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Automatic avoidance of obstacles is a dorsal stream function: evidence from optic ataxia

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When we reach out to pick something up, our arm is directed to the target by visuomotor networks in the cortical dorsal stream. However, our reach trajectories are influenced also by nontarget objects, which might be construed as potential obstacles. We tested two patients with bilateral dorsal-stream (parietal) lesions, both of whom were impaired at pointing to visual stimuli (optic ataxia). We asked them to reach between two cylinders, which varied in location from trial to trial. We found that the patients' reaches remained invariant with changes in obstacle location. In a control task when they were asked to point midway between the two objects, however, their responses shifted in an orderly fashion. We conclude that the dorsal stream provides the visual guidance we automatically build into our movements to avoid potential obstacles, as well as that required to ensure arrival at the target.

When we reach out for an object, for example to pick up a cup, we use a set of exquisitely calibrated visuomotor processes in our brains that unthinkingly take into account the location and physical properties of the target object as well as the location and state of the body, arm and hand. Neurophysiological and functional MRI studies show that these brain systems are largely located in superior parts of the posterior parietal cortex in and around the intraparietal sulcus—the so-called 'dorsal stream'[1–4]. As well as being tailored to the properties of the target, however, our actions also need to take into account the location of any potential obstacles near the intended route of the reaching movement. The brain seems to insure against collisions by building into our movements a tendency to veer away from nontarget objects, even when they are actually too far away to pose a serious threat of collision[5]. As yet, no studies have investigated the brain mechanisms that mediate this implicit obstacle avoidance.

Some recent studies of neurological patients, however, have helped to narrow down the search. Our first study was with patient D.F., who has visual-form agnosia[6]. We asked her to reach out and grasp a target block in the presence of a secondary object placed in locations to the left or right of the target (R.D.M., H.C. Dijkerman, M. Mon-Williams & A.D.M., unpublished data). D.F. took good account of the obstacle's location relative to the target, systematically shifting her reach trajectories in the same manner as control subjects. D.F. has bilateral damage to her ventral stream of visual processing (recently confirmed through high-resolution structural and functional MRI[7]), which severely impairs her form perception. We therefore inferred that she might depend on her functionally intact dorsal stream[7] in achieving this skilled navigation. In other words, we suggested that both target-related processing and obstacle-related processing might share a common parietal substrate.

In a subsequent group study, we tested twelve patients suffering from spatial neglect, a condition that generally spares reaching and grasping performance, despite the presence of marked perceptual and attentional biases in other tasks[8–10]. To see whether this visuomotor sparing extends to obstacle avoidance, we compared the trajectories of arm movements on two tasks, both of which required the patient to steer between two objects[11]. In one task the patients had to point to the midpoint between two objects, while in the other they had to reach between them to a more distant target area. In both tasks, the locations of the left and right object varied independently of each other from trial to trial. We found that all but two of our patients retained their ability to take appropriate account of both objects while reaching between them, though they failed to take adequate account of the ones on the left ('neglected') side when trying to bisect the space between them[11]. The brain damage sustained by most of our neglect patients included areas around the temporo-parietal junction, but generally spared the more superior parietal areas where the human dorsal stream is located[12].

A crucial distinction can be drawn between the demands of our two tasks[11]. The bisection task requires a deliberate perceptual judgment, whereas the reaching task merely requires the programming of a route that will minimize the risk of collision as the hand passes between the objects. Accordingly, we recently tested patient D.F. on a closely similar pair of tasks. We found that she makes normal adjustments to her movements while reaching between the potential obstacles, but fails to do so in the bisection task, where she performs clearly below the normal range (N.J.R., I.S. & A.D.M., unpublished data).

