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RESEARCH ARTICLES

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Preserved prism adaptation in bilateral optic ataxia: strategic versus adaptive reaction to prisms

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Abstract To date the anatomical substrate(s) of prism adaptation remain(s) particularly debated, with two main candidates emerging from the literature: the posterior parietal cortex (PPC) and the cerebellum. The functional processes involved in the acquisition of the adaptive aftereffects also remain largely unknown. The main result shown here is that a patient with a bilateral optic ataxia can adapt to an optical deviation, which allows us to make a step forward on these two issues. First, it demonstrates that the corresponding part of the PPC is not a *necessary* substrate for prism adaptation. Second, since this patient exhibits deficit for fast visuo-motor guidance, it provides direct evidence for a dissociation between on-line visuo-motor control and visuo-motor plasticity. Since the intermanual transfer rate of adaptation is larger in this patient than in control subjects, the PPC may still have an influence on adaptation under normal conditions. We propose a model of the relative contribution of the PPC and the cerebellum during prism exposure, associating these two structures with the two interacting behavioural components of prism adaptation described by previous psychophysical experiments: the *strategic component* would be linked to the PPC and the *adaptive component* to the cerebellum. In this model, the strategic component enters in conflict with the development and the generalisation of the adaptive aftereffects. This idea is compatible with the fact that a lesion of the PPC increases the transfer rate and the generalisation of the adaptation, as is also observed in unilateral neglect.

Keywords Prism adaptation · Optic ataxia · Posterior parietal cortex · Cerebellum · Intermanual transfer · Visuo-motor control

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Introduction

Prism adaptation has been widely used since the end of the nineteenth century as a paradigm of visuo-motor short-term plasticity. But there have been recent developments in four main domains of investigation: the decalibration of visual and proprioceptive inputs (e.g. Rossetti et al. 1993); the distinction between strategic control vs. realignment components of adaptation (e.g. Redding and Wallace 1996; Clower and Boussaoud 2000); the generalisation capacity of the adaptive system (Welch et al. 1993; Bedford 1993; Imamizu and Shimojo 1995; Imamizu et al. 1995; Ghahramani et al. 1996; Ghahramani and Wolpert 1997); and neurological rehabilitation (Rossetti et al. 1998; Tilikete et al. 2001; Pisella et al. 2002; reviews: Rossetti and Rode 2002; Rode et al. 2003; Mattingley 2002). These recent results have raised an interest in the mechanisms and the structures involved in prism adaptation.

Wedge-prisms produce a lateral shift of the visual field so that any visual target appears at a displaced position. Adaptation to such an optical shift is acquired during a set of successive pointing movements. The initial movement approaches the virtual position of the target, but within approximately ten subsequent pointing movements, the pointing error rapidly decreases so that subjects can already point towards the actual target position (e.g. Weiner et al. 1983; Rossetti et al. 1993; Welch et al. 1993). However, this does not mean that *plasticity* has been developed at this stage: *flexibility of motor execution* allows subjects to point precisely towards the target by making corrective movements. In the case of an obvious prismatic shift, a strategic modification of the initial direction of the pointing movement (Rossetti et al. 1993) also allows subjects to reach precisely the actual target position. This contribution to *error reduction* has been initially ascribed to a strategic component of the adaptation process by Weiner et al. (1983) ("cognitive correction"), and then by Redding and Wallace (1996) ("strategic perceptual-motor control"). Further pointing movements are required to reinforce the adaptation and obtain robust

negative aftereffects after removal of the prisms, that are characteristic of the adaptive component ("true adaptation": Weiner et al. 1983; "adaptive spatial alignment": Redding and Wallace 1996). The global reaction to the visual displacement consists of strategic corrections (contributing to error reduction) and adaptive realignment (contributing to both error reduction and aftereffects) developing simultaneously and interacting between each other (Redding and Wallace 1993, 1996, 2002).

Strikingly, the literature still remains controversial about the neural structures involved in prism adaptation. On the one hand, neuropsychological evidence historically suggested that only cerebellar patients are impaired in prism adaptation (e.g. Weiner et al. 1983; review: Jeannerod and Rossetti 1993). A recent lesion study in monkeys (Baizer et al. 1999) confirmed that a focal lesion of the cerebellum (especially of the *vermis*) can abolish the ability to adapt to prisms. On the other hand, recent imaging data (Clower et al. 1996) have suggested that the human posterior parietal cortex (contralateral to the adapted arm) is the only area activated during prism exposure.[1] There is no obvious reason why one of these two structures should play an exclusive role in the reaction to wearing prismatic goggles. One may rather propose that each structure is specialised for a given aspect of prism adaptation, with their interconnections accounting for the functional interactions described between the two components of prism adaptation. In the following, therefore, we will describe (1) the possible role of the cerebellum, (2) the possible role of the PPC and (3) a simple model integrating the respective roles of these two structures in the two behavioural components of prism adaptation.

