and PERL developed in our laboratory.

Using the interactive segmentation tool within MEDx, the images were 'deskulled', the brain surface was registered into the Talairach space (Talairach & Tournoux, 1988), individual functional images were motion-corrected (Woods, Mazziotta, & Cherry, 1993) and spatially smoothed with a Gaussian filter ($6.3 \times 6.3 \times 12$ mm), and then global intensity normalization was performed to normalize the average of each volume to the same mean value. Linear signal intensity drift unrelated to the task was estimated for each voxel and removed from the time series data. Since we used a blocked design

paradigm for all psychophysical tasks the active cortical regions were determined by a *t* test comparison of the fixation discrimination ('off' period) and the motion conditions ('on' periods) in each test. The first four volumes of the EPI scans were discarded from each acquisition to allow the MR signal to stabilize. A statistical significance threshold of $p < .05$ (resel corrected) was applied with a minimum cluster size of five voxels (Worsley *et al.*, 1996). For each subject, the EPI images were registered to the high-resolution structural volume, the same transformation was applied to the statistical volumes, and the structural and statistical volumes were spatially normalized into Talairach space (Talairach & Tournoux, 1988) before the thresholded statistical maps (threshold of 2 for individual subjects) were generated.

To ensure the reliability of the fMRI time courses, for each subject and task, the similarity of statistical maps resulting from individual acquisitions using the normalized cross-correlation was evaluated and weakly correlated ($r < .4$) acquisitions were removed from further analysis. To interpret and localize the neuronal activations elicited by each psychophysical task, we also performed statistical analysis in subject-specific motion ROIs.

Motion specific ROIs were defined separately for each subject in the Talairach atlas space on the basis of retinotopic mapping and hMT/V5 localization in each subject, and by using *a priori* defined motion responsive ROI's by their Talairach coordinates as reported in the fMRI publications from other research groups.

The following 12 ROIs were defined: V1, V2, V3, VP, V4, V3A (DeYoe *et al.*, 1996; Dougherty *et al.*, 2003; Engel *et al.*, 1994), KO (Dupont *et al.*, 1997; Van Oostende, Sunaert, Van Hecke, Marchal, & Orban, 1997; Zeki, Perry, & Bartels, 2003), hMT/V5 complex (Sunaert *et al.*, 1999; Tootell *et al.*, 1995; Watson *et al.*, 1993), LOC (Malach *et al.*, 1995), LIP, VIP, and DIPSA (the dorsal IPS anterior region; Orban *et al.*, 2003). The activations elicited by the psychophysical tasks were described by this functional 'vocabulary', and such functionally equivalent regions defined for each subject provided the basic units for the further statistical analysis.

For each psychophysical test, the visualization of group activation was illustrated on the MNI (Montreal Neurological Institute) average brain template (Evans, Kamber, Collins, & MacDonald, 1994) which was registered in Talairach space at thresholds $z > 5$ and the value for z was computed as $z = 2\sqrt{n}$ where n is the number of subjects used in averaging and two was the activation threshold set for individual subjects.

In addition to the functional localization of the neural substrate of the motion tasks, we also investigated the relationship between regions of fMRI activation and the subject's psychophysical performance. To do this, we analysed correlations of positive fMRI responses (%BOLD increase) in each functionally defined area with subjects' behavioural data. Thus, fMRI activation (%BOLD increase) versus psychophysical performance during scanning for the individual subjects and specific tasks were computed for each ROI (Gilaie-Dotan, Ullman, Kushnir, & Malach, 2002) associated with the psychophysical tasks. A correlation value $r \geq .4$ was considered to indicate involvement of an ROI in the particular motion task.

Results

Pearson correlation analysis of each group's performance on the neuropsychological and psychophysical motion tests showed that for contralesional visual field the patients with rostro-dorsal parietal damage (Group 3) and with frontal–prefrontal lesions

(Group 4), showed a strong correlation between the results of the MCT-radial psychophysical test and the Raven's progressive matrices test of non-verbal intelligence (Group 3: $r > .47$, $p < .03$; Group 4: $r > .70$, $p < .04$). There were no significant correlations for the same comparisons in patients whose brain damage involved the occipito-temporal region (Group 1) or the frontal–prefrontal region (Group 4).