These studies have provided indirect evidence for dorsal-stream involvement in obstacle navigation, by showing that the skill survives damage that mainly affects perceptual processing systems while leaving dorsal-stream structures relatively intact. Our objective in the present study was to test the dorsal-stream hypothesis more directly, by testing two patients with well-attested problems in directing reaches toward visual targets (so-called 'optic ataxia'[1,13])

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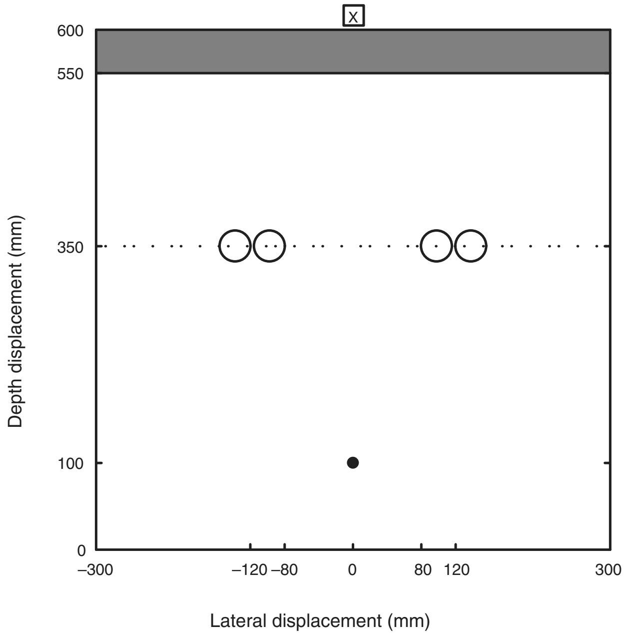

Figure 1 Plan view of the apparatus used in the experiment. Open circles, possible locations of the two cylinders, which were always presented one on the left and one on the right. Black dot, start position. Cross, fixation point.

Table 1 Mean variability of response trajectories in the reaching and bisection tasks

Task	A.T.	I.G.	Controls (mean)	*t* (A.T.)	*t* (I.G.)
Reaching	356.87	140.96	74.80	6.99**	1.64
Bisection	120.89	195.30	48.18	2.54*	5.14**

These figures are mean variance values for p, the point at which reaching movements crossed the imaginary line joining the cylinder locations, averaged across the four cylinder configurations used in each task. $*P < 0.02$; $**P < 0.001$ (one-tailed tests).

following bilateral superior parietal damage. In full confirmation of our prediction, they took no account whatsoever of the obstacle positions during reaching. As before[11], we also tested the same patients on a task of bisecting the space between the two objects, to exclude a purely attentional interpretation of their impairment on the reaching task. In accordance with our hypothesis, the patients took perfectly normal account of the objects in this more explicit ‘perceptual’ task.

RESULTS

Reaching task

The primary dependent variable was p, the position of each reaching response with respect to the midline of the stimulus board at the point of intersection with an imaginary line joining the object (cylinder) locations (**Fig. 1**). The four different cylinder configurations elicited lawful shifts of reaching trajectory in our control subjects (**Figs. 2a** and **3c**). Thus configuration B shows a leftward shift and configuration C a rightward shift, each relative to the symmetrical configurations A and D. This was true for every control subject. In contrast, the two patients showed no such changes in their reaches as a function of the locations of the left or right cylinder. For both patients, the mean trajectories were near-coincident over the four cylinder configurations (**Fig. 3a,b**).

Individual two-way ANOVAs confirmed these observations. There was no effect of left cylinder or right cylinder in either patient (A.T., F1,44(left) = 0.97, F1,44(right) = 0.11; I.G., F1,44(left) = 0.07, F1,44(right) = 2.39). Although the last of these *F*-values ($F = 2.39$) approaches significance ($P = 0.129$), it goes in the ‘wrong’ direction, that is, as if the patient were making reaching adjustments in the direction opposite to the shifts of the right cylinder—presumably the result of random variation. It is clear that neither patient took any account of cylinder location in the execution of their reaching responses. In contrast, every healthy control subject showed a significant effect of both left cylinder and right cylinder. (In every case $P < 0.005$, except for one subject (C4) for whom the left cylinder was significant at only $P = 0.021$.)

