A paradoxical improvement of misreaching in optic ataxia: new evidence for two separate neural systems for visual localization

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We tested a patient (A. T.) with bilateral brain damage to the parietal lobes, whose resulting 'optic ataxia' causes her to make large pointing errors when asked to locate single light emitting diodes presented in her visual field. We report here that, unlike normal individuals, A. T.'s pointing accuracy improved when she was required to wait for 5 s before responding. This counter-intuitive result is interpreted as reflecting the very brief time-scale on which visuomotor control systems in the superior parietal lobe operate. When an immediate response was required, A. T.'s damaged visuomotor system caused her to make large errors; but when a delay was required, a different, more flexible, visuospatial coding system—presumably relatively intact in her brain—came into play, resulting in much more accurate responses. The data are consistent with a dual processing theory whereby motor responses made directly to visual stimuli are guided by a dedicated system in the superior parietal and premotor cortices, while responses to remembered stimuli depend on perceptual processing and may thus crucially involve processing within the temporal neocortex.

Keywords: optic ataxia; parietal lobe; visuomotor control; spatial localization

1. INTRODUCTION

Bilateral damage to the posterior parts of the parietal lobes causes a cluster of symptoms first identified by Bálint (1909; see Harvey 1995) in which there are severe impairments in spatial selective attention and visuomotor control. The latter problem, which Bálint (1909) called 'optic ataxia', showed itself as a gross spatial inaccuracy when his patient attempted to point or reach towards individual objects in his visual field. More recent studies (Jeannerod 1986; Perenin & Vighetto 1988; Jeannerod *et al.* 1994) have confirmed Bálint's (1909) interpretation of optic ataxia as visuomotor in nature, rather than purely visuospatial. Indeed, as Bálint (1909) first reported, the inaccuracies of manual control seen in optic ataxia are frequently restricted to one hand, the success of the other hand thus indicating that the relevant visual information must be adequately processed. A recent illustration of the visuomotor nature of this posterior parietal system is provided in an elegant study by Desmurget *et al.* (1999). These authors applied transcranial magnetic stimulation (TMS) over the intraparietal sulcus region on the left side of the brain of human volunteers and found that the stimulation interfered with visually guided corrections during right-hand reaching movements made towards light emitting diode (LED) targets. The reaching movements were only affected when the target position was shifted (unknown to the observer) and not when the

target remained stationary—indicating that TMS affected the on-line correction of a motor response on the basis of changed visual information, rather than the motor response *per se*. Yet this interference was selective for the limb used, since it affected the right arm but not the ipsilateral left arm. Thus, although the TMS prevented new visual information from being used on-line during the reach, it did not do so globally, but only in relation to one particular effector, namely the contralateral arm.

This posterior parietal lobe system is not limited in its scope to the visuomotor control of reaching in space. Behavioural studies of damage to the system (in both lesioned monkeys and humans with optic ataxia) show that it is also essential for the visual processing required in the initiation and on-line guidance of actions such as grasping, saccadic and pursuit eye movements and whole-body locomotion (Jeannerod 1994; Milner & Dijkerman 1998). Furthermore, electrophysiological studies have shown that the monkey's posterior parietal cortex incorporates multiple egocentric spatial coding networks which can convert the retinal location of a stimulus into various more abstract coordinate frameworks as a result of extra-retinal modulation (Andersen 1997). These networks, in conjunction with linked premotor systems (Caminiti *et al.* 1996; Rizzolatti *et al.* 1997), can then transform visual information directly into motor coordinates for organizing manual and other movements in space.

These visuomotor control networks appear to be able to operate perfectly well without any conscious monitoring of the visual information used. For example, when

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Figure 1. Recent magnetic resonance images of subject A. T.'s brain. Twelve equi-spaced sagittal sections are shown, six from each side of the brain. It is clear that there is symmetrical parietal lobe damage on the two sides of her brain in the absence of damage to the occipito-temporal lobe structures on either side.

a target is shifted during a saccadic eye movement, such that there is no conscious experience of the changed visual information, on-line adjustments of a concurrent reaching movement are still made accurately and seamlessly (Goodale *et al.* 1986). This 'saccadic suppression' technique was used in the above TMS study by Desmurget *et al.* (1999), specifically so that the direct visuomotor pathway had to be used by the observer.