1. Let us first summarise the functional properties of the cerebellar system. Studies involving human brain lesion, imaging and neural modelling have stressed the importance of the cerebellum for short-term and long-term visuo-motor learning (e.g. Gilbert and Thach 1977; Ito 1989; Friston et al 1992; Martin et al. 1996; Imamizu et al. 2000), reflex adaptation (Kawato and Gomi 1992) and saccadic adaptation (Desmurget et al. 1998). In addition, the cerebellum is also known to be implicated in visually directed movement (deficit of visuo-motor guidance called Cerebellar ataxia: Stein 1986; Hallett et al. 1991) and eye-hand coordination (Miall et al. 2000). All these arguments suggest that the cerebellum is implicated in the processing and integration of visual errors and hence is candidate to be crucial in prism adaptation processes (Jeannerod and Rossetti 1993). As suggested by Weiner et al. (1983), the cerebellum may be the structure that realises the central recalibration of sensori-motor correspondences. Recalibration involves a global topological realignment likely to generalise to untrained regions and produces robust aftereffects, indicating a difficulty in returning to the original visuo-motor mapping even with cognitive awareness of the change (Bedford 1993). The cerebellum is known to be a major site for plasticity (Ito 1991, 2000; Armano et al. 2000). It is conceived as a "sensori-motor correlation storage area" that integrates the previous motor outputs (efferences) and the visual error resulting from this output (visual reafference).
2. The other relevant structure, the posterior parietal cortex (PPC) is implicated in sensorimotor and multisensory integration (Mountcastle et al. 1975; Andersen et al 1997; Xing and Andersen 2000) and thus is likely to be involved in the management of some visuo-motor reorganisation and the spatial re-alignment between visual and proprioceptive coordinates. In addition, single-neuron recording (McKay 1992), brain lesion (monkeys: Faugier-Grimaud et al. 1985; Rushworth et al. 1998; deficit of visuo-motor guidance called Optic Ataxia: Perenin and Vighetto 1988; Pisella et al. 2000) and imaging studies (Grafton et al. 1992; Kertzman et al. 1997) indicate that the PPC is critically involved in visually directed movements. The classical prism adaptation procedure precisely involves manual pointing toward visual targets with the hand and the targets visible through displacing prisms (hand exposure). These arguments, together with the result of Clower et al. (1996), suggest that the PPC may participate in prism adaptation processes. A study from Meier (1970) suggested that lesions of the right parieto-frontal network affect the ability to manage a visuo-motor task with reversal or inversion of visual feedback. Numerous imaging studies have confirmed the involvement of the PPC in such cognitive monitoring of new visuo-motor correspondences linked to mental rotation processes (Bonda et al. 1996; Inoue et al. 1997; Sugio et al. 1999). These strategic corrections of visuo-motor discrepancies are unlikely to generalise to untrained regions and tasks, and they rarely lead to substantial aftereffects as opposed to prism adaptation. For example, after learning a new visuo-motor mapping in which the direction of a cursor movement is rotated compared with the hand movement, subjects were able to revert to normal performance when they knowledgeably attempted to operate under the standard visuo-motor condition, with only minimal aftereffects (Cunningham and Welch 1994). In case of prism exposure, the change is made known by the removal of the goggles.
3. The functional and anatomical distinctions made above leads us to speculate that the adaptive realignment depends on the integrity of the cerebellum, whereas the cognitive strategies contributing to the compensation of the prismatic deviation rely on the PPC. Both structures would collaborate in compensating for the visuo-motor

[1] Clower et al. (1996) identified their activation site as area PEG, which is along the intraparietal sulcus in the angular gyrus (upper part of Brodmann area 39, see Fig. 1) according to the classification of Eidelberg and Galaburda (1984) and whose lesion leads to optic ataxia referring to the lesion superimposition work of Perenin and Vighetto (1988). However, re-plotting of the Talairach coordinates of the Clower et al. (1996) study led to rather locate the activation within Brodmann area 40 (supramarginal gyrus), which does not pertain to the focus of lesion leading to optic ataxia (Perenin and Vighetto 1988). We wish to thank an anonymous referee, Isabelle Faillenot and Christine Baleydier for raising and discussing this issue.