A.T. and (to a lesser extent) I.G. each had an idiosyncratic tendency to pass their hand between the cylinders with a rightward or leftward bias (**Fig. 2a**). There was, however, no constraint as to where on the gray strip their reaches should terminate, and in fact I.G.’s mean p score fell within the control range of mean p scores (–10.7 mm – +1.4 mm). Also, while A.T.’s mean p scores fell outside and to the right of the control range, this changed *en route* to the gray strip, so that the actual endpoints of her reaches fell squarely within the normal range (**Fig. 3a,b**).

We also analyzed two indices of sensitivity to the varying locations of the left and right cylinder, dp_L and dp_R respectively[11,14]. These indices measure the mean change in p that is associated with a shift of each cylinder between its two locations (that is, how much the response shifts in relation to a 40 mm shift of one or the other cylinder). Thus dp_L and dp_R represent the ‘weightings’ given to the left and right cylinder location respectively in determining the trajectories. There is a qualitative difference between the patients and the controls (**Fig. 4a**). Both patients have values that hover around zero, lying well outside the normal range. Modified t-test comparisons[15] confirm that A.T. differed significantly from the controls on both dp_L ($t = 3.13$, $P = 0.008$) and dp_R ($t = 3.11$, $P = 0.009$), as did I.G. (dp_L, $t = 2.13$, $P = 0.036$; dp_R, $t = 4.72$, $P = 0.001$).

Trial-to-trial reaching variability (as measured by the mean variance of the p scores; **Table 1**) was higher in the patients than in the controls: significantly so in A.T. (modified $t = 6.99$, $P < 0.001$), though not in I.G. ($t = 1.64$, $P < 0.073$; one-tailed tests). Although this higher variability would have militated against finding significant main effects of left or right cylinder locations in the patients, it would not have affected the values of dp_L and dp_R, which are based on mean trajectories only and take no account of variability.

Bisection task

The individual ANOVAs carried out on the bisection data tell a very different story (**Fig. 2b** and **Fig. 3d–f**). In every subject treated individually, patients as well as controls, there was a highly significant ($P < 0.001$) effect of both left cylinder and right cylinder. For patient A.T., the F values were $F_{1,44}$ (left) = 46.37 and $F_{1,44}$ (right) = 64.52; for I.G. they were $F_{1,44}$ (left) = 40.85 and $F_{1,44}$ (right) = 45.55. Thus both patients took full account of the locations of both cylinders in executing their bisection responses. Furthermore, they both embarked in appropriate heading directions according to the different cylinder configurations, right from the start of the movements (**Fig. 3d,e**).

The values of dp_L and dp_R in the patients and controls (**Fig. 4b**) confirm the normality of the patients’ bisection responses: both patients have values that lie within (indeed at the high end of) the normal range. Modified t-tests[15] confirm this impression: all comparisons between patients and controls were nonsignificant at $P > 0.25$.

The mean variance for each subject’s bisection responses (**Table 1**) is again clearly much higher than that of the controls, as confirmed by