In contrast to these dedicated 'unconscious' systems for coding egocentric spatial location for current motor guidance, there is thought to be a quite separate form of spatial coding in which the location of a stimulus is computed not with respect to the observer, but with respect to other visual stimuli in the environment which the brain assumes to be stable (Paillard 1987; Bridgeman *et al.* 1997). Since this system is sensitive to visual context, it can be easily deceived: for example, a stationary stimulus appears to move when it is enclosed by a frame which is displaced. Reaching and saccadic eye movements do not fall prey to these illusions (Bridgeman *et al.* 1981; Wong & Mack 1991). There is evidence from studies of both normal and brain-damaged subjects that our movements become dominated by this stimulus-relative form of spatial coding when a delay of 2 s or more is interposed between stimulus and response (Bridgeman *et al.* 1997; Rossetti 1998). This time-based switch-over does not appear to be limited to the domain of spatial behaviour. A few seconds' delay interposed in an object-grasping task appears to cause a comparable change from direct visuomotor control to a perception-based control of hand pre-shaping (Goodale *et al.* 1994; Hu *et al.* 1999).

The purpose of the present study was to attempt to gain independent evidence of the separate operation of these two hypothesized spatial systems in guiding orientating movements by testing a patient with bilateral optic ataxia following extensive damage to both parietal lobes

(patient A. T., as previously described by Jeannerod *et al.* (1994)). We expected of course that she would make large errors when pointing to targets immediately upon their presentation, as is characteristic of optic ataxia. However, we also made the counter-intuitive prediction that her accuracy might improve when she was required to delay a few seconds before responding. Our reasoning was that, under these conditions, she might be able to exploit the second hypothesized system for spatial representation if that pathway is at least partially independent of the occipito-parietal system (and, therefore, less damaged in her case).

2. METHODS

(a) *Subjects*

We tested a 44-year-old patient (A. T.) 12 years after an eclamptic attack which provoked a haemorrhagic softening in the territory of both parieto-occipital arteries (branches of the posterior cerebral arteries). Considering the risk of worsening her clinical status, no arteriographic evaluation was attempted. Structural magnetic resonance images early after the episode revealed bilateral parietal damage extending to the upper part of the occipital lobes and slightly to the medial part of the right premotor cortex. The calcarine area remains intact except a part of the upper lip on the left side (see figure 1). Nonetheless, for the initial two weeks after the lesion, A. T. presented a severe visual deficit resembling cortical blindness. At the time of the current testing, A. T. still continues to show the symptoms of Bálint's syndrome, including visual disorientation, simultagnosia and severe optic ataxia for targets in her peripheral visual field. On the other hand, she shows no clinical indications of occipito-temporal damage (e.g. alexia, object agnosia, achromatopsia or prosopagnosia) and she manages now to lead a surprisingly normal life despite the extensive lesions shown by the magnetic resonance images.

In addition, we tested three healthy control subjects, one female aged 50 years and two males aged 47 and 49 years.

(b) *Experimental set-up*

The targets were red LEDs embedded in a black Perspex table at which the subject was comfortably seated. The LEDs were only visible when illuminated. No tactile information was available about the target positions. The LEDs were presented one at a time at seven locations centred radially on the subject's head, which was held steady on a chin rest. The target locations were at -30° , -20° , -10° , 0° , $+10^\circ$, $+20^\circ$ and $+30^\circ$ with respect to the body's sagittal axis. At the start of each trial, the right index finger of the subject rested on the table, at a point on the sagittal axis 25 cm in front of the centre of their body. Throughout each trial, the subject was asked to fixate a green LED placed 2.5 cm in front of the central target location.

(c) *Procedure*

We presented each of the subjects with an LED at one of seven different locations while (s)he fixated the central fixation light. In the 'immediate' pointing condition, a viewing period of 2 s was followed by a tone signalling that (s)he should point to the target while maintaining fixation on the central light. The target remained visible until the end of the trial. In the 'delayed' test condition, we again presented the LED for 2 s, but then asked the subject to wait until (s)he heard a tone 5 s later before pointing to the target location. Four blocks of trials were performed for both the immediate and delayed pointing conditions according to a balanced (ABBA-ABBA) design. Each block contained 14 trials (two for each target).

The pointing movement and end-point positions of the right forefinger were measured using an opto-electronic movement recording system (Optotrak, Northern Digital, Inc., Waterloo Canada). This system recorded the position of an infrared emitting diode attached to the tip of the forefinger throughout the movement at a sampling rate of 200 Hz. Resultant pointing errors and end-point deviations in the x - and y -directions were computed for each trial, based on the coordinates of calibration trials. Calibration trials were collected at both the start and end of each session by continuous illumination of each target, one by one, and allowing the subjects to adjust their terminal fingertip position until they felt they had perfectly occluded the target. As there were two sets of calibration trials for each session, the end-point error was calculated using each set separately, after which the two error values were averaged.

