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CHAPTER 14

Delayed reaching and grasping in patients with optic ataxia

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Abstract: A series of experiments documenting the reaching and grasping of two patients with optic ataxia is presented. We compare their immediate responses with their behavior when required to delay for a few seconds before responding. When the delayed response is 'pantomimed', i.e. made in the absence of the target object, their performance typically improves. This pattern was predicted from a two-visual-systems model in which the cortical dorsal stream mediates normal visually guided actions while the ventral stream deals with visual information that has to be held in memory. We further found that when a 'preview' task was used in which the patients could use memorized information to guide a response to a still-present target object, they did so in preference to using the visual information facing them.

Introduction

The great majority of studies of visually guided prehension have set out to characterize and explain the ways in which humans and animals make movements directly toward targets in their visual field. The ability to execute such skilled actions must have been one of the earliest and most critical adaptive changes in the evolution of the primate brain. There is evidence from a range of converging methodologies that these direct actions are guided through rather 'automatic' sensorimotor transformations mediated by circuits within the posterior parietal and premotor cortex, in close conjunction with brainstem and cerebellar nuclei (Jeannerod et al., 1995; Andersen et al., 1998; Milner and Dijkerman, 1998). The major visual input for these systems appears to filter through from V1 via the primate 'dorsal stream' of cortical processing (Milner and Goodale, 1995). This stream extends anteriorly to include the parietal areas that transform visual information into action coordinates. Dorsal-stream lesions in monkeys have long been known to result in a spectrum of visuomotor deficits, including deficits of reaching in space and of grasping small objects (Ferrier, 1890; Ettlinger, 1977; Faugier-Grimaud et al., 1978; Glickstein et al., 1998).

We have made a number of observations in recent years with two human subjects who have sustained fairly symmetrical bilateral parietal lesions. Both patients show 'optic ataxia' when using either hand to respond to either side of their peripheral visual field. The primary defining disorder in optic ataxia is a failure to point or reach accurately toward objects presented visually. Generally the pointing difficulty does not extend to non-visual targets, nor is it necessarily associated with a visuospatial perception deficit (Perenin and Vighetto, 1988). Indeed in his original description of optic ataxia in 1909, Bálint reported that his patient's inaccuracy of manual con-

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trol was largely restricted to one hand. To enable successful reaching with the other hand, the relevant spatial information must have received adequate visual processing. Like the lesioned monkeys described by Ferrier and his 20th-century successors, patients with optic ataxia also have problems in orienting the wrist (Perenin and Vighetto, 1988), and scaling their grip appropriately during prehension (Jakobson et al., 1991; Jeannerod et al., 1994). These human parietal lesions appear to have disrupted visuomotor processing systems homologous to those identified in the dorsal stream of the monkey. Current lesion and functional neuroimaging evidence locates these systems superiorly in the human parietal lobe, in and around the intraparietal sulcus (Perenin and Vighetto, 1988; Binkofski et al., 1998; Culham and Kanwisher, 2001).

Not all investigators, however, have restricted themselves to examining *direct* prehension. In a pioneering set of experiments, Goodale and colleagues (1994) compared movements made by subjects in immediate and *delayed* grasping tasks. Their immediate task was straightforward: the subject had to reach out and pick up a rectangular block presented directly in front of him or her. To examine delayed grasping, Goodale et al. (1994) devised two tasks: 'delayed real grasping' and 'delayed pantomimed grasping'. In the former case, the subject examined the block for a short period, but had to refrain from responding until after a delay period, during which the block was kept out of sight. In pantomimed grasping, the block was no longer present after the delay (having been covertly removed), so that the subject had to reach out and *pretend* to grasp it. Grasping in the 'real' delayed task could thus be guided by external visual cues just like immediate grasping, since the object was visible at the time of responding. In contrast, pantomimed grasping could *only* be driven by information that was retained internally — presumably in working memory — since the object itself was no longer present.

A good indicator of efficient visual guidance during prehension is provided by the correlation between the maximum anticipatory finger–thumb opening during the reach and the actual width of the object (Jeannerod, 1981). Goodale et al. (1994) reported that when normal subjects performed the delayed pantomime task, their maximum grip size correlated highly with object width, even after delays as long as 30 s. However, systematic differences between the kinematics of the immediate and pantomimed actions led the authors to suggest that the latter were not driven by the normal visuomotor control systems that govern immediate actions. Adopting the theoretical framework presented by Goodale and Milner (1992) (Milner and Goodale, 1993, 1995), they proposed that immediate grasping was implemented via dedicated visuomotor transformations within the dorsal stream. The pantomime task, in contrast, would have to rely on visual information outlasting that transiently available within the dorsal stream, specifically in the form of a stored perceptual representation of the target object. For this, they proposed that the services of the ventral visual stream would have to be enlisted.

In support of their interpretation, Goodale et al. (1994) presented data from the visual-form agnosic patient D.F. This patient presented with a profoundly impaired ability to perceive shape, size and orientation (Milner et al., 1991). Her perceptual disorder appears from functional MRI evidence to be due to bilateral damage of ventral stream visual areas, and/or a disconnection of these areas from contour processing systems in primary visual cortex (Murphy et al., 1998). D.F. nonetheless shows excellent scaling of her grip with respect to object width during immediate grasping (Goodale et al., 1991). Her intact visuomotor skills have been putatively attributed to a relatively intact dorsal stream (Milner and Goodale, 1995). Yet despite her preserved immediate grasping, D.F. showed no grip scaling in the pantomime task, even after a delay of only 2 s (Goodale et al., 1994). She dutifully opened her hand on each trial in her efforts to pretend to grasp the previewed block, but her grip size did not correlate with the width of the block she had been shown.

This selective failure in the delayed pantomime condition was attributed to D.F.'s inability to store, even for a few seconds, suitable information about the object to guide her grasping movements. Goodale et al. (1994) argued that only the perceptual system, in the ventral visual stream, could provide the necessary visual information for her working memory to use. Since in D.F. this perceptual system was unable to encode the target object's dimensions, no such visual information would be available to her work-

ing memory. In other words, the indirect route from vision to action via perceptual representations would be closed to D.F., because her brain could not form those intermediary perceptual representations.

Goodale et al.'s (1994) interpretation is attractive, but it relies on a single dissociation. Patient D.F. performed normally on the immediate grasping task and very poorly on the delayed task, but such a pattern could arise because delayed grasping is intrinsically more difficult than immediate grasping. On the other hand, if Goodale et al.'s hypothesis is correct, it should be possible to observe the converse pattern of performance in patients with damage to the immediate visuomotor system in the dorsal stream. Specifically, an optic ataxic patient, provided that her ventral stream remained relatively intact, might perform paradoxically *better* when tested on delayed pantomimed grasping than on immediate grasping. The reasoning behind this prediction is that some optic ataxic patients at least should be able to circumvent their damaged visuomotor system by bringing a relatively intact perceptual system into play to guide their actions, just as Goodale et al. (1994) postulated for healthy subjects. This secondary system, because of its slower operating constraints, would be unable, or much less able, to guide immediate grasping.

This line of argument need not be restricted to grasping behavior. By the same token, we might also predict improved *spatial* accuracy in optic ataxia, if the patient could be induced to delay a few seconds after target offset before initiating a pointing movement. In other words, the reaching disorder that is the defining essence of optic ataxia might be ameliorated when the action is delayed. In the present chapter we review relevant data from two patients with bilateral optic ataxia (A.T. and I.G.). Our aim was to look for changes in visually guided behavior when a delay was interposed between stimulus and response. We first describe two experiments in the domain of object size, and then our studies relating to spatial location.

The patients

Patient A.T. was aged between 44 and 46 at the times of testing, twelve years after an eclamptic attack which provoked a hemorrhagic softening in the territory of both parieto-occipital arteries (branches of the posterior cerebral arteries). Structural MR images early after the episode 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 (see Fig. 1). Nevertheless, 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. continued to show the symptoms of Bálint's syndrome, including visual disorientation, simultanagnosia, and severe optic ataxia for targets in her peripheral visual field. On the other hand, she showed no clinical indications of occipito-temporal damage (e.g. alexia, object agnosia, achromatopsia, or prosopagnosia), and she was able to lead a surprisingly normal life despite her extensive lesions.

Patient I.G. had suffered bilateral parieto-occipital infarction 17 months before we began the present testing, during which she was aged 31 to 32. She initially presented with severe headache, dysarthria and bilateral blindness, which lasted for 3 days. Subsequently, bilateral optic ataxia and simultanagnosia became apparent (Pisella et al., 1999, 2000), but by the start of our testing her simultanagnosia had subsided, at least for presentations of two to three objects (Pisella et al., 2000). I.G. received a diagnosis of ischemic stroke, related to acute vasospastic angiopathy in the posterior cerebral arteries. MRI revealed a hyperintense signal on T2 sequences that was near-symmetrically located in the posterior parietal and upper and lateral occipital cortico-subcortical regions testing (see Fig. 2). Reconstruction of the lesion indicated that it involved mainly Brodmann's areas 7, 18, 19, the intraparietal sulcus, and part of area 39.

Studies of delayed grasping

We tested both patients on immediate grasping and pantomimed grasping, and in both cases found evidence for improved scaling of the grasp in the pantomime condition (Milner and Dijkerman, 2001). However, the results are clearer in I.G., and we will concentrate on those data here.