Psychophysical study of motion perception in stroke patients

In the 45 control subjects, the thresholds for all psychophysical tests were not statistically significantly different for presentation in either the left or right visual field ($p > .05$; Supplementary Table 1) and therefore threshold values for the two visual fields were averaged. Furthermore, the comparison between the young ($N = 35$, age ≤ 65) and old ($N = 10$, age > 65) control groups was not statistically significant (Supplementary Table 2) on any of the psychophysical tasks ($p > .05$ in all six tests), and thus their results were combined into one control subject group for further comparisons with different patient groups.

Table 2 shows the patients' thresholds and standard deviations on each psychophysical task for stimulus presentation in the contralesional and the ipsilesional visual field. These data are also illustrated graphically in Figure 1, right column, where we also indicate (by '*') the tests and visual fields for which the difference between the average threshold of patients' groups and healthy controls was statistically significant.

Comparison of performance in the contralesional and ipsilesional visual field

Figure 1 (second column), shows the thresholds of the controls combined and the four patient groups for all the motion psychophysical tasks. In all tasks, the patients with occipito-parietal lesions (Group 2) performed significantly worse for stimuli presented in the contralesional visual field than for stimuli shown in the ipsilesional visual field [DDT ($t(23.4) = 3.69$, $p = .001$); SDT ($t(39.4) = 2.20$, $p = .034$); motion coherence (MCT; $t(24.7) = 4.02$, $p = .001$); MDT ($t(20.7) = 3.93$, $p = .001$); 2D-FFM ($t(22.6) = 2.99$, $p = .007$); radial motion tests ($t(20.1) = 2.99$, $p = .007$)]. Group 3 patients, with rostro-dorsal parietal lesions, had a significantly asymmetric performance only in Expt 6 (MCT-radial; $t(9.57) = 2.73$, $p = .022$).

A similar comparison for patients with occipito-temporal lesions (Group 1) and with frontal–prefrontal lesions (Group 4) showed no statistically significant difference of the thresholds for stimuli presented in the contralesional or ipsilesional visual field on any of the motion tasks [Group 1: DDT ($t(23.6) = 0.68$, $p = .503$); SDT ($t(22) = -1.25$, $p = .226$); MCT ($t(23.1) = -1.35$, $p = .189$); MDT ($t(22) = -1.02$, $p = .317$); 2D-FFM ($t(14.7) = -1.55$, $p = .143$); radial motion tests ($t(24) = -0.07$, $p = .949$); Group 4: DDT ($t(10.7) = -0.84$, $p = .420$); SDT ($t(9.67) = 0.09$, $p = .932$); MCT ($t(11.5) = -0.41$, $p = .689$); MDT ($t(9.64) = -0.21$, $p = .842$); 2D-FFM ($t(5.88) = -.50$, $p = .635$); radial motion tests ($t(9.01) = -0.84$, $p = .423$))].

Performance for stimuli in the contralesional visual field

In Expt 1 (DDT) the performance of patients in Group 2, with occipito-parietal lesions, was statistically significantly worse than the performances of the controls and of Group 1, with occipito-temporal lesions, [Kruskall–Wallis: $\chi^2(4) = 11.69$, $p = .020$]. In Expt 2 (SDT), Groups 2 and 3 had a significantly worse performance compared with

Table 2. Mean psychophysical performances (threshold ± 1 *SD*) of healthy controls and the four patient groups for the six psychophysical tasks: DDT, local SDT, MCT translational, MDT, 2D-FFM, and MCT-radial