3. RESULTS

As can be seen from figure 2, A. T.'s responses were very inaccurate, except when pointing to targets at the vertical midline of the visual field (cf. Jeannerod *et al.* 1994). Her errors averaged up to 173 mm depending on the position of the LED. However, when we asked A. T. to wait until she heard a tone 5 s later before pointing to the target location, her errors dropped significantly in magnitude (see figure 2a). Statistical analysis revealed a highly reliable difference in A. T.'s absolute errors between the two tasks ($t=4.35$, d.f. = 55 and $p < 0.001$). In contrast, needless to say, healthy individuals are less accurate when required to delay before making a localized pointing response in this way. All three of the controls we tested showed larger pointing errors in the delayed than the immediate condition and the difference

Figure 2. (a) The mean pointing errors made by A. T. to a target LED either immediately on its onset (open bars) or after a delay of 5 s (filled bars). The means were arrived at by averaging the absolute errors within the horizontal x - y plane across all eight trials for each of the seven targets separately. (b) The mean pointing errors made by control subject C. M. (a 50-year-old female) in immediate (open bars) and delayed (filled bars) pointing conditions.

was statistically significant in two of them. Representative data are presented in figure 2b: this particular subject (C. M.) doubled the size of her average errors in the delayed response compared with immediate reaching. Thus, the difference between the two conditions was highly significant, but in the opposite direction to A. T. ($t=7.43$, d.f. = 55 and $p < 0.001$; for the other two control subjects, $t=0.26$, d.f. = 53 and n.s. (subject J. M.) and $t=3.99$, d.f. = 53 and $p < 0.001$ (subject J. C.)).

A. T.'s pointing errors were predominantly made medially to the targets: her ' x -axis' errors differed significantly between the immediate and delayed conditions ($t=4.92$,

d.f. = 55 and $p < 0.001$). In contrast, there was no significant difference in the y - (near-far) direction ($t = 0.75$, d.f. = 55 and n.s.). There was no such systematic trend among the control subjects. Subjects C. M. and J. C. each showed significantly less accuracy with delay in both the x - and y -directions (x -axis, $t = 5.54$ and $p < 0.001$ and $t = 3.94$ and $p < 0.001$ and y -axis, $t = 3.97$ and $p < 0.001$ and $t = 1.95$ and $p < 0.05$, respectively), while control subject J. M. showed no significant differences between the immediate and delayed pointing in either direction ($t = 1.09$ and $t = 0.07$, respectively).

All of A. T.'s 'immediate' pointing responses except one were initiated within 1500 ms after the 'go' signal. Nevertheless, we found that the mean latency of her immediate responses to the visual signal was higher in the immediate pointing task than to the tone signal in the delayed task (548 ms for immediate pointing versus 370 ms for delayed pointing, $t = 3.41$ and $p < 0.002$). Again this result is exactly opposite to that seen in the healthy control subjects, all three of whom made significantly lower-latency responses in the immediate pointing condition (overall means 372 ms for immediate pointing versus 537 ms for delayed pointing).

4. DISCUSSION

The results of this investigation are striking. Our optic-ataxic patient A. T. responded not only more accurately but also more promptly when making delayed rather than immediate pointing responses to targets in the peripheral visual field. In contrast, the healthy controls showed the opposite pattern on both measures. This remarkable result is very difficult to explain on the assumption of a unique representation of visual space in the parietal lobe, damage to which might be thought to cause the localization difficulties characteristic of optic ataxia.

Furthermore, there is complementary evidence that damage elsewhere in the brain can have converse effects to those we have reported here for A. T. A few rare patients exist who show a dissociation between perception and visuomotor control in the opposite direction from that seen in optic ataxia, such that, while their visual perception is profoundly impaired, they are nonetheless able to perform a number of visuomotor tasks with ease. One such patient (D. F.) has been extensively studied and it has been argued that her intact visuomotor skills depend precisely upon those parietal-lobe mechanisms that are disrupted in optic ataxic patients such as A. T. (Milner *et al.* 1991; Milner & Goodale 1995; Milner 1997). Indeed, when we assessed D. F. on immediate and delayed pointing, we found that her performance was as accurate as three matched control subjects when she was allowed to respond immediately to the target (Milner *et al.* 1999). In contrast, however, when the target was turned off and a delay of 10 s was interposed, D. F. became highly inaccurate, making pointing errors twice as large as the control subjects (Milner *et al.* 1999). This result is consistent with observations that D. F. also performed poorly on non-delay tasks which explicitly require the visual encoding of spatial relationships (Dijkerman *et al.* 1998; Murphy *et al.* 1998). It should be noted that D. F.'s low accuracy in delayed pointing implies that, although interposing a delay would in

theory provide A. T. with more time for movement preparation, in practice this putative benefit is not apparent in either healthy subjects or in other patients with severe visual impairment.