As in several previous studies (e.g. Goodale et al., 1991, 1994), we used rectangular blocks varying in

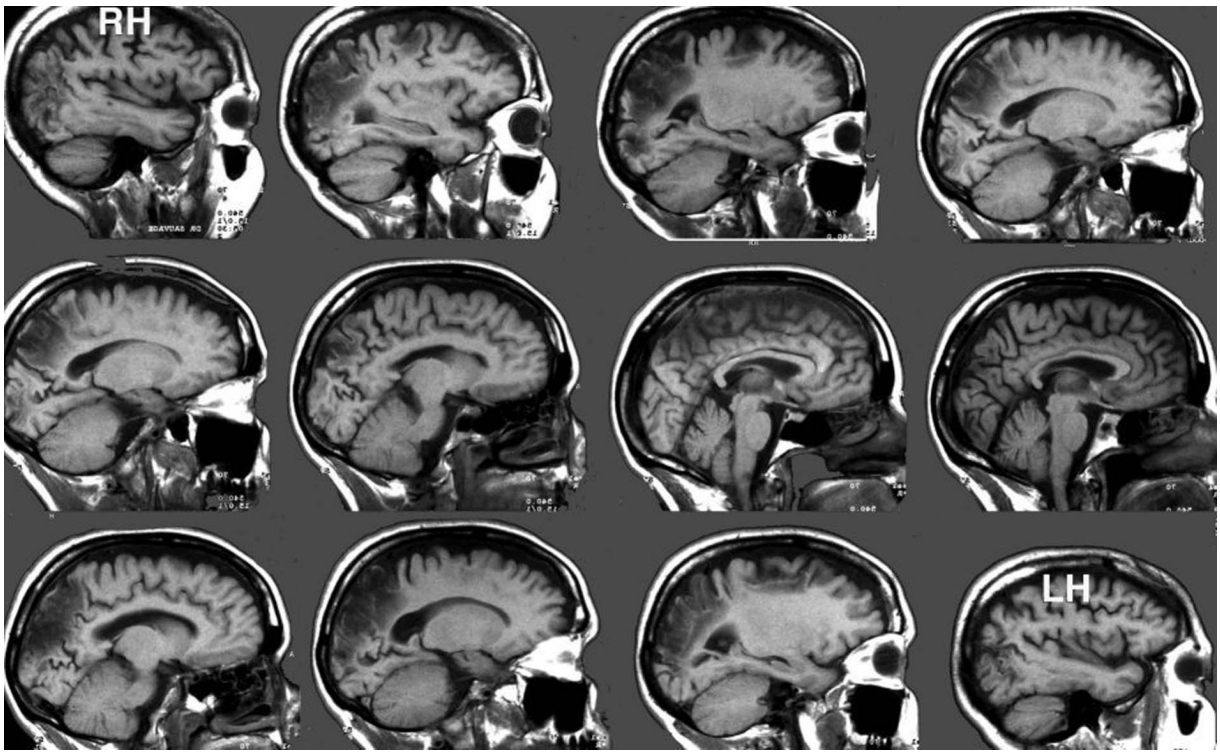

Fig. 1. Magnetic resonance images of A.T.'s brain. Twelve equi-spaced sagittal sections are shown, six from each side of the brain. There is symmetrical parietal lobe damage on the two sides of her brain, in the absence of damage to occipito-temporal lobe structures on either side.

width, but of constant surface area. Four different blocks were used, with the dimensions 5 cm × 5 cm, 4 cm × 6.25 cm, 3 cm × 8.3 cm, and 2 cm × 12.5 cm. They were made of dark gray plastic with a thickness of 1 cm, and were presented on a table against a white background. Due to the fact that I.G.'s optic ataxia chiefly affects non-foveal vision, we presented the objects eccentrically, using a central red fixation spot. The left edge of each object was positioned 6 cm (approximately 5°) to the right of this spot. Fixation was checked continually by an experimenter facing the patient. We recorded finger–thumb separation throughout all of the reaching and grasping movements, or for 1 s in the case of I.G.'s size judgments in the matching task (see below). The dependent variable of interest was the maximum grip aperture attained during reaching (MGA), or the mean finger–thumb aperture in the case of matching. Previous studies (Jeannerod, 1981; Jeannerod and Decety, 1990; Goodale et al., 1994) have shown that these measures are linearly related to object size in healthy subjects in all of our tasks. For more details of this study, see Milner et al. (2001).

Experiment 1

In the first session, I.G. performed three tasks in the following order: (a) perceptual matching; (b) delayed real grasping; (c) delayed pantomimed grasping. The perceptual task required her to make a manual size estimate using her forefinger and thumb without reaching toward the object. In pantomimed grasping, I.G. was required to delay grasping the object for 5 s — during which the object was removed — and then to pretend to grasp it (see Fig. 3). In the delayed 'real' grasping task, the procedure was similar, except that the object remained present after the delay period and was available for grasping afterwards. This task was chosen for comparison with pantomimed grasping because it more closely mirrors the time-course of that task than does a straightforward immediate grasping task.

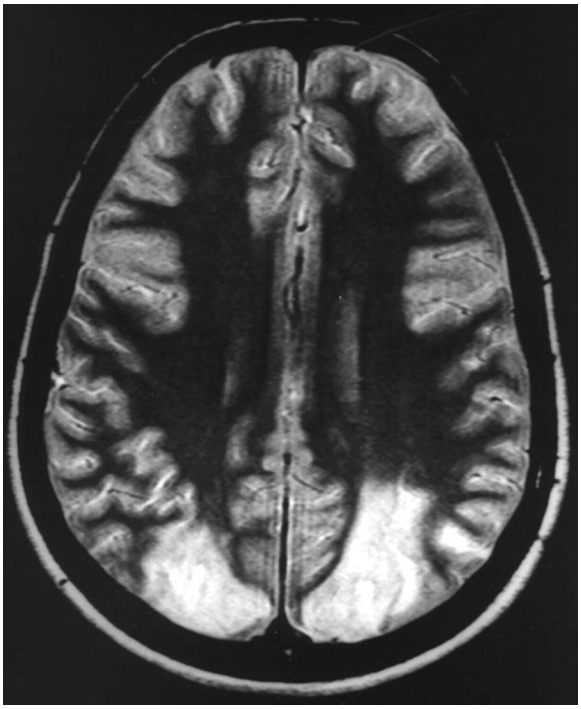

Fig. 2. A horizontal section through I.G.'s brain, visualized with structural MRI. Extensive damage is present bilaterally in the posterior parietal lobes.

The results are shown in Fig. 4. I.G. reliably varied her finger–thumb grip in proportion to the object size in the perceptual task (Fig. 4a), as has been reported before in optic ataxic patients (Jakobson et al., 1991; Jeannerod et al., 1994). As predicted, she also showed reliable grip scaling in the delayed pantomime task (Fig. 4c). Thus I.G. could tailor her grip to the size of an object both in an explicitly perceptual task (matching), and in one that relied on visual memory (pantomimed grasping). Yet much as expected, there was only weak evidence of grip scaling in the delayed *real*-grasping task (Fig. 4b).

These data demonstrate the predicted improvement of grip scaling when the stimulus was no longer present, as compared with when it was. Nevertheless, there was still a mild trend for grip scaling in the delayed real-grasping task, a trend that had not been predicted. We therefore tested I.G. in a second session in which we compared delayed real grasping with immediate real grasping.

In this second session, I.G. performed the following tasks, presented in an 'abccba' design: (a) immediate grasping, (b) delayed real grasping, and (c) delayed pantomimed grasping. We found no significant grip scaling during immediate grasping. In delayed real grasping, however, grip scaling was now evident, with I.G. opening her hand significantly less wide for the narrowest object than for the other three objects (Fig. 5b). Finally, clear grip scaling was again found in the delayed pantomimed-grasping task (Fig. 5c). There was also a general reduction in I.G.'s initially exaggerated grip apertures from the first to the second testing blocks.

Thus I.G. was unable to scale her grip size when an immediate grasp was required for a new object: yet when she could preview the object 5 s *before* grasping, she could adjust her grip quite well. Of course, in contrast to the immediate or pantomimed tasks, for which only one source of visual information could be used, both present *and* past visual information were potentially available in the delayed real grasping task. We had assumed that the prior information would be entirely superseded by the new sensory information available to guide action on-line, as has been shown in healthy subjects in a different context for proprioceptive targets (Rossetti and Pisella, 2002). I.G.'s relative success in pantomimed grasping, however, suggests that prior information might actually provide her with better visual guidance than current information. Therefore she might have used such stored information in the delayed real-grasping task, rather than relying on the currently visible object. We set out to test directly which of these two sources of visual information she used during delayed real grasping. To do this, we created a new series of delayed real-grasping trials in which occasional 'incongruent' test trials were embedded.