	DDT			SDT			MCT		
Subjects	*N*		Threshold (*SD*)	*N*		Threshold (*SD*)	*N*		Threshold (*SD*)
Healthy controls	42		2.56 (0.85)	42		1.21 (0.07)	45		10.68 (4.74)
Lesion group		Contralesional	Ipsilesional		Contralesional	Ipsilesional		Contralesional	Ipsilesional
1	13	2.64 (0.91)	2.90 (1.03)	12	1.28 (0.13)	1.21 (0.12)	13	15.01 (8.22)	11.02 (6.76)
2	21	4.27 (2.12)	2.49 (0.62)	21	1.46 (0.18)	1.33 (0.20)	19	24.69 (11.52)	13.08 (5.08)
3	13	3.38 (2.23)	2.36 (1.09)	7	1.42 (0.21)	1.25 (0.20)	10	32.16 (20.64)	21.63 (13.33)
4	7	3.42 (2.17)	2.58 (1.50)	6	1.31 (0.22)	1.32 (0.18)	7	13.56 (8.80)	11.80 (7.18)
	MDT			2D-FFM			Radial motion		
Subjects	*N*		Threshold (*SD*)	*N*		Threshold (*SD*)	N		Threshold (*SD*)
Healthy controls	34		21.95 (5.21)	34		16.47 (3.54)	43		10.56 (4.55)
Lesion group		Contralesional	Ipsilesional		Contralesional	Ipsilesional		Contralesional	Ipsilesional
1	12	23.05 (5.70)	20.64 (5.82)	10	22.27 (12.76)	14.98 (7.66)	13	11.43 (7.87)	11.23 (7.83)
2	18	42.96 (15.64)	27.62 (4.84)	14	42.58 (17.96)	25.36 (11.89)	18	30.83 (19.04)	16.82 (5.73)
3	9	37.88 (18.25)	33.10 (7.57)	10	37.21 (22.30)	26.90 (14.57)	10	38.18 (22.58)	18.39 (4.03)
4	6	21.47 (5.22)	20.91 (4.29)	5	21.43 (5.48)	18.68 (10.97)	6	15.29 (7.88)	11.98 (5.58)

Note. The table shows the number of subjects in each group, thresholds for the controls, and thresholds in the contralesional and ipsilesional visual fields for each patient group, for each of the psychophysical tasks.

the controls, and Group 2, with occipito-parietal lesion, performed significantly worse than Group 1, with occipito-temporal lesions [$\chi^2(4) = 27.53$, $p < .0001$]. Similarly, in Expt 3 (MCT), Groups 2 and 3 performed significantly worse than the controls. Moreover, the performance of patients with rostro-dorsal parietal lesions (Group 3) was significantly worse that of Groups 1 and 4 [$\chi^2(4) = 28.75$, $p < .0001$]. In Expt 4 (MDT), Groups 2 and 3 performed significantly worse than the controls and Groups 1 and 4 [$\chi^2(4) = 32.07$, $p < .0001$]. In Expt 5 (2D-FFM), Groups 2 and 3 were significantly impaired relative to the controls. Furthermore, Group 2 performed significantly worse on this task than Groups 1 and 4 [$\chi^2(4) = 29.73$, $p < .0001$]. In Expt 6 (MCT-radial), patients with occipito-parietal (Group 2) and rostro-dorsal parietal (Group 3) lesions performed significantly worse than the controls and patients with occipito-temporal lesions (Group 1). Also Group 3 patients had a significantly poorer performance than the patients in Group 4 [$\chi^2(4) = 39.01$, $p < .0001$].

Performance for stimuli in the ipsilesional visual field

In Expt 3 (MCT), the patients with rostro-dorsal parietal lesions (Group 3) performed significantly worse than controls and patients in the other three groups [$\chi^2(4) = 10.00$, $p = .040$]. In Expt 4 (MDT), patients with occipito-parietal and rostro-dorsal parietal lesions (Groups 2 and 3) performed significantly worse than that of controls and Group 1, with occipito-temporal lesions. Furthermore, Group 3 was also more impaired on this task than Group 4 [$\chi^2(4) = 27$, $p < .0001$]. Similarly in Expts 5 (2D-FFM) and 6 (MCT-radial), Groups 2 and 3 performed significantly worse than controls and Group 1 [2D-FFM: $\chi^2(4) = 13.06$, $p = .011$; MCT-radial: $\chi^2(4) = 24.35$, $p < .0001$].