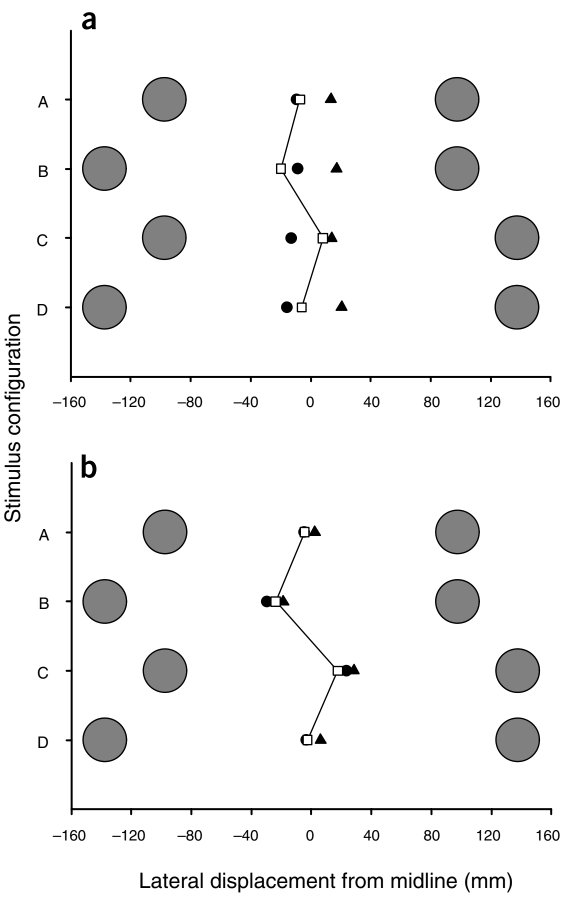

Figure 2 Mean responses in the reaching task (**a**) and bisection task (**b**). Data for the two patients are given as filled triangles (A.T.) and filled circles (I.G.), with the mean data for the eight control subjects given as open squares. The responses plotted are '*p*' scores, that is, the points where each response intersects the imaginary line joining the four possible cylinder locations. The dark gray circles depict the stimulus cylinder locations in the four configurations (A, B, C, D).

modified t-tests (A.T., $t = 2.54$, $P = 0.019$; I.G., $t = 5.14$, $P < 0.001$, both one-tailed tests). However, although this elevated variability during bisection is even clearer than in the reaching task, it did not prevent the highly significant effects of cylinder ocation noted above.

DISCUSSION

The aim of the present experiment was to test whether damage to the parietal lobes, as well as causing the pointing errors symptomatic of optic ataxia, would have a specific effect on a task requiring reaching between two obstacles. The results were very clear. Both patients made reaches between the two objects that took no account at all of the varying locations of the objects. Yet in the bisection task, the patients were completely unimpaired in taking account of identical object shifts.

Table 2 Kinematic parameters of movements in the reach task

Subject	MT	PV	TPV
A.T.	830.7	1,033.6	324.7
I.G.	561.4	1,598.2	171.6
C1	480.3	1,757.8	189.9
C2	590.4	1,671.5	220.7
C3	656.2	1,458.1	207.4
C4	454.4	2,008.9	156.3
C5	711.1	1,295.2	209.8
C6	617.3	1,226.8	260.6
C7	601.3	1,365.3	251.2
C8	454.0	1,959.5	142.8
Mean C	570.6	1,592.9	204.8

MT, mean movement time (ms); PV, mean peak velocity in the horizontal (*x*-*y*) plane (mm/s); TPV, time to peak velocity in the *x*-*y* plane (ms). The start and end of each movement was defined as a rise or fall below a threshold velocity of 50 mm/s. Data are given individually for patients A.T. and I.G. and for 8 healthy control subjects (C1–C8).

There are, of course, other differences between the two tasks that could potentially explain why our patients behaved so differently on them. For example, it could be argued that the reaching task, being carried out with more speed, and without instructions for accuracy, would inevitably cause the patients to take little account of the left and right objects. This idea gains no support, however, from the present data or from previous data. First, the healthy controls almost all showed highly significant dp_{L} and dp_{R} indices in the reaching as well as in the bisection task, although the mean magnitudes were slightly smaller. And second, in our previous study, a group of severely brain-damaged patients with spatial neglect showed an opposite result: they took normal account of the two objects during the reaching task, despite showing reduced weightings of the left object in the bisection task[11].

A converse argument might be that our two patients, due to their severe brain damage, would perform their reaches somewhat more slowly than the controls, and that this might reduce the need for them to give the obstacles a suitably wide berth. However, movement times were slow only in patient A.T.; they were normal in I.G. (**Table 2**). Furthermore, as mentioned in the Introduction, our visual agnosia patient D.F. has been tested in a similar task. Her movement times in the reaching task were even longer than those of A.T. (mean 932.8 ms). Yet D.F. showed the converse pattern of results to A.T. and I.G., taking good account of the shifts in object location during reaching.