The converse pattern of pointing impairments in A. T. and D. F. supports the conclusions arrived at by others from a number of studies, mainly of normal individuals (Bridgeman *et al.* 1997; Rossetti 1998), that there are two systems for spatial representation in the brain, apparently specialized for two broadly different purposes. One system is dedicated to the immediate guidance of our actions in space and, hence, uses spatial information coded in motor (i.e. egocentric) coordinates. Human lesion and functional neuroimaging evidence locates this visuomotor system superiorly in the parietal lobe, in and around the intraparietal sulcus (e.g. Perenin & Vighetto 1988; Grafton *et al.* 1996; Kawashima *et al.* 1996). The other system is designed for longer-term coding of spatial relationships for perceptual and cognitive purposes and may lie in a more inferior (parieto-temporal) location in the human brain (perhaps predominantly in the right hemisphere) (Milner & Goodale 1995). This system could operate 'allocentrically' in the present delay task by computing the target location relative to the fixation point. Given the present evidence that it can function relatively well in a patient with extensive bilateral parietal damage, this second system may receive information about spatial relationships through occipito-temporal visual areas. In support of this idea, the relative coding of stimulus location within a visual array has recently been physiologically demonstrated in neurons in the monkey's temporal neocortex (Baker *et al.* 1999; Missal *et al.* 1999).

We suggest that, when reaching towards target stimuli present within the visual array, A. T. cannot help but use the dedicated visuomotor system, even though the result is that she makes large errors. It is only when the visual information in this 'immediate' system is not acted upon and is allowed to decay that the second system comes into play. Normally this second system will provide a less accurate spatial metric, designed only to orientate the observer to the general 'ballpark' location of a target in preparation for the 'on-line' system to come into operation. This lesser accuracy is apparent in the delayed pointing of controls in this as in previous studies (e.g. Elliott & Madalena 1987; Berkinblit *et al.* 1995; Milner *et al.* 1999). Indeed, Elliott & Madalena (1987) explicitly inferred from their data that visual information useful for guiding manual aiming movements does not persist for longer than 2 s. However, due to A. T. having suffered damage to the dedicated visuomotor system, she has lost the advantage that immediate responding would normally offer, so that a paradoxical improvement can appear whenever a time-delay forces the more general-purpose perceptual system into operation.

A. T. showed this improved performance with delay despite the fact that she is impaired in a range of attentional and cognitive tasks, impairments that probably reflect the fact that her lesions (like those of Bálint's (1909) original patient) include a large proportion of both parietal lobes. Nevertheless, A. T.'s cortical damage is chiefly restricted to the parietal lobes and entirely spares the temporal lobes (see figure 1). We suggest that A. T.'s intact temporal lobes can partially compensate for

her parietal damage by retaining information about the relative location of the target with respect to the fixation point, thus enabling improved pointing under delayed conditions. Although the damage to inferior parts of A. T.'s parietal lobes may prevent her from attaining completely normal accuracy in this, particularly for targets in the peripheral visual field, the improvement she shows is nevertheless a remarkable one.