Overall summary

In all four groups of patients, the results on the neuropsychological tests of spatial perception (the position discrimination, number localization, and dot counting) from the visual object and space perception battery of Warrington and James (1991) were not correlated or only weakly correlated with their performance on the psychophysical motion tasks. At first glance, this is surprising because various aspects of spatial discrimination and of motion perception are mediated by mechanisms whose neural substrates are believed to involve dorsal cortical areas that were included in the lesions of patients in Group 2 and 3, with the occipito-parietal rostro-dorsal parietal lesions. However, the spatial discrimination tests address the ability to perceive relative positions and to perform spatial scanning, and neither abilities were required for any of the motion tasks. In the patients whose lesions involved the rostro-dorsal parietal (Group 3) or frontal–prefrontal (Group 4) areas, there was a strong correlation between performance on Raven's progressive matrices test and the performance on the MCT-radial motion task, which is not surprising as both tasks involve the perception of visual patterns (textured patterns, spatial-textured patterns, or complex motion patterns). Furthermore, in all patients except those with occipito-temporal lesions (Group 1) there was a moderate to strong correlation between the performance on the three neuropsychological visual spatial tasks and on Raven's progressive matrices test. This is consistent with the model of Lovett, Forbus, and Usher (2007), who argue that the Raven's progressive matrices test requires manipulation of spatial relations and spatial arrangements.

Taken together the pattern of results on the psychophysical motion tests shows that, especially for stimuli presented in the contralesional side, patients with lesions involving the posterior parietal cortex (Group 2) were impaired on all tasks compared with the controls. For stimuli presented in the contralesional side, patients with rostro-dorsal parietal lesions (Group 3) were impaired on all the motion tests, except DDT, which is a computation carried out mostly in the earlier stages in the visual motion processing hierarchy. The deficits on SDT showed by Group 3 patients (for the stimulus presented in the contralesional side) may be due to the ubiquitous representation of speed in the visually responsive cortex. The patients whose lesion was confined to the occipito-temporal region (Group 1) or to the frontal–prefrontal region (Group 4) performed normally on all motion tasks (Figure 1).

Cortical activity evoked by the visual motion tasks in normal subjects

The DDT, SDT, MDT, and 2D-FFM were active tasks in which subjects discriminated attributes defined by motion. The MCT-radial task was used to localize area hMT/V5, and here subjects were only asked to discriminate changes in the intensity of the central fixation mark. Figure 2 illustrates the pattern and localization of activations, averaged across the eight subjects, for each of the four active tests. The activations, which are always in comparison to the appropriate static display, are overlaid on a rendered view of the lateral surface of the left and right hemispheres. In Figure 2 (A3, B3, C3, D3), the bar graphs show the increase in BOLD signal in right and left hemisphere in 11 ROIs. All tests, indiscriminately elicited strong signal change in V1, unsurprisingly since it is the site of almost all initial cortical visual processing. Furthermore, the off condition was fixation, thus the data analysis did not cancel activation due to luminance in the motion stimuli. Therefore area V1 is not shown in the bar graphs of Figure 2.