It could alternatively be argued that simultanagnosia, a component of the 'Bálint syndrome' associated with large bilateral parietal lesions, might prevent our patients from attending to more than one object at once. If so, one would expect them to give a reduced weighting to potential obstacles during reaching. There are, however, several reasons to reject this suggestion. First, I.G. shows very little sign of simultanagnosia, having no difficulty in perceiving up to three objects presented together. Patient A.T. does retain a degree of simultanagnosia, but she only experiences it when viewing time is restricted to 500 ms or less. Thus neither patient was likely to have encountered a problem in the present testing conditions. Second, both patients performed absolutely normally on the bisection task, even though the same objects, in identical configurations and for the same duration, were present in that task as well. Third, although neither A.T. nor I.G. reported any difficulty in seeing both of the nontarget stimuli, patient D.F. did report such difficulties. Yet as we mentioned in the Introduction, her data showed the opposite pattern from that described here. And fourth, we have recently tested an optic ataxic patient (M.H.) with left parietal damage, whose pointing impairment is limited to responding with his right hand to targets in his right visual field (I.S., N.J.R., M.G. Edwards, G.W. Humphreys & A.D.M., unpublished data). This patient takes normal account of obstacles when reaching with his left hand, but selectively fails to take account of obstacles on the right side when using his right hand. This highly specific pattern of impairment cannot be accounted for by simultanagnosia.

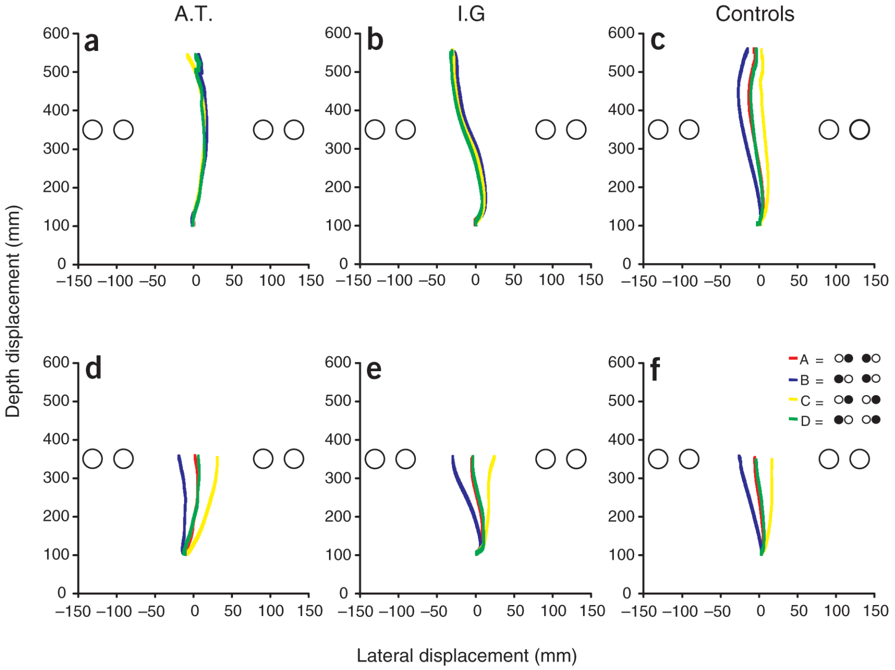

Figure 3 Mean trajectories of reaching (**a–c**) and bisection (**d–f**) movements made by the two patients, shown separately for each of the 4 different cylinder arrangements A, B, C and D (see **Fig. 2**). A, red; B, blue; C, yellow; D, green. Right, mean trajectories of the control group. The four cylinder configurations elicited appropriately different bisection movements in both patients (**d,e**), but failed to elicit different reaching movements (**a,b**). The reaches of the control subjects (top right) diverged maximally at a point approximately level with the cylinder locations, consistent with their treating the cylinders as potential obstacles.

Have we demonstrated anything new, or would our results simply follow from the well-attested problems that our patients have with target-directed reaching—in other words, their optic ataxia? Against this idea is the fact that like most patients with optic ataxia, A.T. and I.G. show little or no impairment for simple reaching to fixated targets[16,17]. Therefore our task, where the target for pointing (the gray strip) was fixated directly, should have presented no serious problem. Nevertheless, both patients did show a high variance in their reach trajectories, which would have led to a reduced *F*-value in any statistical comparison of their trajectories (such as on our measure *p*) across the four different cylinder configurations. This would not be true, however, of our analysis of the indices dp_L and dp_R, which were computed from mean values of the variable *p* and then compared directly between each patient and the controls. This analysis could not have been affected by trial-to-trial variability, and therefore gives the most unambiguous evidence of a loss of obstacle avoidance skill in A.T. and I.G.