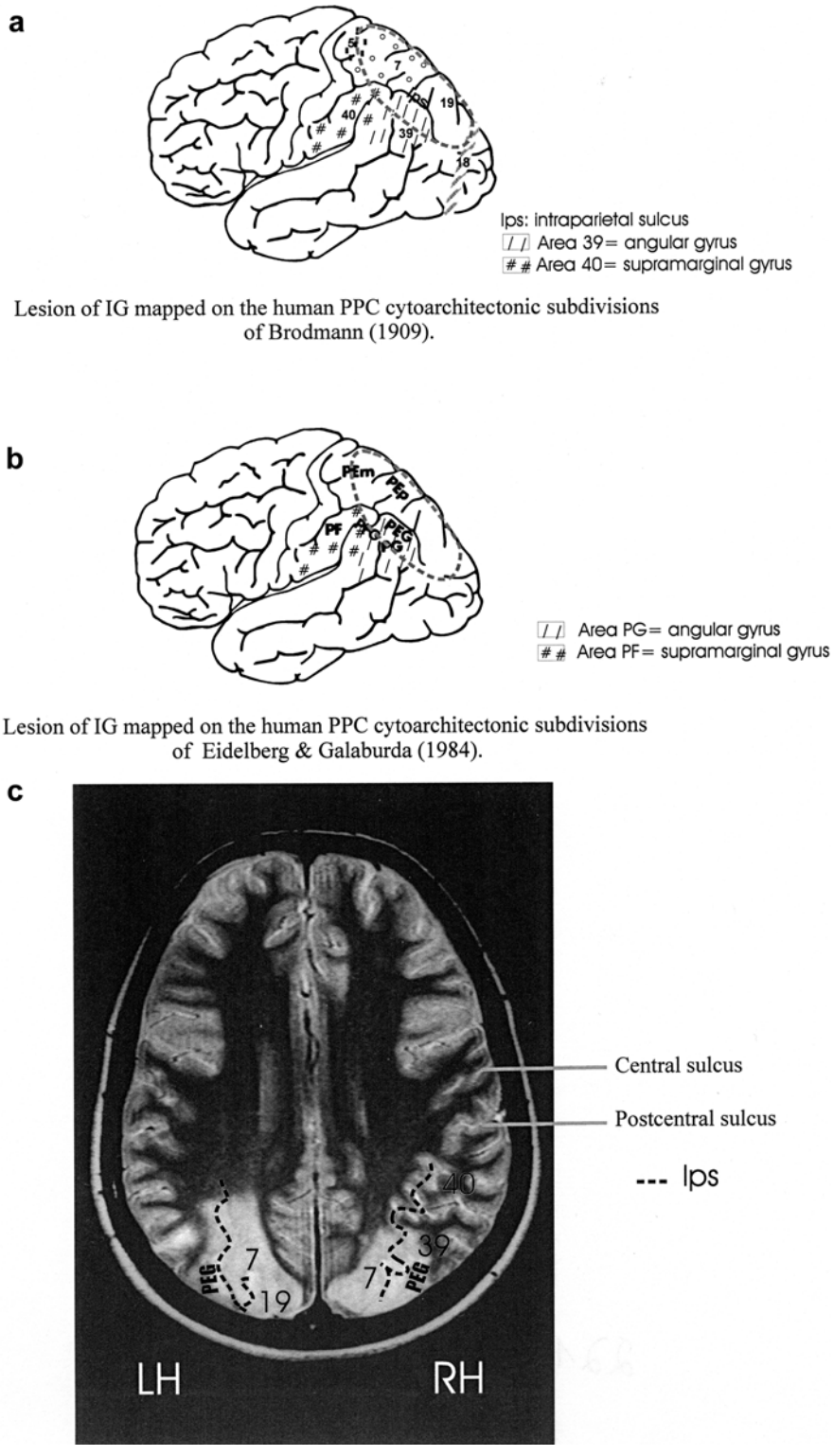

Fig. 1 **a** Schematised mapping of the lesion of patient I.G. with respect to subdivisions of the posterior parietal lobe in Brodmann areas (1909). **b** Schematised mapping of the lesion of patient I.G. with respect to subdivisions of the posterior parietal lobe in areas defined by Eidelberg and Galaburda (1984). **c** Horizontal section through I.G.'s brain, visualised with structural MRI. Focal damage is present bilaterally in the posterior parietal lobes, including part of extrastriate areas (areas 18 and 19), superior parietal lobule (area 7), intraparietal sulcus and upper part of the angular gyrus (area 39)