Experiment 2

In this experiment, only delayed real grasping was tested. However, although the usual four objects were used throughout, half of the trials with the widest and narrowest objects were made into incongruent test trials. On these occasions, the narrowest (2 cm) object was covertly replaced during the delay interval by the widest (5 cm), or the widest replaced

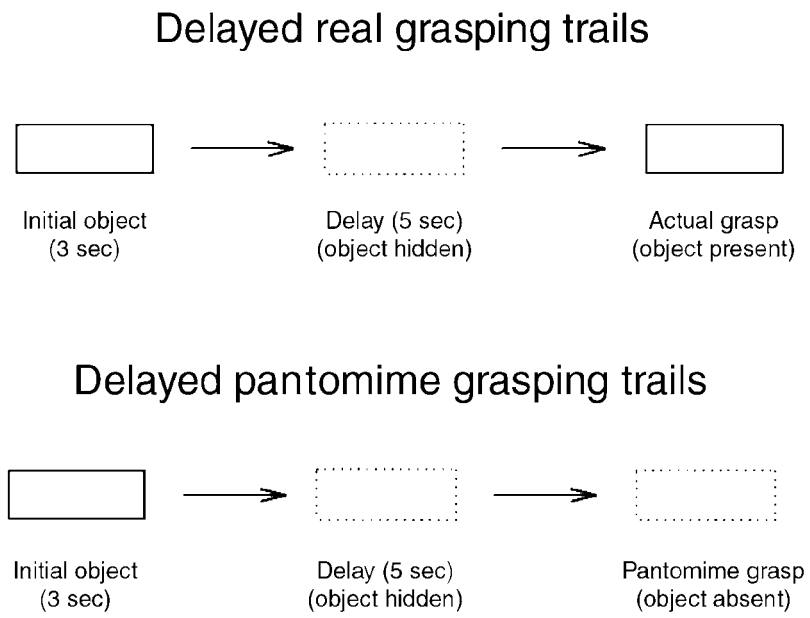

Fig. 3. The delayed grasping tasks used in the present study. In both delayed tasks (real and pantomimed), the object was first viewed for 3 s, and then shielded from view for 5 s. In delayed real grasping, the subject then had to reach out and grasp the object. In pantomimed grasping, however, the subject had to *pretend* to reach out and grasp the object after this delay, as it had been covertly removed during the delay period.

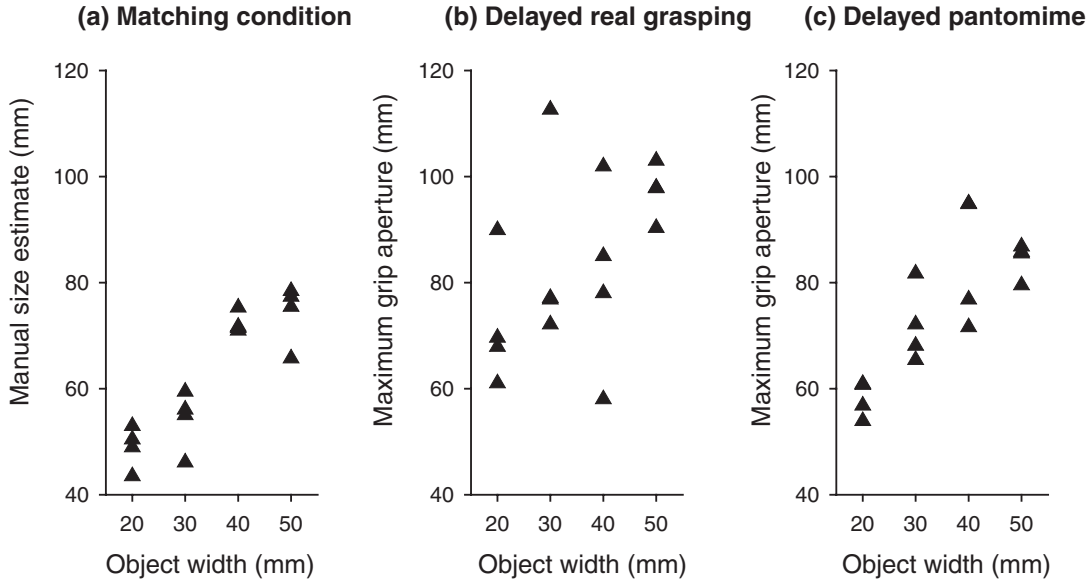

Fig. 4. Experiment 1: I.G.'s maximum grip aperture (MGA) during a perceptual matching task and two delayed prehension tasks.

by the narrowest (see Fig. 6). In addition to I.G., six age-matched right-handed healthy control subjects were also tested.

We confirmed that our control subjects scaled their grip in accordance with the size of the object facing them (Fig. 7). It made no difference whether they had

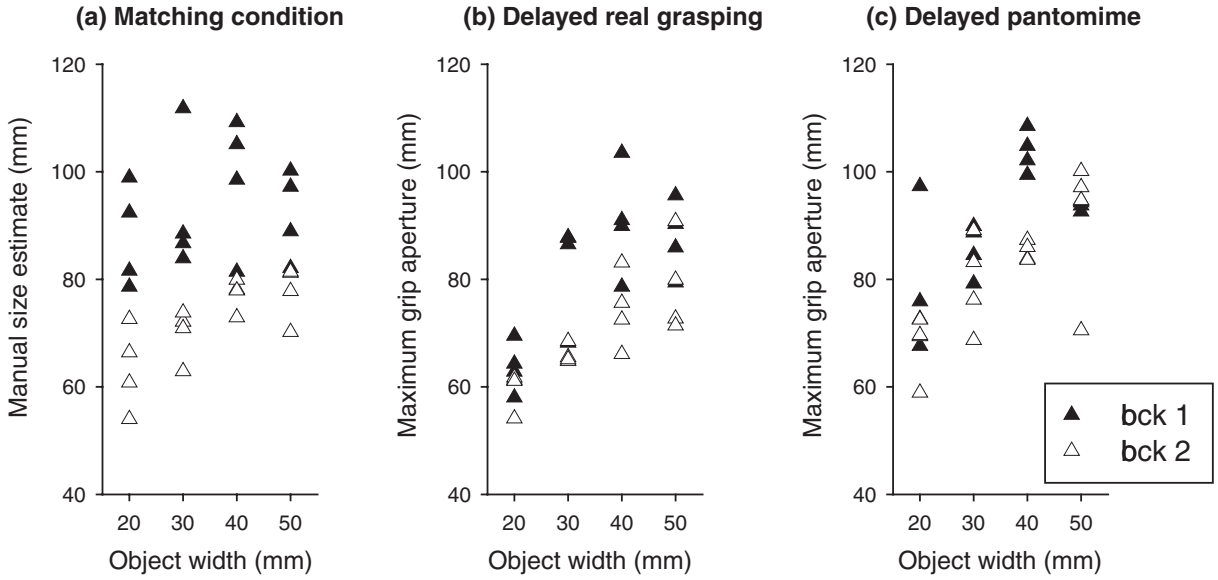

Fig. 5. Experiment 1: I.G.'s maximum grip aperture during three different prehension tasks. (a) In the immediate grasping task, the subject simply had to reach out to pick up the target object, front to back, using forefinger and thumb, as soon as it became visible. (b) During delayed real grasping, however, clearly significant grip scaling was observed. (c) As expected, highly significant grip scaling was also found in the delayed pantomimed grasping task.

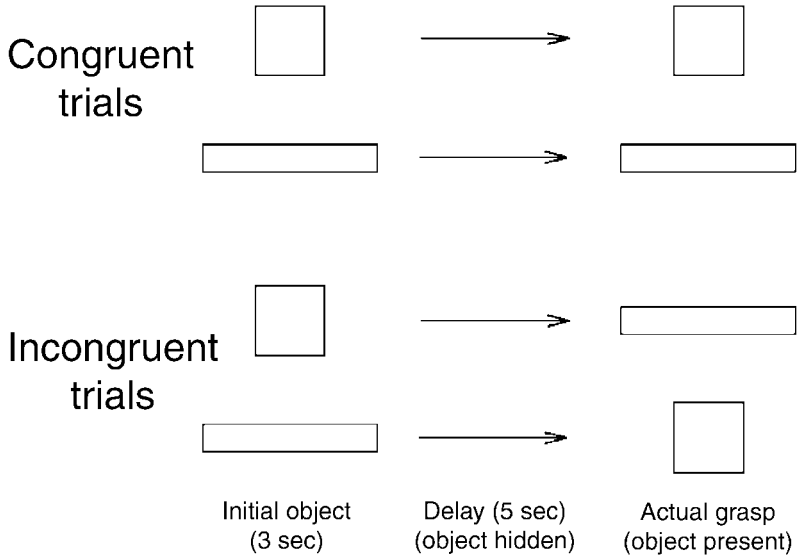

Fig. 6. Schematic of Experiment 2. In a quarter of all trials, the widest object (50 mm) was covertly replaced by the narrowest (20 mm), or vice versa, during the delay period (incongruent trials, bottom). In another quarter of the trials the narrowest and widest objects remained unchanged (congruent trials, top). In the remaining half of the trials, objects of intermediate widths were used (30 and 40 mm, not depicted here), and remained unchanged throughout each trial (congruent filler trials).

been shown the same or a different block 5 s earlier. In contrast, I.G. opened her hand widely whenever the wide object had been previewed, even when reaching out to grasp the narrow one (Fig. 7, right). Evidently I.G. used a memory-based route to by-pass her visuomotor deficit, while the controls never did this.