In both the DDT (Figure 2a) and SDT (Figure 2b) tasks, the highest activation occurred in the occipital lobe bilaterally in areas V3, VP, V3a, V4, and KO. Areas LOC and hMT/V5 were least active for SDT. This is surprising given that MT neurons are highly responsive to speed (Maunsell & Van Essen, 1983) and previous functional imaging studies in humans showed significant activation in this area on SDT tasks (Kawakami *et al.*, 2002; Orban *et al.*, 1998; Sunaert *et al.*, 1999). DDT also activated area V2 in both hemispheres, while SDT elicited activation in the parietal regions (LIP, VIP, DIPSA) especially in the left hemisphere. In addition to the posterior occipital areas, the DDT and 2D-FFM tasks elicited the strongest activation bilaterally in hMT/V5, LIP, VIP, and DIPSA as well as in the prefrontal gyrus (not shown). Figure 2 (C1, C2 and D1, D2) illustrates that at a threshold of $z > 5$, the 2D-FFM task activated a larger cortical surface than the MDT task which would be expected as the former involved discrimination of form in addition to the detection of discontinuity in a noisy motion display. Area V4 was active in all the tasks (especially in the right hemisphere for DDT and SDT). However, because the retinotopy of V4 is controversial (Wandell, Brewer, & Dougherty, 2005), this attribution is tentative. Furthermore, single cell recording in areas V4, MT, and 7a in the macaque reported that roughly a third of V4 neurons are directionally selective (Ferrera & Maunsell, 2005), suggesting that area V4 should not be 'overlooked as potentially reliable source of conventional motion signals outside of areas traditionally associated with motion processing' (Ferrera & Maunsell, 2005).

Figure 3 illustrates the cortical regions that revealed significant BOLD signal increase for the four actively performed motion tasks, overlaid on a rendered three-dimensional view of the lateral surface of the left and right hemispheres and on the appropriate axial