conflict introduced by the prisms. When one of the two structures is lesioned, then the other one would be more strongly activated and have to produce by itself the reaction to the visual distorsion in the form of either strategic compensation or adaptive realignment. Specifically, according to this hypothesis the PPC participates in adaptation without being necessarily involved in the production of aftereffects. There are two necessary conditions for this hypothesis to be valid. First, patients with cerebellar lesion should exhibit decreased or absent abilities to adapt to prisms. As mentioned above, several case reports or group studies already support this prediction (review: Jeannerod and Rossetti 1993). Second, patients with PPC lesion

should exhibit normal or even increased adaptation rates as assessed by the measurement of negative aftereffects. In addition, they may possibly show a relative lengthening of their error reduction phase.

It has been shown that prism adaptation can be used as a technique for rehabilitation of hemineglect patients, irrespective of the site of their lesion (Rossetti et al. 1998). Individual data from this initial study showed that each of the eight tested patients were able to adapt to right-deviating prisms, as revealed by the aftereffect observed on the manual straight-ahead demonstration. Five of these patients exhibited a lesion involving the parietal lobe (at least partially). For two of these patients (J.J.L. and M.C.), the lesion involved a large portion of the PPC. These results therefore suggested that patients with a lesion of the PPC can easily adapt to a prismatic deviation. Note, however, that first, neglect patients have unilateral lesions, so it can still be argued that the left (intact) parietal lobe is responsible for adaptation. Second, two main functional regions can be distinguished within the PPC based on neuropsychological data. The right *inferior parietal lobule* and the temporo-parietal junction are generally acknowledged as the common intersection site of the lesions producing unilateral neglect (Vallar and Perani 1986; Karnath et al. 2000). The *superior parietal lobule* symmetrically, and the region including and surrounding the *intraparietal sulcus,* represents the focus of the lesions producing the visuo-motor deficits known as 'optic ataxia' (Perenin and Vighetto 1988). Therefore, the present study tests whether a bilateral lesion of the PPC leading to bilateral optic ataxia affects prism adaptation. To this aim, patient I.G. was tested for adaptive aftereffects after performing a standard visuo-motor pointing procedure with prismatic goggles. Interestingly, this patient has been previously shown to be unable to perform automatic corrective movements (Pisella et al. 2000; Gréa et al. 2002). If on-line visuo-motor corrections during the pointing procedure are important to acquire visuo-motor adaptation to prisms, then this lack of on-line flexibility should prevent our patient from showing adaptive aftereffects.

Methods

This study was conducted with the informed consent of the patient, in agreement with the French law (4 March 2002) and the Helsinki declaration relative to patients' rights.

Case report

I.G. is a 29-year-old woman who suffered from an ischemic stroke related to acute vasospastic angiopathy in the posterior cerebral arteries established with an angiogram. Magnetic resonance imaging revealed a hyperintense signal on T2 sequencing that was fairly symmetrically, located in the posterior parietal and upper and lateral occipital cortico-subcortical regions (Fig. 1). Reconstruction of the lesion (Talairach and Tournoux 1988) indicated that it involved mainly Brodmann's areas 19, 18, 7, a limited part of area 39 and the intraparietal sulcus.

Visual fields showed a partial right inferior homonymous quadrantanopia with temporal crescent sparing. Pattern-visual evoked potentials generated for each eye and for each visual hemifield were normal. Recordings of saccades and smooth pursuit eye movements elicited by a LED in the dark showed normal gain, direction and velocities. However, when she was asked to search for an object presented in the real world she often had wandering exploratory eye movements for a few seconds before fixating at the target. She had no hemineglect syndrome during conventional testing but demonstrated bilateral optic ataxia. Reaching and grasping inaccuracy predominated for her right hand in her right peripheral hemifield. During reaching, her hand posture was often inappropriate in terms of aperture and orientation, and she usually corrected her grip only through tactile reafferences after she had completed the movement. However, visually elicited hand movements were generally accurate when performed in foveal vision.

Note that IG initially showed simultanagnosia, which prevented her to see the target and her hand at the same time and thus to adapt to prisms. This could account for contradictory result (Newport et al. 2004). The present experiment was conducted when the bilateral optic ataxia persisted without associated simultanagnosia.