The obstacle avoidance we have studied in this experiment is of one specific kind—an 'automatic' modification of reaching movements that allows people to minimize the risk of collision with a nontarget object without having to think about what they are doing. It is automatic in the sense of being quite unintentional; indeed the separations we used would pose very little risk of collision in healthy subjects. However, this behavior also seems to be automatic in the stronger sense of operating independently of visually awareness. In a recent study of a single patient suffering from visual extinction, we showed that conscious awareness of the obstacles during reaching is unnecessary for successful obstacle avoidance[18].

Of course in some circumstances we need to do more than minimize the risk of collision; we need to remove the risk entirely, either to protect the object or ourselves—for example when the potential obstacle is fragile or noxious, respectively. In this case, we can assume that perceptual processing, vested in the ventral visual stream[19,20], must be involved; otherwise the fragile or noxious nature of the obstacle could not be identified. The result will typically be a far more cautious navigation around the obstacle than otherwise, giving it a wider berth and slowing down more than usual[21]. This 'perceptual' form of obstacle avoidance will presumably often involve conscious monitoring of the hand as well as the obstacle during a reach, a scenario that thereby resembles our bisection task more than our reaching task. Such conscious control would be necessary also in situations where the clearance available to the hand is more limited than in our task, or where the obstacle lies directly in the path of the intended reaching movement.

If this reasoning is correct, then one would predict impairments of this second kind of obstacle avoidance in certain patients who are unimpaired on the kind tested here. For example, we would predict that patients with spatial neglect should paradoxically show an

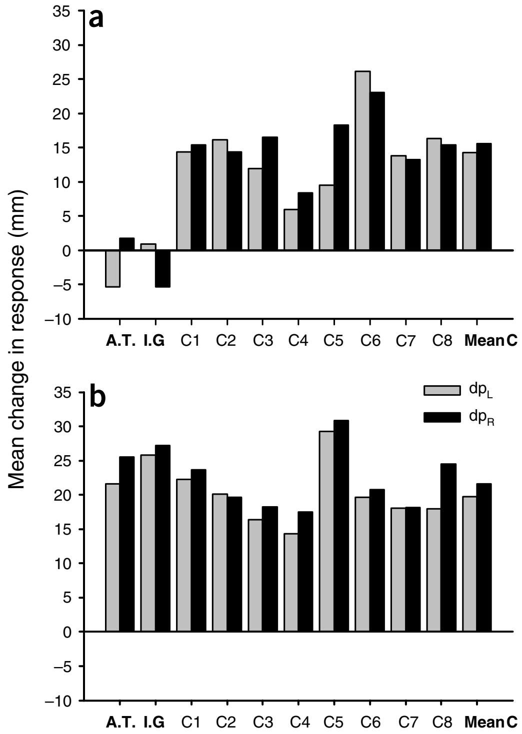

Figure 4 'Weightings' given to the two cylinders. The mean change in response induced by a 40 mm shift in the location of the left cylinder (dp_L) or right cylinder (dp_R) is plotted separately for the reaching task (**a**) and bisection task (**b**). Patients A.T. and I.G. are shown on the left of each graph, while the eight controls are shown individually, and also averaged as a group on the extreme right.