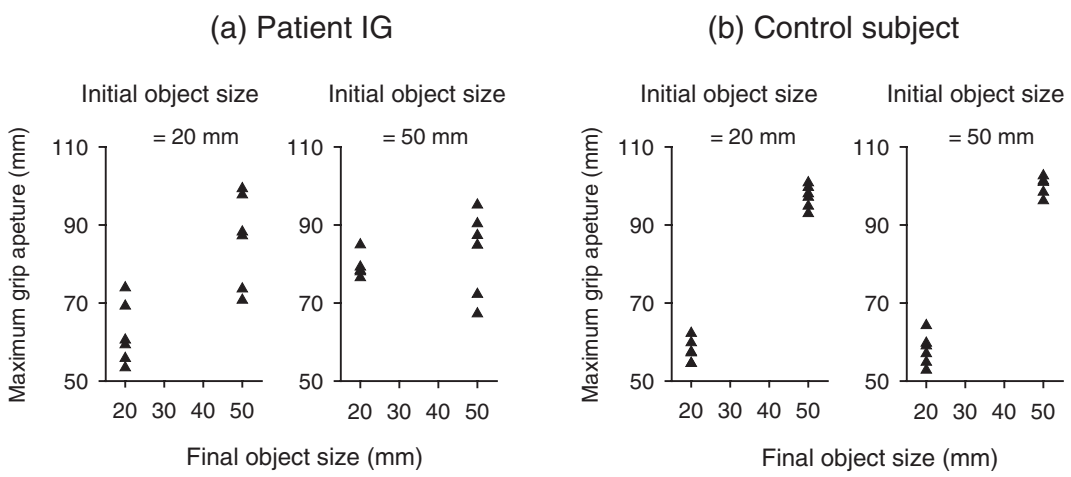

Fig. 7. Experiment 2: maximum grip aperture a function of final object size for patient I.G. and one representative control subject. When the initial object was 5 cm wide and covertly replaced by the 2 cm wide object, I.G. programmed her grip size on the basis of the initial large object width. All of the six control subjects always used the final object size for programming their MGA, irrespective of whether it had changed during the trial.

On the incongruent trials where the narrow object was replaced by the wide one, however, I.G.'s grip did reach an appropriately wide aperture (Fig. 7, left). Presumably, the initially programmed small grip aperture had to be corrected during the course of the reach in order for her to eventually grasp the wide object, and this would be reflected in the measured maximum grip aperture. In support of this interpretation, we found that the velocity profile of handgrip opening differed reliably on these narrow-to-wide incongruent trials from that seen on congruent 'wide' trials. During the incongruent reaches, the rate of grip opening was significantly slower, and it reached its peak significantly later in the movement, presumably reflecting late perceptually based adjustments made to the initially programmed small aperture. These findings counter the objection that I.G. might simply have reacted to the uncertainty introduced by the incongruent trials by adopting a conservative strategy of opening her hand wide on all trials. In any case, this argument could not account for her appropriately small grip apertures on congruent trials with the small object.

Two visual routes to grasping

We established in Experiment 1 that I.G.'s visuomotor difficulties included the misgrasping of objects of different widths presented in peripheral vision. At the same time we showed that, like patient A.T. (Jeannerod et al., 1994), I.G. *perceived* the object widths quite accurately, and could signal these percepts manually. Most crucially, we confirmed our prediction that she should show an improvement in her grasping movements when performing a pantomime task. Taken together with the data from D.F. (Goodale et al., 1994), these findings complete a double dissociation. They are consistent with the idea that posterior parietal visuomotor systems are part of the neural circuitry for mediating normal immediate grasping, while not being essential for *delayed* responses of an ostensibly similar kind (Rossetti, 1998; Rossetti and Pisella, 2002).

Independent support for the idea that a delay interposed in a grasping task causes a change from direct visuomotor control to a perception-based control of grip formation, has been provided in a recent study by Hu and Goodale (2000). These authors used a virtual-reality technique in which an irrelevant larger or smaller object was present in the visual array along with the target object. As expected, there was a substantial size-contrast illusion in a perceptual report task: a given target was judged to be smaller when paired with a larger object, than when paired with a smaller one. Yet immediate grasping was immune

to this illusion. Most importantly, after a delay of 5 s, grip size when reaching for the target object now did become subject to the illusion. In other words, in this test situation healthy subjects showed a qualitative difference in the nature of their visual grip scaling during delayed as compared with immediate responding.

In our study, we successfully predicted good *pantomimed* grasping by I.G.; but we did not expect that her *real* grasping behavior would improve when she had seen the object a few seconds earlier. We had assumed that I.G. would use the information present in her visual field whenever she attempted to grasp a real object. Instead, she improved when a preview was given. Experiment 2, however, showed that her manner of achieving good delayed real grasping was quite different from that of normal observers. Interspersing incongruent trials within a delayed real-grasping test session confirmed that healthy control subjects completely disregarded the previewed information. In sharp contrast, I.G. pre-programmed her grasp on the basis of this prior information, without regard to the current visual scene. Consequently when a wide object was covertly replaced by a narrow one, she opened her hand too widely for the object in front of her.

The present data are consistent with Goodale et al.'s (1994) proposal that vision can guide grasping actions through the perceptual processing networks in the ventral stream as well as through the visuomotor systems of the parietal lobe. These networks evidently allowed I.G.'s grasping difficulties to be circumvented, albeit by taking a slower and more circuitous route from vision to action. While less unequivocal, the data we obtained from testing the older and more severely brain-damaged patient A.T. in a similar fashion supports the same conclusion (Milner and Dijkerman, 2001).

Studies of delayed pointing in optic ataxia

A parallel set of predictions can be made for delayed pointing. A number of studies have indicated that healthy subjects use a different form of spatial coding when they use remembered information about target location to guide the action. It has been proposed that for immediate motor guidance the brain uses a spatial code that is tied to an egocentric frame of reference, but for delayed actions a quite different, context-based form of spatial coding is employed. In this latter type of coding, the location of a stimulus is computed with respect to other visual stimuli in the environment, which the brain assumes to be stable (Paillard, 1987; Milner and Goodale, 1995; Bridgeman et al., 1997; Rossetti, 1998). Since this system is sensitive to visual context, it can be deceived easily: for example, a stationary stimulus enclosed by a frame that is rapidly displaced appears to shift in the converse direction. Quick reaching movements to the target location do not fall prey to this or related illusions (Bridgeman et al., 1981, 1997, 2000). However, studies of both normal and brain-damaged subjects suggest that our movements become dominated by such context-relative spatial coding when a delay of 2 s or more is interposed between stimulus and response (Rossetti, 1998; Bridgeman et al., 2000). This time-based switchover between spatial coding systems bears an unmistakable family resemblance to that inferred for shape processing by Goodale et al. (1994) and Hu and Goodale (2000).

Relevant evidence is again available from patient D.F. When we assessed her on immediate and delayed pointing, we found that her performance was as accurate as for normal subjects when responding immediately to the target. 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 those of the controls (Milner et al., 1999b). This result is consistent with D.F.'s poor performance on certain non-delay tasks that demand the visual perception of spatial relationships (Dijkerman et al., 1998; Murphy et al., 1998). The suggestion therefore is not that D.F. has a specific impairment of visuospatial memory, but rather that her perceptual disorder deprives her working memory of crucial visual information. Again, this hypothesis predicts that a complementary dissociation should be possible in optic ataxia, such that the pointing responses of optic ataxic patients might *improve* under conditions of delayed responding. Our reasoning was that they might be able to base their delayed reaching on the context-based spatial system, assuming that this 'perceptual' route was relatively unscathed by their parietal-lobe damage. We tested both A.T. and I.G. to assess this prediction.

Experiment 3: immediate and delayed pointing

Our initial study of pointing was carried out with patient A.T. We presented a red target LED at one of 7 different locations, while she fixated a green LED placed 2.5 cm in front of the central target location. The LEDs were embedded in black Plexiglas, and were visible only when illuminated. They were arranged in an arc of 55 cm radius around the center of A.T.'s body at eccentricities of $-30°$, $-20°$, $-10°$, 0, $+10°$, $+20°$ and $+30°$ with respect to her body center.

In the immediate pointing condition, a viewing period of 2 s was followed by a tone cueing A.T. to point to the target, while maintaining central fixation. The target remained visible throughout the reach. In the delayed condition, we presented the LED for 2 s only, and asked A.T. to wait until she heard a tone 5 s later before pointing to the target location, again maintaining fixation. Since the target was no longer present, this delayed task was effectively one of 'pantomimed pointing'. For more details, see Milner et al. (1999a).

In immediate pointing, A.T. responded very inaccurately, except for targets close to the center of her visual field (cf. Jeannerod et al., 1994). However, when A.T. was required to delay before pointing, her errors reduced dramatically, particularly at the most peripheral locations (see Milner et al., 1999a). In sharp contrast, all three healthy controls were *less* accurate in the delayed than in the immediate condition. A.T.'s pointing responses were predominantly medial to and short of the targets. Interestingly, her improvement in the delayed condition was specific to the directional component of her responses (errors of movement amplitude were not significantly altered).

These directional effects are clearly evident in Fig. 8, which shows spatially averaged trajectories (with lateral displacement normalized against depth displacement) for A.T. and a control subject, C.M. It is important to note that each average trajectory in Fig. 8 is plotted only for depth displacements common to all responses in that condition, so that each plot goes no further than its shortest component trajectory. Thus the endpoint of each average trajectory does not represent the mean endpoint of the responses comprising it. Fig. 8 illustrates that A.T.'s reaches have an abnormally strong directional bias toward the midline right from the outset. In other words, a severe disorder in calibrating the initial heading direction of her reaches constitutes a major component of A.T.'s misreaching behavior. A.T.'s reduced directional bias in the delayed condition is also present from the outset of the reach.

In a subsequent study, we compared immediate and delayed pointing in patient I.G., but here we used only four peripheral target locations, all within the right visual field. Throughout each trial, fixation was maintained on a 5-mm diameter red spot, 20 cm to the left of the hand start position and at a depth of 28 cm with respect to the start position. Peripheral targets were located at the same depth as the fixation spot and 6, 12, 18 or 24 cm to the right of fixation.