Control subjects

Four naive control subjects (two males and two females 24, 23, 26 and 36 years of age, respectively) participated in the experiment. They were right-handed medical undergraduate volunteers from the Neurology Unit. They had self-reported normal vision and proprioception with no history of neurological disorder.

Design

The testing procedure consisted of a pre-test session, followed by the prism adaptation procedure, and then by a post-test session. The pre-test and post-test sessions consisted of an open-loop pointing task performed without goggles.

The comparison of the performance obtained in the pre-test and post-test sessions with the open-loop pointing task performed with the (right) exposed arm attested for the presence and the magnitude of adaptive aftereffects (Fig. 3).

The comparison of the performances between pre-test and post-test sessions on the open-loop pointing task performed with the (left) unexposed arm allowed us to investigate the presence and the magnitude of intermanual transfer of adaptation (Fig. 4).

Apparatus

The apparatus used in this experiment is similar to that employed by Redding and Wallace (1996). Specifically, this structure consisted of a two-layer rectangular black wooden box-like frame (30 cm high, 80 cm wide and 80 cm deep) placed on a table and opened on the side facing the subject. Throughout the experiment, subjects were seated in front of the structure and placed their arms within the structure. Their head was kept aligned with the body sagittal axis using a chin rest situated on the top of the box. A piece of foam placed on the lower layer of the box near the sternum of the subjects indicated the hand starting position. Sight of the starting hand position and of the first approximately 15 cm of the pointing surface was not permitted by the structure. The last part of their pointing trajectory remained visible throughout the adaptation session. The area between the starting position and the targets was totally occluded during the testing phase. Indeed, two upper horizontal plywood covers of two different sizes were designed for the prism adaptation procedure and the open-loop target pointing task. Throughout the experiment, subjects were required to point on the

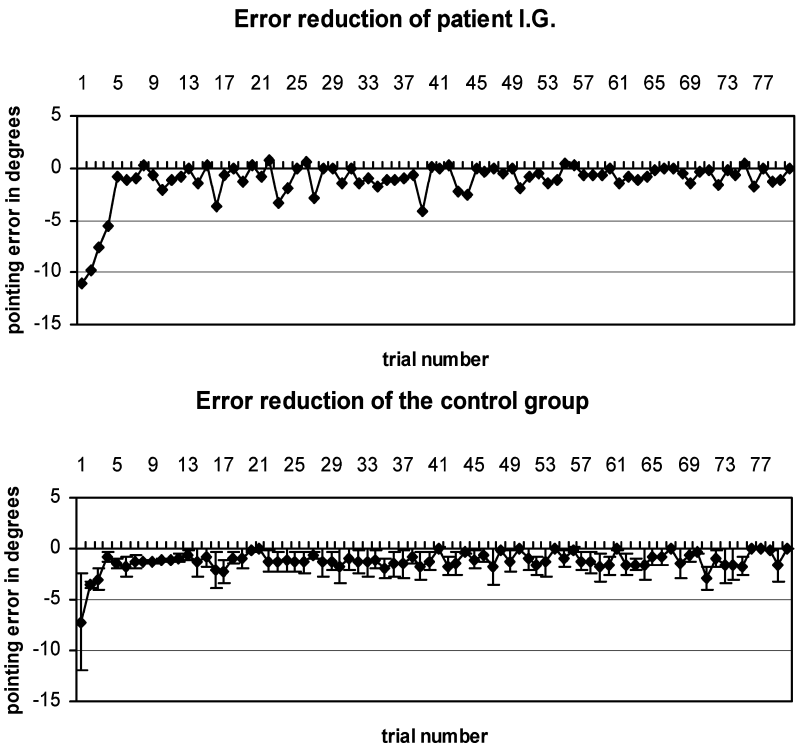

Fig. 2 Error reduction during prism exposure. These graphs show the progressive reduction of pointing errors in degrees when performing the pointing procedure toward the two targets with prisms goggles for patient I.G. and the group of control subjects

lower surface of the box and return to the starting position after each trial. The lower horizontal surface of the box was covered by electrosensitive paper that allowed the movement endpoints to be recorded via a metallic thimble attached to the tip of a subject's index finger. This apparatus produced measurements with an accuracy of 0.1°.