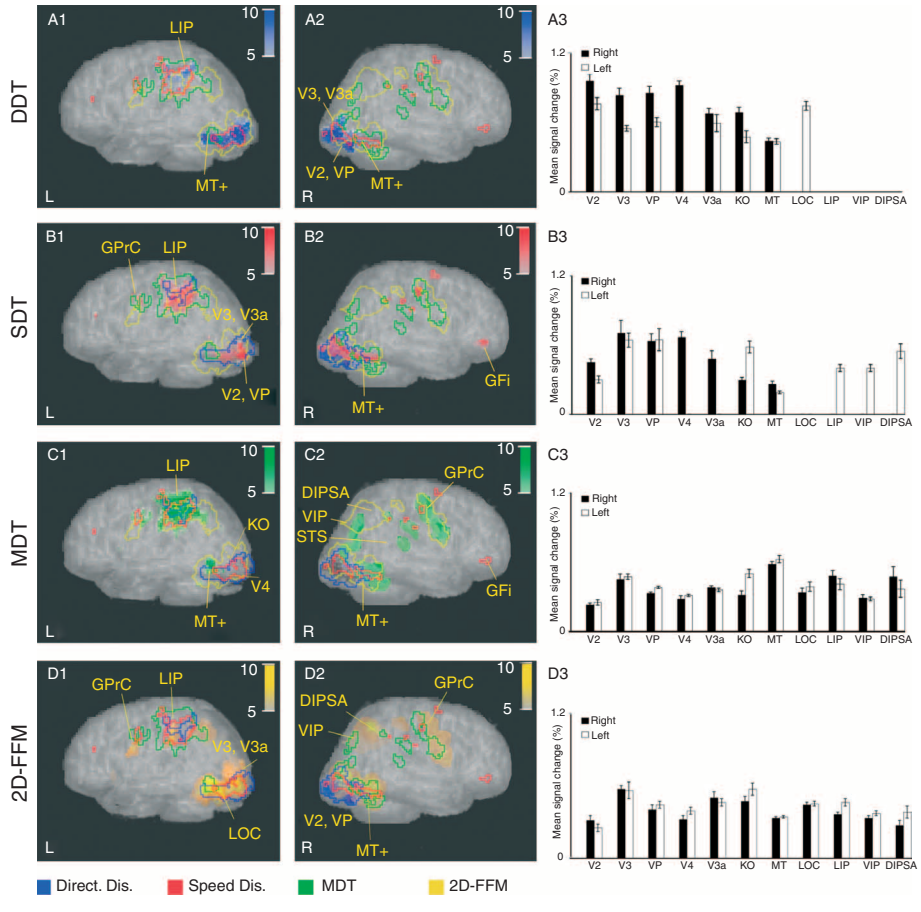

Figure 2. Averaged activation maps and per cent BOLD signal change for the motion psychophysical tasks. Activations related to the different motion tests are rendered on the lateral surface of the canonical MNI brain. First (A1, B1, C1, D1) and second (A2, B2, C2, D2) columns illustrate the left and right hemisphere activation, respectively, for the four motion tasks performed actively in the fMRI study (Blue: DDT; Red: SDT; Green: MDT; and Yellow: 2D-FFM). The cortical activity is shown for each test in a different colour, as illustrated by the colour of the z-score bar indicator. Outlined, keeping the colour convention, are shown the loci of activations produced by each of the tests. In the third column (A3, B3, C3, D3), the bar graphs show the per cent BOLD signal change as compared with baseline in the most significant motion responsive functionally defined areas in the occipital and parietal lobes. The black bars indicate per cent signal change in the right hemisphere, and the unfilled bars indicate per cent signal change in the left hemisphere. Error bars indicate standard deviations from the mean.

slices. Each row represents comparisons between the specific location of cortical activations in the controls while actively performing motion discrimination tasks, and the cortical involvement of the lesion in the four groups patients who performed the same tasks. Any correspondence cannot be exact because the lesions were larger than the cortical activations obtained in the fMRI study, the latter being specific to the stimuli presented. The most conspicuous activation took place in the occipito-parietal region, which was involved in patients of Group 2, who exhibited the worst performance in the psychophysical results. As also seen in Figure 2 (A1, A2 and B1, B2), significant