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REFERENCES

- Andersen, R. A. 1997 Multimodal integration for the representation of space in the posterior parietal cortex. *Phil. Trans. R. Soc. Lond. B* **352**, 1421–1428.
- Baker, C. I., Keyser, C., Jellema, T. & Perrett, D. I. 1999 Coding of spatial position in the superior temporal sulcus of the macaque. *Curr. Psychol. Lett.: Behav. Brain Cognit.* (In the press.)
- Bálint, R. 1909 Seelenlähmung des 'Schauens', optische Ataxie, räumliche Störung der Aufmerksamkeit. *Monatsschr. Psychiatr. Neurol.* **25**, 51–81.
- Berkinblit, M. B., Fookson, O. I., Smetanin, B., Adamovich, S. V. & Poizner, H. 1995 The interaction of visual and proprioceptive inputs in pointing to actual and remembered targets. *Exp. Brain Res.* **107**, 326–330.
- Bridgeman, B., Kirch, M. & Sperling, A. 1981 Segregation of cognitive and motor aspects of visual function using induced motion. *Percept. Psychophys.* **29**, 336–342.
- Bridgeman, B., Peery, S. & Anand, S. 1997 Interaction of cognitive and sensorimotor maps of visual space. *Percept. Psychophys.* **59**, 456–469.
- Caminiti, R., Ferraina, S. & Johnson, P. B. 1996 The sources of visual information to the primate frontal lobe: a novel role for the superior parietal lobule. *Cerebr. Cort.* **6**, 319–328.
- Desmurget, M., Epstein, C. M., Turner, R. S., Prablanc, C., Alexander, G. E. & Grafton, S. T. 1999 Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neurosci.* **2**, 563–567.
- Dijkerman, H. C., Milner, A. D. & Carey, D. P. 1998 Grasping spatial relationships: failure to demonstrate allocentric visual coding in a patient with visual form agnosia. *Consc. Cognit.* **7**, 424–437.
- Elliott, D. & Madalena, J. 1987 The influence of premovement visual information on manual aiming. *Q. J. Exp. Psychol. A* **39**, 541–559.
- Goodale, M. A., Pélisson, D. & Prablanc, C. 1986 Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature* **320**, 748–750.
- Goodale, M. A., Jakobson, L. S. & Keillor, J. M. 1994 Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia* **32**, 1159–1178.
- Grafton, S. T., Fagg, A. H., Woods, R. P. & Arbib, M. A. 1996 Functional anatomy of pointing and grasping in humans. *Cerebr. Cort.* **6**, 226–237.
- Harvey, M. 1995 Translation of 'Psychic paralysis of gaze, optic ataxia, and spatial disorder of attention' by Rudolph Bálint. *Cogn. Neuropsychol.* **12**, 261–282.
- Hu, Y., Eagleson, R. & Goodale, M. A. 1999 The effects of delay on the kinematics of grasping. *Exp. Brain Res.* **126**, 109–116.
- Jeannerod, M. 1986 The formation of finger grip during prehension: a cortically mediated visuomotor pattern. *Behav. Brain Res.* **19**, 99–116.
- Jeannerod, M. 1994 The hand and the object: the role of posterior parietal cortex in forming motor representations. *Can. J. Physiol. Pharmacol.* **72**, 535–541.
- Jeannerod, M., Decety, J. & Michel, F. 1994 Impairment of grasping movements following bilateral posterior parietal lesion. *Neuropsychologia* **32**, 369–380.
- Kawashima, R. (and 10 others) 1996 Topographic representation in human intraparietal sulcus of reaching and saccade. *NeuroReport* **7**, 1253–1256.
- Milner, A. D. 1997 Vision without knowledge. *Phil. Trans. R. Soc. Lond. B* **352**, 1249–1256.
- Milner, A. D. & Dijkerman, H. C. 1998 Visual processing in the primate parietal lobe. In *Comparative neuropsychology* (ed. A. D. Milner), pp. 70–94. Oxford University Press.
- Milner, A. D. & Goodale, M. A. 1995 *The visual brain in action*. Oxford University Press.
- Milner, A. D. (and 10 others) 1991 Perception and action in 'visual form agnosia'. *Brain* **114**, 405–428.
- Milner, A. D., Dijkerman, H. C. & Carey, D. P. 1999 Visuospatial processing in a pure case of visual-form agnosia. In *The hippocampal and parietal foundations of spatial cognition* (ed. N. Burgess, K. J. Jeffery & J. O'Keefe), pp. 443–466. Oxford University Press.
- Missal, M., Vogels, R., Li, C.-Y. & Orban, G. A. 1999 Shape interactions in macaque inferior temporal neurons. *J. Neurophysiol.* **82**, 131–142.
- Murphy, K. J., Carey, D. P. & Goodale, M. A. 1998 The perception of spatial relations in a patient with visual form agnosia. *Cognit. Neuropsychol.* **15**, 705–722.
- Paillard, J. 1987 Cognitive versus sensorimotor encoding of spatial information. In *Cognitive processes and spatial orientation in animal and man. II. Neurophysiology and developmental aspects* (ed. P. Ellen & C. Thinus-Blanc), pp. 43–77. Dordrecht, The Netherlands: Martinus Nijhoff.
- Perenin, M.-T. & Vighetto, A. 1988 Optic ataxia: a specific disruption in visuomotor mechanisms. I. Different aspects of the deficit in reaching for objects. *Brain* **111**, 643–674.
- Rizzolatti, G., Fogassi, L. & Gallese, V. 1997 Parietal cortex: from sight to action. *Curr. Opin. Neurobiol.* **7**, 562–567.
- Rossetti, Y. 1998 Implicit short-lived motor representations of space in brain damaged and healthy subjects. *Consc. Cognit.* **7**, 520–558.
- Wong, E. & Mack, A. 1981 Saccadic programming and perceived location. *Acta Psychol.* **48**, 123–131.