I.G.'s immediate pointing responses were directed accurately when made to the fixation point, but became progressively less accurate with increasing eccentricity. Her responses to targets close to fixation tended to be less accurate following a delay, but for the most peripheral locations, where her optic ataxia was most severe, I.G. pointed significantly *more* accurately following a delay. When I.G.'s absolute errors were analyzed in terms of directional and amplitude components, the beneficial effects of delay were found to be specific to the directional component, exactly as noted earlier in patient A.T. These directional effects are evident in Fig. 9, which shows spatially averaged trajectories for I.G., created in the same way as for A.T. (see above).

Just as previously observed for A.T., I.G.'s pointing responses are misdirected from their outset and veer markedly toward fixation for targets at the most peripheral locations. Similarly, the differences between I.G.'s immediate and delayed reaches are most pronounced at peripheral locations and are present throughout the entire trajectories. These results indicate that I.G.'s optic ataxic errors cannot be due solely to her known inability to apply rapid on-line corrections to an ongoing movement (Pisella et al., 2000; Gréa et al., 2002). As with A.T., her errors seem to result in large part from a faulty calibration of the initial reach parameters. This miscalibration remains, but becomes smaller, under conditions of delayed responding.

These delayed pointing data show very similar patterns in our two optic ataxic patients. Both patients responded with greater directional accuracy

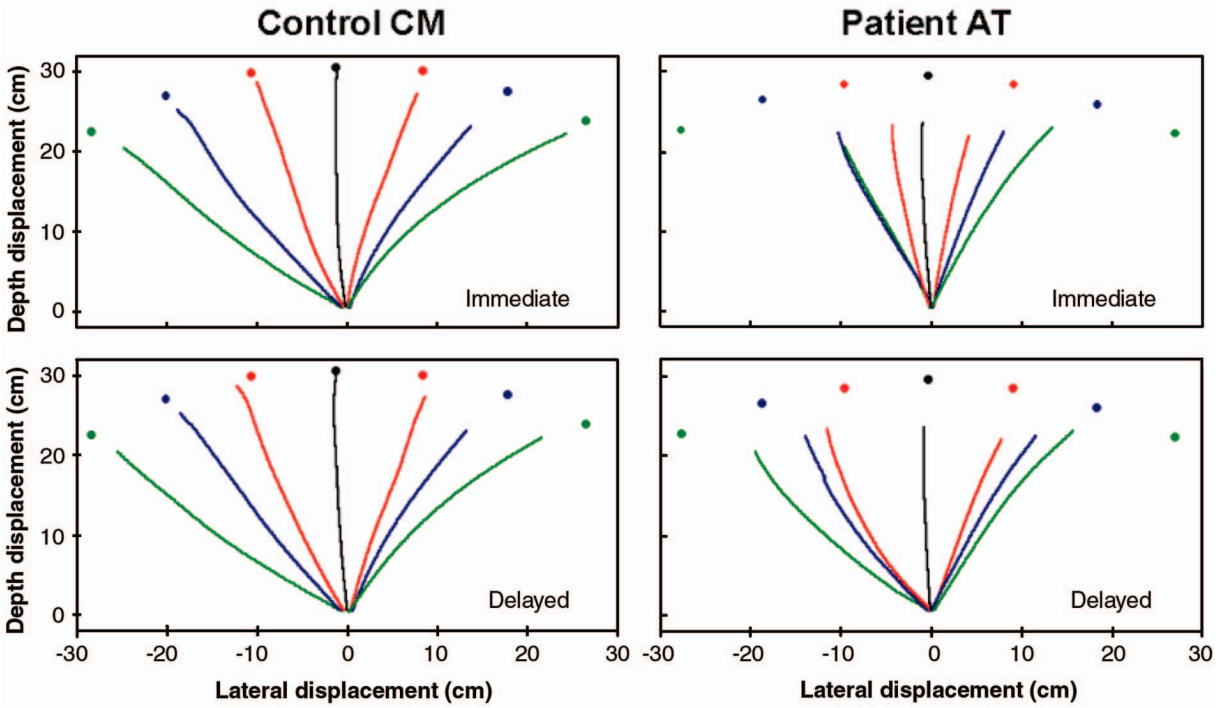

Fig. 8. Immediate and delayed pointing trajectories in patient A.T. and the control subject C.M., averaged only over the depth points common to all reaches. A.T.'s medial errors are present throughout her reach, and the improvements conferred by the delay condition are also evident throughout the trajectories.

when making delayed rather than immediate pointing responses to locations in the peripheral visual field. This improvement under conditions of delayed responding is particularly striking given that healthy controls show the opposite pattern (Milner et al., 1999a).

Experiment 4

The observed pattern of superior performance for delayed over immediate pointing prompted us once more to test whether our patients might use memorized information (in this case about target location) in preference to that available on-line. To do this, we used a delayed *real* pointing task, in which both immediate and previewed location information were available and were occasionally brought into conflict. We used the same layout as for patient I.G. in Experiment 3 (see Fig. 9), though only the four rightmost target locations were used, with fixation maintained at the leftmost location throughout all trials. As before, a warning tone sounded on each trial, and a target was exposed (at location 1) for 2 s. The display was then occluded for a 5-s delay, whereupon the target was re-exposed (at location 2). The subject was required to point immediately to the target at this second location. 75% of the trials were congruent, with the target retaining its location during the delay period, i.e. locations 1 and 2 were the same. The remaining trials were incongruent, with the target location being changed covertly during the delay period. Incongruent trials involved the near and far target positions only. On half of the incongruent trials the target was presented initially at the near position and re-appeared at the far position following the delay (near → far), and on the others the reverse sequence was used (far → near). While all reaches were recorded, only those trials (congruent and incongruent) involving the near and/or the far target positions were analyzed. We tested both A.T. and I.G. on this task.

Fig. 10 shows spatially averaged trajectories for three control subjects and for the two patients, with lateral displacement normalized against depth dis-

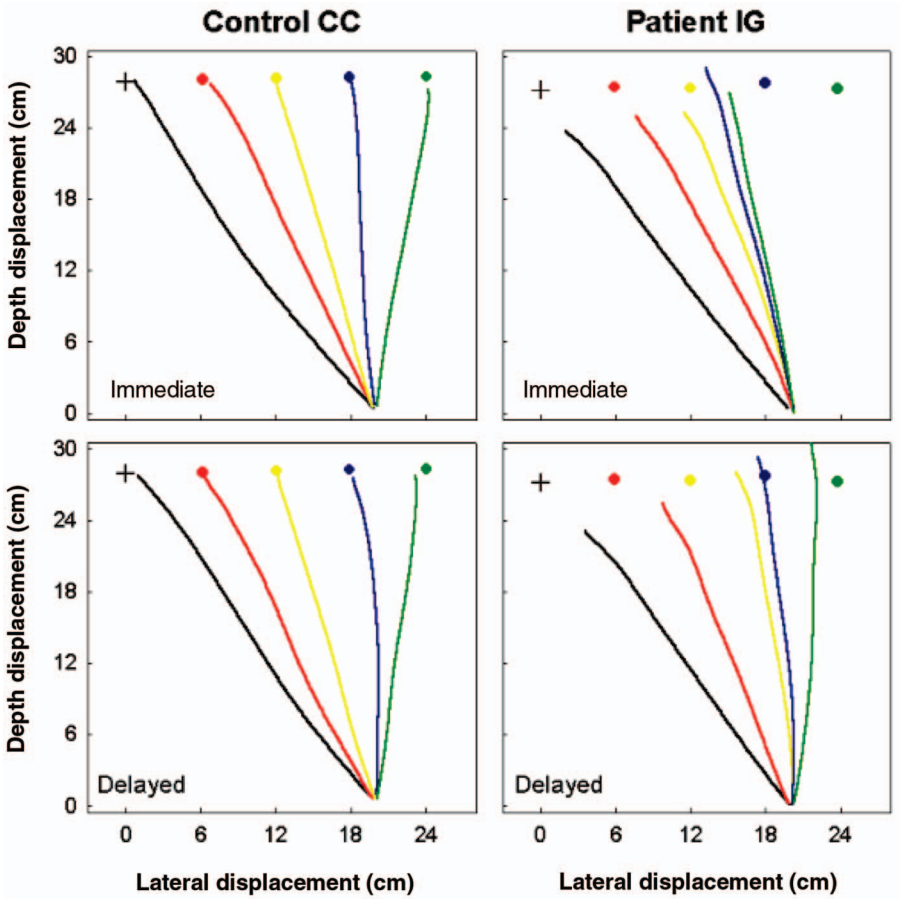

Fig. 9. Immediate and delayed pointing trajectories in patient I.G. and the control subject C.C., averaged only over the depth points common to all reaches. I.G.'s medial (i.e. leftward) errors are clearly present throughout her reach, as are the changes induced by the delay condition.

placement. Control subjects were uninfluenced by the location of the target seen prior to the delay (location 1), and responded exclusively to the target shown at the time of response (location 2). However, this was not the case for the optic ataxic patients, both of whom were influenced strongly by location 1. Fig. 10 shows that the influence of location 1 was dominant in the early part of the reach and that location 2 gained progressively in influence as the reach unfolded. Additionally, there is a strong suggestion of an interaction between the effects of the two targets, such that target 2 had more influence in the far → near condition than in the near → far condition. To assess the development of these patterns over the spatial course of the reaches, multiple ANOVAs were performed for each subject. The heading angle of the right index finger with respect to its starting position was used as the dependent variable, and separate ANOVAs by target 1 (near vs. far) and target 2 (near vs. far) were performed at several different depth displacements. These were focused particularly on the early part of the reach (i.e. depth displacements of 5 cm and less).