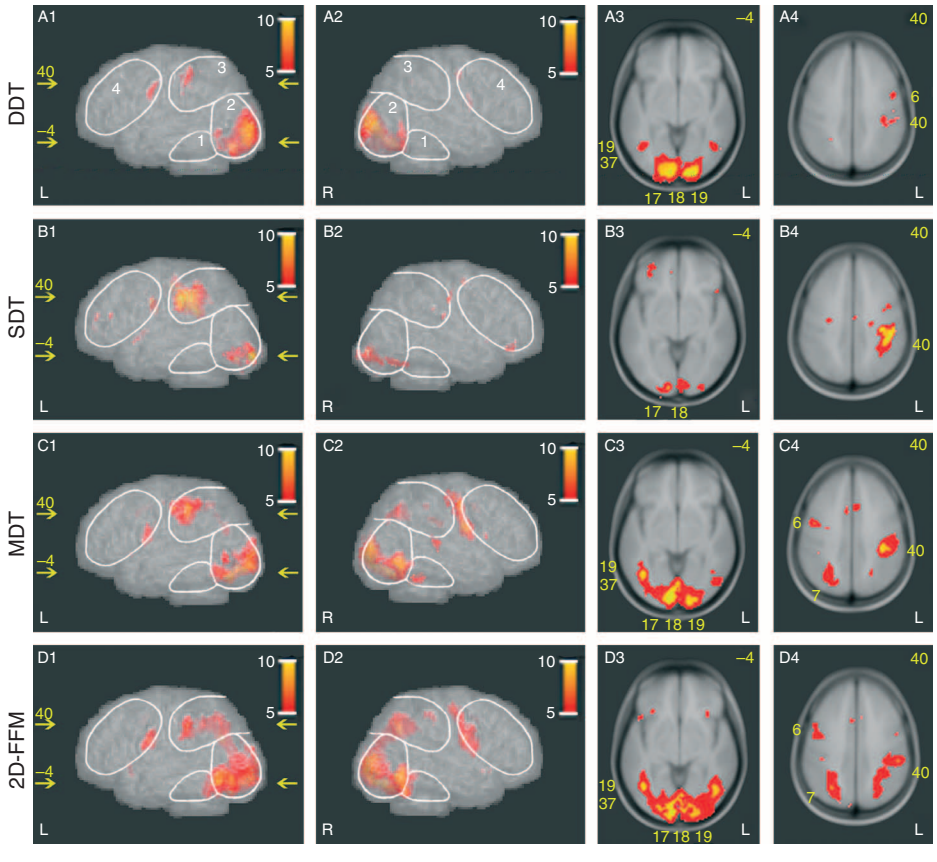

Figure 3. Motion activations in eight healthy controls and the lesion localization in the four groups of patients, together with superimposed Brodmann areas. Cortical activations in eight normal subjects, thresholded at $z > 5$, and the cortical areas involved in the lesions of the four patient groups are shown for four actively performed motion tasks, superimposed on the canonical MNI brain template. The two left columns (A1, B1, C1, D1, A2, B2, C2, D2), illustrate averaged statistical maps from the motion tests projected on the rendered views of a three-dimensional brain surface (left and right hemisphere, respectively). In the two right columns (A3, B3, C3, D3 and A4, B4, C4, D4), the same statistical maps are projected on the axial brain slices of the MNI brain, corresponding to Talairach coordinates of $z = -4$ and 40. (First row) DDT test: axial slices illustrate foci of significant activation in Brodmann areas 17–19, and in the left parietal and frontal lobes, Brodmann areas 40 and 6. (Second row) SDT test: slices show significant foci of activation bilaterally in Brodmann areas 17 and 18. (Third row) MDT test: slices show activations in Brodmann areas 17–19; occipital and temporal lobes bilaterally, Brodmann areas 19 and 37; parietal lobe bilaterally, Brodmann areas 7 and 40; frontal lobe bilaterally, Brodmann area 6. (Fourth row) 2D-FFM test: slices illustrate activations very similar to those found for the MDT test.

activation during DDT and in the SDT tasks, was also present in the occipital lobe, corresponding to the damage in the latero-ventral occipito-parietal cortex (Group 2). The activations included area VP but not ventral V4 and the latter was usually spared in the lesions of Group 2. In addition, for all the four motion tasks in Figure 3, there was almost no significant activation in the occipito-temporal and frontal–prefrontal regions of the cortex, which is consistent with the fact that patients in Groups 1 and 4 performed almost as well as the control subjects in these tasks.

Interestingly, the BOLD activation in area hMT/V5 was weaker in DDT and SDT than in MDT and in the passive viewing of the MCT-radial. Figure 3 shows that the SDT task produced significantly more change in BOLD activity than the DDT task in the rostral and dorsal lateral and ventral parietal cortex, including areas VIP and DIPSA, corresponding to the patients with rostro-dorsal parietal lesions (Group 3). With respect to MDT the occipito-parietal and dorsal parietal activations were prominent and the latter were bilateral, including the pre-cuneus, LIP, VIP, and DIPSA. The most extensive and strongest pattern of activation was present during the 2D-FFM test in all functionally defined areas where the cortical areas damaged in patients of Groups 1–3 were all involved, as were parts of the pre-central gyrus and the inferior frontal gyrus.

Correlation with behaviour

As expected, in area hMT/V5 the eight subjects' performance on all four active psychophysical tasks (DDT, SDT, MDT, and 2D-FFM) was highly correlated (from 0.62 for MDT and 0.93 for SDT) with the per cent of BOLD signal increase. The BOLD signals in the dorsal cortical areas V3 ($r > .4$) and V3a ($r > .6$) were correlated with performance on MDT, 2D-FFM, and SDT. These results are consistent with previous studies on patients with lesions involving these cortical areas (Vaina, Cowey, Jakab, & Kikinis, 2005) and with performance of patients in Group 2, with occipito-parietal lesions in this study whose cortical lesion, by definition, involved these areas.