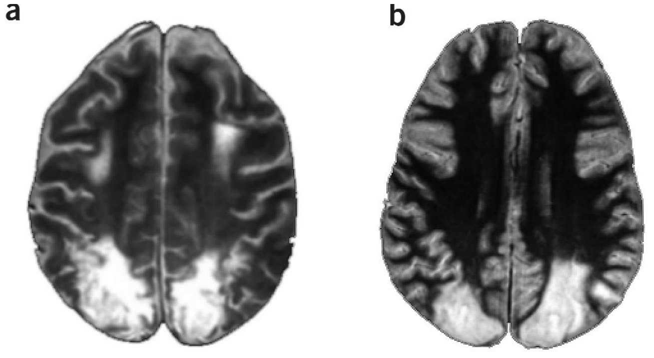

Figure 5 Axial slices through the parietal lesions of patient A.T. (**a**) and patient I.G. (**b**). More detailed information about both patients' lesions can be found elsewhere[24].

asymmetry in the influence of (for instance) delicate obstacles, giving these a wide berth only when they are on the right. The proposed distinction we are making is parallel to one made recently[16,22] in the context of error-correction during reaching. The authors distinguished two kinds of corrections that are made to a reach trajectory when the target is suddenly displaced during the reach. They observed many quick involuntary corrections in healthy subjects, which are all but abolished in patient I.G., and presumably depend on the integrity of the dorsal stream, just like the automatic obstacle avoidance we have studied in the present experiment. But in addition, they identified a separate category of slow voluntary corrections, which are unaffected in I.G. In contrast to I.G., they found that a patient with prefrontal damage did show impairment on this second kind of error correction[16,22]. One might predict a similar impairment if such a patient were to be tested on a task requiring the proposed 'perceptual' kind of obstacle avoidance.

Our conclusions also cannot be generalized to the avoidance of collision with obstacles during locomotion, as this skill is likely to present different demands from the reaching task used here. There is anecdotal evidence that patient I.G. does have such difficulties, for example in avoiding collisions with other people when walking through a busy railway station. Of course complex dynamic environments like this demand visual processing of not only static location but also of the movement trajectories of others, and indeed require a reading of other people's intentions.

METHODS

Subjects. Two patients with optic ataxia following bilateral parietal damage (A.T. and I.G.), along with 8 age-matched healthy controls (median age 39.5 years, range 32–50), took part in the experiment. All subjects were right-handed by self-report.

Patient A.T. was 48 years old at the time of testing, 14 years after an eclamptic attack that provoked a hemorrhagic softening in the territory of both parieto-occipital arteries (branches of the posterior cerebral arteries). Early structural MRI scans revealed bilateral parietal damage extending to the upper part of the occipital lobes and encroaching slightly into the medial part of the right premotor cortex. The calcarine area remained intact except for a part of the upper lip on the left side (**Fig. 5a**). At the time of the current testing, A.T. continued to show symptoms of Bálint's syndrome, including visual disorientation, simultanagnosia and a severe optic ataxia for targets in her peripheral visual field.

Patient I.G. was tested at the age of 33, after bilateral parieto-occipital infarction 3 years earlier. Shortly after the lesion, bilateral optic ataxia and simultanagnosia became apparent[23], but by the start of our testing the simultanagnosia had subsided, at least for presentations of up to three objects[16]. I.G. received a diagnosis of ischemic stroke, related to acute vasospastic angiopathy in the posterior cerebral arteries. MRI revealed near-symmetrical damage in the posterior parietal and upper and lateral occipital cortico-subcortical regions (**Fig. 5b**). The lesion involves mainly Brodmann's areas 7, 18 and 19, the intraparietal sulcus and part of area 39.

Additional sections through the lesions of both patients are published elsewhere[24].

Testing procedure. The subject sat facing a 60-cm-square white stimulus board placed flat on a table, with her right index finger at the start position (**Fig. 1**). Two dark gray cylinders made of sponge rubber (24.5 cm tall and 3.5 cm in diameter) could be fixed into the board, one on either side of the midline, at a distance of 25 cm from the start position. Each cylinder could occupy one of two possible locations, with its inside edge either 8 cm or 12 cm away from the midline. The factorial combination of these locations thus created four stimulus configurations. A strip of 5-cm-wide gray tape spanned the far edge of the board, at a depth of 20 cm behind the cylinder locations. The bisection task and the reaching task were performed in separate blocks, with the order balanced across subjects within the control group. Patient I.G. was first tested on the reaching task and then the bisection, while A.T. was tested in the converse order. Responses were recorded by sampling the position of a marker attached to the nail of the right index finger, at a frequency of 86.1 Hz, using an electromagnetic motion analysis system (*Minibird*, Ascension Technology) for 3 s following movement onset. Every movement in both the reaching task and the bisection task was recorded in full.