The analyses showed that during the initial portion of the reach (the first 1–2 cm), both patients' responses were determined predominantly by the target location prior to the delay and presumably memorized (location 1). Only as the trajectory unfolded did the influence of the physically present target (location 2) develop in strength. Moreover, the influence of the physically present target was stronger when it lay close to fixation than when it lay far

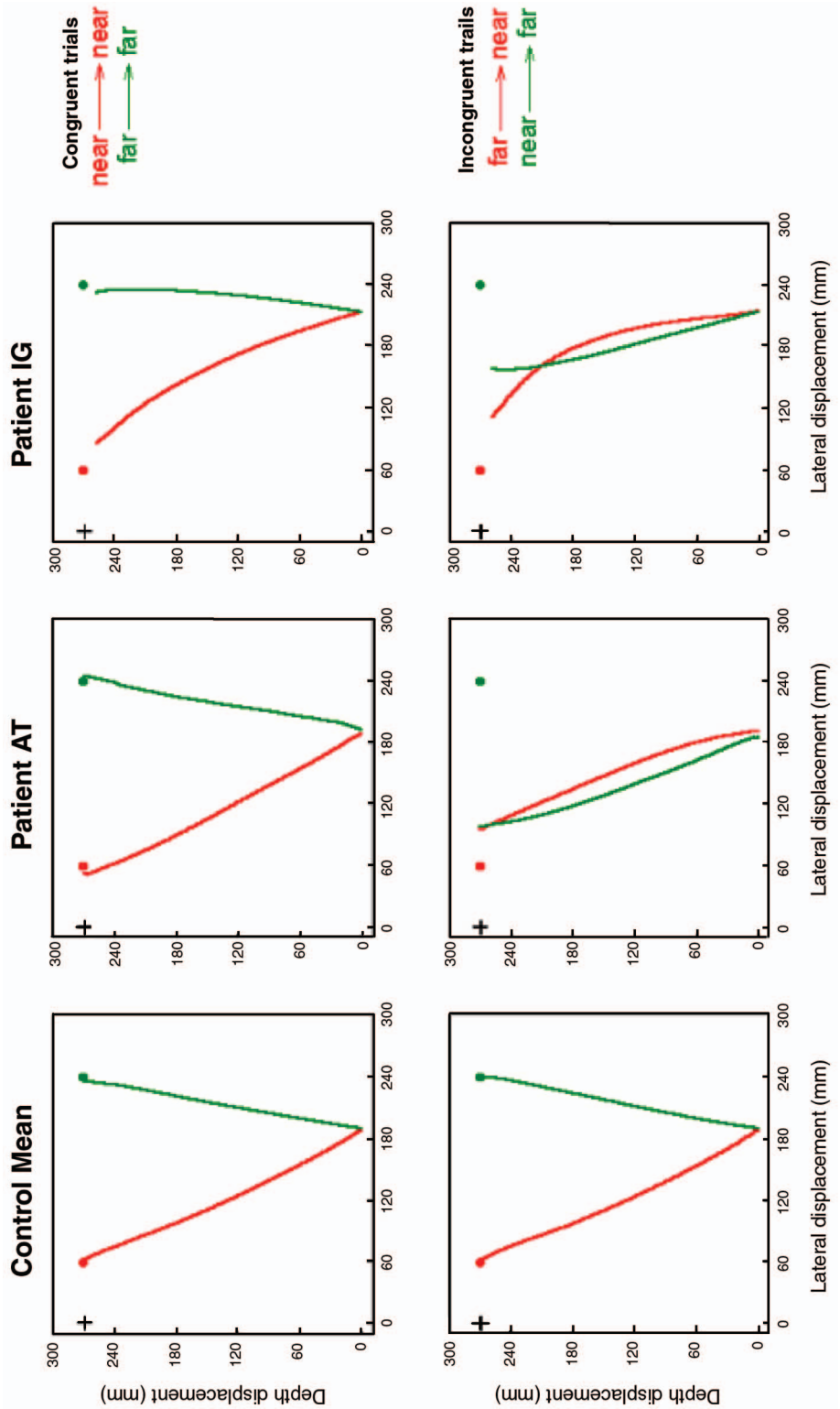

Fig. 10. Reaching trajectories in Experiment 4. Congruent pointing trials are shown at the top, in which the target has been previewed 5 s earlier at the same location (near or far) as it is presented for pointing. In the incongruent trials (bottom), the target has been previewed at the opposite location. On the left are the mean trajectories of three healthy controls. Reaches with the near target present at the time of response are shown in red, and those to the far target in green. Whether reaching for the most peripheral or the least peripheral target, the controls are unaffected by where they have previously seen the target located. The two patients, in contrast, set out in quite the wrong directions on the perturbed trials, and had to correct their trajectories en route. These corrections are more prominent when the patients are reaching toward the more central location.

from fixation. This latter interaction was highly significant for patient A.T., although it only approached significance for patient I.G. ($p < 0.1$ from a depth displacement of 4 cm onward). It seems that our optic ataxic patients were both better able to make use of on-line sensory information to guide their actions if this information was from a visual location closer to fixation. Thus, the severity of the immediate pointing deficit was greatest at the most peripheral locations, the benefits of delayed responding were most apparent at those locations, and the influence of current visual location information was weakest there.

Two visual routes to pointing

The main results of these pointing experiments are clear. Both of our optic ataxic patients responded more accurately when making delayed rather than immediate pointing responses to peripheral targets. This general pattern of improvement under conditions of delayed responding is opposite to that seen in patient D.F. (Milner et al., 1999b), and to the prevailing pattern in controls (Milner et al., 1999a). These results are 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. If that were so, then no improvement should be possible with delay. In addition, the benefits of pointing on the basis of stored location information were clearly exploited by both A.T. and I.G. in a real delayed pointing task, i.e. *even though the target was still present to guide action after the delay*. The evidence for this is provided by Experiment 4, in which we covertly shifted the location of the target between preview and pointing. Both patients programmed their reaches initially on the basis of the previewed target location, and so had to modify their initial heading direction on-line, presumably using an intact but slow 'intentional' correction system (Pisella et al., 2000).

This dissociating pattern of visuospatial impairments in optic ataxia and visual-form agnosia supports the conclusions arrived at from a number of studies of normal individuals (Rossetti, 1998; Bridgeman et al., 2000). It seems that there are at least two separate systems for spatial representation in the brain, each specialized for broadly different purposes. One system is dedicated for the immediate guidance of action, and hence uses spatial information coded in egocentric coordinates. It is almost certainly embodied in the superior parts of the parietal lobe. The other system is designed for the longer-term coding of spatial relationships for perceptual and cognitive purposes, and seems to lie in a more inferior (probably temporo-parietal) location in the human brain, predominantly in the right hemisphere (Milner and Goodale, 1995). This system could operate on a contextual basis in the present delay task by computing the target location relative to the fixation point. The present evidence that this second system can function relatively well in patients with extensive bilateral parietal damage is consistent with its receiving information about spatial relationships through the ventral (occipito-temporal) visual stream. In support of this idea, relative coding of stimulus location within a visual array has recently been physiologically demonstrated in neurones in the monkey's temporal neocortex (Missal et al., 1999; Baker et al., 2000).

When reaching rapidly toward targets within the visual array, A.T. and I.G. cannot, like healthy subjects, use the dorsal-stream visuomotor system effectively, yet there is insufficient time to engage the ventral system fully. The result is that they make large errors. The ventral system's normal role in spatial orientation would only be to signal the general 'ball-park' location of a target in relation to other stimuli, in contrast to the high absolute accuracy of the dorsal system. This lesser accuracy is apparent in the delayed pointing of controls, in this as in previous studies (e.g. Elliott and Madalena, 1987; Berkinblit et al., 1995; Milner et al., 1999b). Due to their brain damage, A.T. and I.G. no longer have ready access to the dedicated visuomotor system, and so have lost the advantage that immediate responding would normally offer. As a result, they show a paradoxical improvement when a time delay allows their more general-purpose perceptual system to come into full operation.

The nature of the pointing bias in optic ataxia

Experiment 3 allowed us to determine the extent to which the misreaches that were made to targets out-

side the central part of the visual field by AT. and I.G. were due to failures to correct their movements, as opposed to failures to initially direct the movements accurately (see also Prablanc et al., 2003, this volume). Despite the different set-ups used, Figs. 9 and 10 show very similar patterns for the two patients. It is clear that the pattern of medially biased errors is present right from the very start of the reaches. This bias remains present during delayed pointing, though it becomes less severe in both patients. Our data thus indicate that as well as having a problem with making rapid on-line corrections (Pisella et al., 2000; Gréa et al., 2002), patients with optic ataxia also make large initial directional errors when reaching for targets in peripheral vision. Their failure to apply on-line corrections is likely to compound this deficit, and indeed the immediate pointing trajectories plotted in Figs. 8 and 9 give no hint of on-line corrections.