BOLD signal in areas KO and LOC was also correlated with performance on the DDT, MDT, and 2D-FFM. The correlation of behavioural performance on DDT with V2 signal change is consistent with the results of Thompson and Liu (2006), which may be explained by the fact that this task involved discriminating perceived direction of motion to the imagined vertical whereas the other two tasks involved perception of a kinetic boundary in order to make the correct decision. The activations in parietal areas LIP, VIP, and DIPSA were significantly correlated with behaviour ($.4 < r < .7$), in MDT, 2D-FFM, and SDT.

Discussion

There are several illuminating examples of specific deficits in the perception of some aspect of motion perception following small cortical lesions in individual patients (see Introduction). Such single case studies remain particularly important in neuropsychology but they are bound to be rare. There is always the possibility that an equally small lesion elsewhere in visual cortex might have a similar effect, making it difficult to attribute an impairment solely to a particular functionally or anatomically defined visual area. The current study was designed to clarify this problem by studying a large number of patients with damage restricted to one of four different regions that are known to be involved in some aspect of motion processing. Such an investigation complements single case studies.

The present functional imaging results strongly support the notion that occipito-temporal cortex (lesion Group 1) and frontal–prefrontal cortex (lesion Group 4) are not essential for most or any of the discriminations involving the different types of motion tasks used here. Because the neuronal substrate of the psychophysical tasks embodied in Expts 1–5 suggests early visual processing, we first compared the performance of the four groups of patients among themselves and against the control subjects for stimuli

presented in the contralateral visual field. The current view of the functional architecture of the human visual motion system suggests that there should be differences between the four patients groups, which were defined on anatomical criteria. The task in Expt 6, however, is higher-level and assumed to be mediated by neurons whose receptive fields are very large and encompass a large portion, if not the whole, visual field.

The fMRI results and psychophysical data from the four patients' groups support the proposal that both occipito-parietal (Group 2) and rostro-dorsal parietal areas (Group 3) are important for efficient global motion perception, although not in an identical manner. For instance, although patients with occipito-parietal lesions (Group 2) were impaired on all tasks except 2D-FFM, patients with rostro-dorsal parietal lesions (Group 3) were not impaired on direction and SDT. The latter were the two tasks that produced least and only unilateral activation in the dorsal parietal cortex of the normal subjects.

One of the most influential notions about the gross organization of the cortical visual system is that it is divisible into dorsal (chiefly parietal) and ventral (chiefly occipito-temporal) functional systems (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982). The results of the present study point unequivocally to the involvement of the dorsal pathway in the motion discrimination tasks. However, patients with occipito-parietal lesions (Group 2) was more impaired than the patients with rostro-dorsal parietal lesions (Group 3) indicating that the crucial damage is probably to the areas in the intraparietal sulcus and the inferior parietal lobule and corresponding to areas VIP, AIP, LIP, and MIP, as defined anatomically and physiologically in macaque monkeys and functionally in human neuroimaging studies. It also suggests that motion areas such as PO, which lie more medially in the parietal lobe, are less important with respect to these tasks. The finding that the group with occipito-temporal lesions was not impaired on any of the tasks is entirely consistent with the notion the ventral pathway is much more concerned with the perception of colour and form than with motion, although motion can be used to create form. Nevertheless, there were functional activations in this region (see Figures 2 and 3) correlated with the tasks of motion discrimination thresholds and 2D-FFM.

The absence of any impairment following prefrontal lesions is also interesting because it indicates that although the frontal eye-fields and the supplementary eye-fields contain abundant motion selective neurons in macaque monkeys, and are regions often functionally activated in human subjects by moving displays, their activation is not required for visual motion discrimination *per se*. Nor were they functionally activated in the present study with the possible exception of frontal area six in the task involving the discrimination of 2D-FFM. Visual motion is evidently processed in a variety of cortical brain regions for different purposes: as a means of perceiving motion itself, in order to create form from motion, to segment a complex moving scene, and to provide the information for appropriate motor responses like eye movements and reaching and grasping. Brain lesions can inform us about where these occur in a manner still difficult with single cell recording in monkeys or functional neuroimaging in humans.

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