Throughout testing on both tasks, subjects wore liquid-crystal shutter glasses. Subjects initiated each trial by depressing the start button with the right index finger, whereupon the shutter glasses cleared to allow them to see the apparatus. Viewing time was unrestricted. In preparation for responding, subjects were required to fixate a cross at the back of the board, located centrally 16 cm above the surface of the board. They were asked if they were ready, and were then given a verbal 'go' signal to respond. The shutter glasses closed immediately when the start button was released, so that subjects could see neither the fixation cross nor the cylinders when making their responses. Thus movements were performed entirely in visual open loop. The fixation procedure was used so that the cylinders would be seen in peripheral vision, which is where target stimuli elicit the most severe pointing errors in optic ataxia[16,17]. An experimenter was seated directly in front of subjects and checked their fixation.

Bisection task. Subjects were told that this was a test of "accuracy of judgment" and that their task was to point with the right index finger exactly midway between the two cylinders, following the 'go' signal. On every trial, a strip of white card was placed between the cylinders to prevent subjects from using any visible holes in the board to aid their judgments. Subjects were informed that the positions of the cylinders would vary from trial to trial, but that there would always be one on the left and one on the right. The end position of the finger was defined as that recorded on the frame at which hand velocity fell below a threshold of 50 mm/s. The dependent measure on each trial was the average lateral position (p) of the finger marker on this last frame, with respect to the midline of the stimulus board. Each subject made 48 bisection responses, 12 trials for each of the four cylinder configurations, in a fixed pseudo-random order.

Reaching task. Subjects were told that this was a test of "speed of movement" and that their task was to reach out and touch the gray strip with their right index finger as quickly as possible following the 'go' signal. They were permitted to touch any part of the target strip, to encourage them to make reaches that were geared more to obstacle avoidance than to end-point accuracy. Subjects were informed that, whenever a cylinder was present, there would be one on the left and one on the right, and that they should pass their hand between the two cylinders, rather than around the outside edge of the board. The cylinders were not mentioned again during the rest of the experiment. The dependent measure was again the lateral position (p) of the finger marker, as it crossed the virtual line joining the two cylinder locations. (The exact value of p was estimated by linear interpolation.) Each subject made 60 reaches, with 12 trials for each of the four cylinder configurations, and 12 trials in which no cylinder was present. The 12 no-cylinder trials were included to check for any systematic spatial biases when the reaching response was not constrained by potential obstacles. They were not included in the analyses presented here.

Analyses. The primary dependent variable p codes the absolute lateral position of each response, without reference to the center of the gap between the two cylinders presented on that trial. The main analyses were two sets of two-way repeated-measures ANOVAs of response positions p, with the factors left cylinder location (near, far) and right cylinder location (near, far). A separate ANOVA was carried out on the data of each individual subject.

A second set of analyses were made of the weighting indices dp_L and dp_R, which were calculated according to the following equations[11,14] (**Fig. 2**):

$$dp_L = (\text{mean } p \text{ in configurations A and C}) - (\text{mean } p \text{ in configurations B and D})$$

$$dp_R = (\text{mean } p \text{ in configurations C and D}) - (\text{mean } p \text{ in configurations A and B}).$$

A modified *t*-test[15] was used to make a separate statistical comparison between each patient and the control group on each of the two indices in each test condition.

In a third set of analyses, the variability of reaches was assessed by calculating the standard deviation of p scores for each of the four test configurations, and averaging these to give a mean variability score for each subject.

All of our analyses exploit the formal correspondence between our two tasks, without making any assumptions about causality in either case. The analyses simply treat both tasks as requiring a spatial response that depends simultaneously on the location of objects (cylinders) on the two sides of space.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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