What is the nature of these directional errors in optic ataxia? Their most obvious characteristic is their medial bias, in both A.T. and I.G.: A.T. was fixating centrally and veered inwards on both sides, while I.G. was fixating to the left and so tended to err leftwards. This medial misreaching is not a new observation: it was noted some years ago both in monkeys with posterior parietal lesions (Bates and Ettlinger, 1960; Lamotte and Acuña, 1978) and in unilateral optic ataxic patients (Perenin and Vighetto, 1983). It is as if the arm movements are drawn inwards toward the line of sight from either side, somewhat reminiscent of the 'magnetic misreaching' behavior described by Carey et al. (1997). Their patient was so severely affected that she was unable to reach to targets located away from the fixated object at all, her hand always being drawn to the fixation point instead of to the target object. A similar patient has been described by Buxbaum and Coslett (1997). Both patients had superior damage to the parietal lobes bilaterally, but there was additional cortical damage elsewhere in both cases. These reports may give a clue to the nature of the residual visual guidance retained by more typical optic ataxic patients like A.T. and I.G.

Magnetic misreaching can perhaps be regarded as a 'primitive' form of reaching, in which the hand automatically follows the eye. Even healthy subjects, while reaching toward a fixated object, cannot reorient gaze to a new target during the movement: instead their saccades are delayed until after the end of the reach (Neggers and Bekkering, 2000, 2001). This tendency for fixation and reaching to be coupled to the same stimulus may be embodied in hard-wired subcortical circuitry. For example, there are visuomotor neurons in the superior colliculus and adjacent midbrain tegmentum that fire when a monkey reaches toward a fixated target (Werner et al., 1997a,b). It might well be that without any cortical modulation, this subcortical system would produce magnetic misreaching as a kind of default behavior. An important role of the superior parietal cortex may therefore be to exercise inhibitory control over this midbrain mechanism, allowing the normal person to make hand movements elsewhere than to the object currently fixated. In effect, this downstream modulation would free the brain to transform visual location information directly into limb coordinates when programming a reach, instead of having to rely on the saccadic system as an intermediary. Damage to the parietal visuomotor system would diminish this downstream inhibition, causing reaching to be more influenced by the subcortical system. Reaches would therefore tend to stray toward the center of gaze, accounting for the medial biases shown by A.T. and I.G.

However, despite these biases, both patients still make reaching movements that correlate highly with target location. There are two alternative ways of understanding this preserved visual guidance. First, it is possible that in both patients there is some spared function in the visuomotor systems of the posterior parietal cortex. On this hypothesis, their immediate reaching behavior would still receive partial visual guidance through the normal dorsal-stream route, but this would be supplemented by a significant contribution from the subcortical system. By this way of thinking, magnetic misreaching might result in cases where the parietal damage is more complete than that present in A.T. or I.G., so that reaching becomes entirely 'subcortical'. This account, however, would incorporate no role for the ventral stream in guiding action. Therefore it would have difficulty explaining why there is a qualitatively similar pattern of reaching errors in our patients when response is delayed, since in this case we have argued that the ventral stream is guiding reaching.

The second possibility is that the preserved visual guidance seen in our patients, even in immediate reaching, is provided entirely by the ventral processing stream (in association with the right inferior parietal cortex), without any reference to the damaged (superior parietal) dorsal system. This temporo-parietal spatial representation system, in tandem with frontal structures, may itself be able to partially suppress the subcortical reach system, though less completely than an intact dorsal stream. This possibility is supported by the known presence of heavy projections to the superior colliculus from frontal areas in the monkey. Again this account could explain the medial biases observed in A.T. and I.G. when pointing to peripheral targets. One could further argue that *optic ataxia with magnetic misreaching* would result if this temporo-parietal route was itself disrupted along with damage to the dorsal stream, leaving only the subcortical system in control.

Our initial predictions were based on the assumption that imposing a delay before making a reaching response would allow our optic ataxic patients to improve their accuracy by use of the ventral visual stream, thus circumventing the disrupted dorsal stream. This assumption is supported by the results we have reported. However, the delay turned out only to have the effect of reducing the medial bias, which still remained present throughout the trajectories. This was true in both of our patients. This persistence of the medial bias is more consistent with the second hypothesis set out above. Although the ventral stream would come fully to the fore during delayed reaching, it would be parsimonious to assume that it was also providing (partial) visual information to guide action in the immediate reaching task as well.

Our proposal then is that in both immediate and delayed reaching, the ventral stream provides the visual information to program reaching movements in optic ataxic patients. The difference is that the ventral route is better able to resist the influence of the subcortical reach system in the delayed case. In the immediate reaching task, the rather slow ventral route would not have time to become fully functional, and thus not be able to inhibit the subcortical system so effectively. Of course in the normal individual, the ventral stream would have little or no influence on the visuomotor control of immediate reaching, due to the pre-emptive action of the faster dorsal stream (see Rossetti, 1998; Rossetti and Pisella, 2002).

Our suggestion of a subcortical system supporting reaching to fixated objects would explain the central sparing in A.T. and I.G., because targets near to fixation would not need to rely so much on the dorsal stream. It would also explain why delayed responding benefited reaching most clearly at peripheral locations. Finally it would explain why in our last experiment, in which target location was perturbed on some trials, the influence of current target location information was weakest in the periphery.

A related idea that has been developed in a different context is the 'covert orienting' of visual attention (Posner, 1980), a crucial element of which is the disengagement of attention away from fixation. There is strong evidence that the posterior parietal cortex plays a crucial role in this process (Posner et al., 1984; Robinson et al., 1995; Colby and Goldberg, 1999; Corbetta et al., 2000). Indeed a severe difficulty in switching attention away from fixation was described by Bálint (1909) as part of the biparietal syndrome exhibited by his original patient. According to the 'premotor theory' of visual attention (Rizzolatti et al., 1994), covert orienting is embodied in the same visuomotor systems that guide overt orienting movements. These similar notions of disengagement would merit fuller comparative discussion in another context.

We have tentatively suggested that it is the ventral stream, rather than the damaged dorsal stream, which provides the residual visual guidance for immediate reaching in optic ataxia. One way to test this idea would be to see whether such reaching is influenced by context-based visual illusions such as the Roelofs effect (Bridgeman et al., 1997, 2000). Rapid reaching is resistant to this illusion in intact individuals, presumably because it is controlled by the dorsal stream; but if reaching in optic ataxia is controlled by the ventral stream instead, it should now become vulnerable to the illusion. The present account also makes a prediction about the behavior of magnetic misreaching patients, whose use of either cortical stream for guiding reaching is assumed to be disrupted. If that is so, then their misreaching should remain unchanged after a delay — that is, their pointing errors should fail to improve, since we

have argued that a delay serves only to maximize the ventral stream's role in guiding reaching.

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References

Andersen, R.A., Snyder, L.H., Batista, A.P., Buneo, C.A. and Cohen, Y.E. (1998) Posterior parietal areas specialized for eye movements (LIP) and reach (PRR) using a common coordinate frame. In: G.R. Bock and J. Goode (Eds.), *Sensory Guidance of Movement*. Wiley, Chichester, pp. 122–128.

Baker, C.I., Keysers, C., Jellema, T., Wicker, B. and Perrett, D.I. (2000) Coding of spatial position in the superior temporal sulcus of the macaque. *Curr. Psychol. Lett.*, 1: 71–87.

Bálint, R. (1909) Seelenlähmung des 'Schauens', optische Ataxie, räumliche Störung der Aufmerksamkeit. *Monatsschr. Psychiatrie Neurol.*, 25: 51–81.

Bates, J.A.V. and Ettlinger, G. (1960) Posterior parietal ablations in the monkey. *Arch. Neurol.*, 3: 177–192.

Berkinblit, M.B., Fookson, O.I., Smetanin, B., Adamovich, S.V. and Poizner, H. (1995) The interaction of visual and proprioceptive inputs in pointing to actual and remembered targets. *Exp. Brain Res.*, 107: 326–330.

Binkofski, F., Dohle, C., Posse, S., Stephan, K.M., Hefter, H., Seitz, R.J. and Freund, H.-J. (1998) Human anterior intraparietal area subserves prehension. A combined lesion and functional MRI activation study. *Neurology*, 50: 1253–1259.

Bridgeman, B., Kirch, M. and Sperling, A. (1981) Segregation of cognitive and motor aspects of visual function using induced motion. *Percept. Psychophys.*, 29: 336–342.

Bridgeman, B., Peery, S. and Anand, S. (1997) Interaction of cognitive and sensorimotor maps of visual space. *Percept. Psychophys.*, 59: 456–469.

Bridgeman, B., Gemmer, A., Forsman, T. and Huemer, V. (2000) Processing spatial information in the sensorimotor branch of the visual system. *Vis. Res.*, 40: 3539–3552.

Buxbaum, L.J. and Coslett, H.B. (1997) Subtypes of optic ataxia: reframing the disconnection account. *Neurocase*, 3: 159–166.

Carey, D.P., Coleman, R.J. and Della Sala, S. (1997) Magnetic misreaching. *Cortex*, 33: 639–652.

Colby, C.L. and Goldberg, M.E. (1999) Space and attention in parietal cortex. *Annu. Rev. Neurosci.*, 22: 319–349.

Corbetta, M., Kincade, J.M., Ollinger, J.M., McAvoy, M.P. and Shulman, G.L. (2000) Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nat. Neurosci.*, 3: 292–297.

Culham, J.C. and Kanwisher, N.G. (2001) Neuroimaging of cognitive functions in human parietal cortex. *Curr. Opin. Neurobiol.*, 11: 157–163.

Dijkerman, H.C., Milner, A.D. and Carey, D.P. (1998) Grasping spatial relationships: failure to demonstrate allocentric visual coding in a patient with visual form agnosia. *Conscious. Cogn.*, 7: 424–437.

Elliott, D. and Madalena, J. (1987) The influence of premovement visual information on manual aiming. *Q.J. Exp. Psychol.*, 39A: 541–559.

Ettlinger, G. (1977) Parietal cortex in visual orientation. In: F.C. Rose (Ed.), *Physiological Aspects of Clinical Neurology*. Blackwell, Oxford, pp. 93–100.

Faugier-Grimaud, S., Frenois, C. and Stein, D.G. (1978) Effects of posterior parietal lesions on visually guided behavior in monkeys. *Neuropsychologia*, 16: 151–168.

Ferrier, D. (1890) *Cerebral Localisation. The Croonian Lectures*. Smith, Elder, London.

Glickstein, M., Buchbinder, S. and May, J.L. (1998) Visual control of the arm, the wrist and the fingers: pathways through the brain. *Neuropsychologia*, 36: 981–1001.

Goodale, M.A. and Milner, A.D. (1992) Separate visual pathways for perception and action. *Trends Neurosci.*, 15: 20–25.

Goodale, M.A., Milner, A.D., Jakobson, L.S. and Carey, D.P. (1991) A neurological dissociation between perceiving objects and grasping them. *Nature*, 349: 154–156.

Goodale, M.A., Jakobson, L.S. and Keillor, J.M. (1994) Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, 32: 1159–1178.

Gréa, H., Pisella, L., Rossetti, Y., Desmurget, M., Tilikete, C., Grafton, S., Prablanc, C. and Vighetto, A. (2002) A lesion of the posterior parietal cortex disrupts on-line adjustments during aiming movements. *Neuropsychologia*, 39 (in press).

Hu, Y. and Goodale, M.A. (2000) Grasping after a delay shifts size-scaling from absolute to relative metrics. *J. Cogn. Neurosci.*, 12: 856–868.

Jakobson, L.S., Archibald, Y.M., Carey, D.P. and Goodale, M.A. (1991) A kinematic analysis of reaching and grasping movements in a patient recovering from optic ataxia. *Neuropsychologia*, 29: 803–809.

Jeannerod, M. (1981) Intersegmental coordination during reaching at natural visual objects. In: J. Long and A. Baddeley (Eds.), *Attention and Performance XI*. Erlbaum, Hillsdale, NJ, pp. 153–168.

Jeannerod, M. and Decety, J. (1990) The accuracy of visuomotor transformation: an investigation into the mechanisms of visual recognition of objects. In: M.A. Goodale (Ed.), *Vision and Action: The Control of Grasping*. Ablex, Norwood, pp. 33–48.

Jeannerod, M., Decety, J. and Michel, F. (1994) Impairment of grasping movements following bilateral posterior parietal lesion. *Neuropsychologia*, 32: 369–380.

Jeannerod, M., Arbib, M.A., Rizzolatti, G. and Sakata, H.

?#1

(1995) Grasping objects: the cortical mechanisms of visuomotor transformation. *Trends Neurosci.*, 18: 314–320.

Lamotte, R.H. and Acuña, C. (1978) Deficits in accuracy of reaching after removal of posterior parietal cortex in monkeys. *Brain Res.*, 139: 309–326.

Milner, A.D. and Dijkerman, H.C. (1998) Visual processing in the primate parietal lobe. In: A.D. Milner (Ed.), *Comparative Neuropsychology*. Oxford University Press, Oxford, pp. 70–94.

Milner, A.D. and Dijkerman, H.C. (2001) Direct and indirect visual routes to action. In: B. De Gelder, E. De Haan and C.A. Heywood (Eds.), *Out of Mind: Varieties of Unconscious Processes*. Oxford University Press, Oxford, pp. 241–264.

Milner, A.D. and Goodale, M.A. (1993) Visual pathways to perception and action. *Prog. Brain Res.*, 95: 317–337.

Milner, A.D. and Goodale, M.A. (1995) *The Visual Brain in Action*. Oxford University Press, Oxford.

Milner, A.D., Perrett, D.I., Johnston, R.S., Benson, P.J., Jordan, T.R., Heeley, D.W., Bettucci, D., Mortara, F., Mutani, R., Terazzi, E. and Davidson, D.L.W. (1991) Perception and action in 'visual form agnosia'. *Brain*, 114: 405–428.

Milner, A.D., Paulignan, Y., Dijkerman, H.C., Michel, F. and Jeannerod, M. (1999a) A paradoxical improvement of optic ataxia with delay: new evidence for two separate neural systems for visual localization. *Proc. R. Soc. Lond. B*, 266: 2225–2230.

Milner, A.D., Dijkerman, H.C. and Carey, D.P. (1999b) Visuospatial processing in a pure case of visual-form agnosia. In: N. Burgess, K.J. Jeffery and J. O'Keefe (Eds.), *The Hippocampal and Parietal Foundations of Spatial Cognition*. Oxford University Press, Oxford, pp. 443–466.

Milner, A.D., Dijkerman, H.C., Pisella, L., McIntosh, R.D., Tilikete, C., Vighetto, A. and Rossetti, Y. (2001) Grasping the past: delay can improve visuomotor performance. *Curr. Biol.*, 11: 1896–1901.

Missal, M., Vogels, R., Li, C.-Y. and Orban, G.A. (1999) Shape interactions in macaque inferior temporal neurons. *J. Neurophysiol.*, 82: 131–142.

Murphy, K.J., Carey, D.P. and Goodale, M.A. (1998) The perception of spatial relations in a patient with visual form agnosia. *Cogn. Neuropsychol.*, 15: 705–722.

Neggers, S.F.W. and Bekkering, H. (2000) Ocular gaze is anchored to the target of an ongoing pointing movement. *J. Neurophysiol.*, 83: 639–651.

Neggers, S.F.W. and Bekkering, H. (2001) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. *J. Neurophysiol.*, 86: 961–970.

Paillard, J. (1987) Cognitive versus sensorimotor encoding of spatial information. In: P. Ellen and C. Thinus-Blanc (Eds.), *Cognitive Processes and Spatial Orientation in Animal and Man, Volume II. Neurophysiology and Developmental Aspects*. Nijhoff, Dordrecht, pp. 43–77.

Perenin, M.-T. and Vighetto, A. (1983) Optic ataxia: a specific disorder in visuomotor coordination. In: A. Hein and M. Jeannerod (Eds.), *Spatially Oriented Behavior*. Springer-Verlag, New York, NY, pp. 305–326.

Perenin, M.-T. and 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.

Pisella, L., Tiliket, C., Rode, G., Boisson, D., Vighetto, A. and Rossetti, Y. (1999) Automatic corrections prevail in spite of an instructed stopping response. In: M. Grealy and J.A. Thomson (Eds.), *Studies in Perception and Action*. Erlbaum, Hillsdale, NJ, pp. 275–279.

Pisella, L., Gréa, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D. and Rossetti, Y. (2000) An 'automatic pilot' for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. *Nat. Neurosci.*, 3: 729–736.

Posner, M.I. (1980) Orienting of attention. *Q.J. Exp. Psychol.*, 32: 3–25.

Posner, M.I., Walker, J.A., Friedrich, F.J. and Rafal, R.D. (1984) Effects of parietal lobe injury on covert orienting of attention. *J. Neurosci.*, 4: 1863–1874.

Prablanc, C., Desmurget, M. and Gréa, H. (2003) Neural control of on-line guidance of hand reaching movements. In: C. Prablanc, D. Pélisson and Y. Rossetti (Eds.), *Neural Control of Space Coding and Action Production. Progress in Brain Research*, Vol. 142. Elsevier, Amsterdam, pp. 155–170 (this volume).

Rizzolatti, G., Riggio, L. and Sheliga, B.M. (1994) Space and selective attention. In: C. Umiltà and M. Moscovitch (Eds.), *Attention and Performance, XV. Conscious and Nonconscious Information Processing*. MIT Press, Cambridge, MA, pp. 231–265.

Robinson, D.L., Bowman, E.M. and Kertzman, C. (1995) Covert orienting of attention in macaques, II. Contributions of parietal cortex. *J. Neurophysiol.*, 74: 698–712.

Rossetti, Y. (1998) Implicit short-lived motor representations of space in brain damaged and healthy subjects. *Conscious. Cogn.*, 7: 520–558.

Rossetti, Y. and Pisella, L. (2002) Several 'vision for action' systems: a guide to dissociating and integrating dorsal and ventral functions. In: W. Prinz and B. Hommel (Eds.), *Attention and Performance, XIX. Common Mechanisms in Perception and Action*. Oxford University Press, Oxford, pp. 62–119.

Werner, W., Dannenberg, S. and Hoffmann, K.-P. (1997a) Arm-movement-related neurons in the primate superior colliculus and underlying reticular formation: comparison of neuronal activity with EMGs of muscles of the shoulder, arm and trunk during reaching. *Exp. Brain Res.*, 115: 191–205.

Werner, W., Hoffmann, K.-P. and Dannenberg, S. (1997b) Anatomical distribution of arm-movement-related neurons in the primate superior colliculus and underlying reticular formation in comparison with visual and saccadic cells. *Exp. Brain Res.*, 115: 206–216.

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?#1: To be updated? (page 241)