Prism adaptation procedure

The right-based wedge prisms used in the adaptation procedure were wide field glasses inserted into light glacier goggles and afforded a wide binocular vision (the total visual field was 105° constituted by the two monocular visual fields (30° each) and a binocular visual field of 45°). With these goggles on, the visual field is uniformly displaced to the left side with minimal visual distortion. During the exposure period, the subjects wore prismatic goggles producing a 15° leftward visual shift and performed pointing trials during 20 min with the right index finger (exposed arm). The two visual targets were coloured dots situated at 10° to the right and to the left of the body midline at reaching distance (30 cm away from the starting point) on the lower surface of the box. Subject's head was held vertical with a chin rest such that the eyes were downward toward the targets. During this pointing session, patients were asked to point under a light speed constraint, alternating towards the two visual targets. The pointing speed was constrained by the experimenter indicating where ("right" or "left" target) to direct the next pointing following a random order list; 80 pointing movements were performed in a session of 10-min duration, with small breaks after each series of 20 pointings. During this adaptation procedure, the upper surface of the box was a narrow plywood that occluded the first part of the pointing trajectory. Subjects therefore could see only the targets and the second half of their pointing trajectory, as well as their terminal error. The progressive reduction of the pointing errors during the prism adaptation procedure was recorded for each subject.

Open-loop target pointing

In this visually directed pointing test, subjects were required to point on the lower surface in alignment with a single visual target, from the hand starting position located near their sternum. For these periods (pre-test and post-test), the upper cover consisted in a plywood just shorter than the box length, allowing the subjects to see the white target bar positioned at eye level on the back vertical surface without allowing them to see their moving arm or their terminal errors. The visual target was situated straight-ahead of the subjects, and out of reach of the pointing limb (80 cm). The pointing error was measured as the distance between the pointing position and the target position and carried a minus sign for leftward errors and a plus sign for rightward errors. Six trials were successively performed, first with the right arm (exposed arm) and then with the left arm (unexposed arm) in order to obtain a reliable average for each arm in the pre-test session. The task was identically repeated just after the prism adaptation procedure (post-test session).

This task is generally considered as a measure of the total shift (TS) of the adaptive aftereffects produced by prism manual adaptation (e.g. Redding and Wallace 1996).

Statistics

In order to test the existence of aftereffects in the patient a factorial analysis of variance was performed with trials (n=6) as the random factor. An identical one-way ANOVA was also performed for each normal individual in order to assess the patient and the healthy controls in the same way. In addition, a repeated measure ANOVA was performed for the group of control subjects (n=4) between the pre-test and the post-test sessions in order to assess the presence of adaptive aftereffects (open-loop target pointing movements with exposed hand) and the presence of intermanual transfer (open-loop target pointing movements with unexposed hand) at the group scale.

Table 1 Adaptation (exposed hand)

Task	Subjects	Mean shift (deg)	*F*-value	*p*
Visual pointing (open-loop)	**I.G.**	**5.0**	$F_{(1,10)}$=28.01	**<0.01**
	Controls	**6.8**	$F_{(1,3)}$=19.85	**<0.05**
	Control 1	7.2	$F_{(1,10)}$=24.65	<0.01
	Control 2	2.7	$F_{(1,10)}$=217.80	<0.01
	Control 3	7.3	$F_{(1,10)}$=307.70	<0.01
	Control 4	10.2	$F_{(1,10)}$=476.70	<0.01

Results

Error reduction

Figure 2 shows the progressive reduction of the pointing errors during the prism adaptation procedure for patient I. G. and the group of control subjects. At first pointing, patient I.G. exhibited a larger error than control subjects with a magnitude closed to the total prismatic deviation (11 deg). Patient I.G. then maintained this pointing error until the fifth trial. Control subjects exhibited an initial pointing error of about 8 deg in mean. As early as at the second trial, the error was reduced to the level of pointing variability (within 3 deg).

Adaptation

The four control subjects showed significant negative aftereffects as assessed by the pointing errors in the open-loop target pointing task performed with the exposed (right) hand after prisms removal (one-way ANOVA $p<0.01$ for each subject, repeated measures ANOVA $p<0.05$ for the group, see Table 1, Fig. 3). Similarly, the patient I.G. exhibited a significant rightward deviation of her pointing errors between the pre-test and the post-test sessions in the same task (one-way ANOVA $p<0.01$, see Table 1, Fig. 3).

This compensatory aftereffect demonstrates that the patient adapted to the optical deviation. The magnitude of the adaptive aftereffect observed for the patient I.G. (5.0 deg) was somewhat less than the average for the control subjects' group (6.5 deg) but comparable in magnitude to that usually obtained in prism adaptation

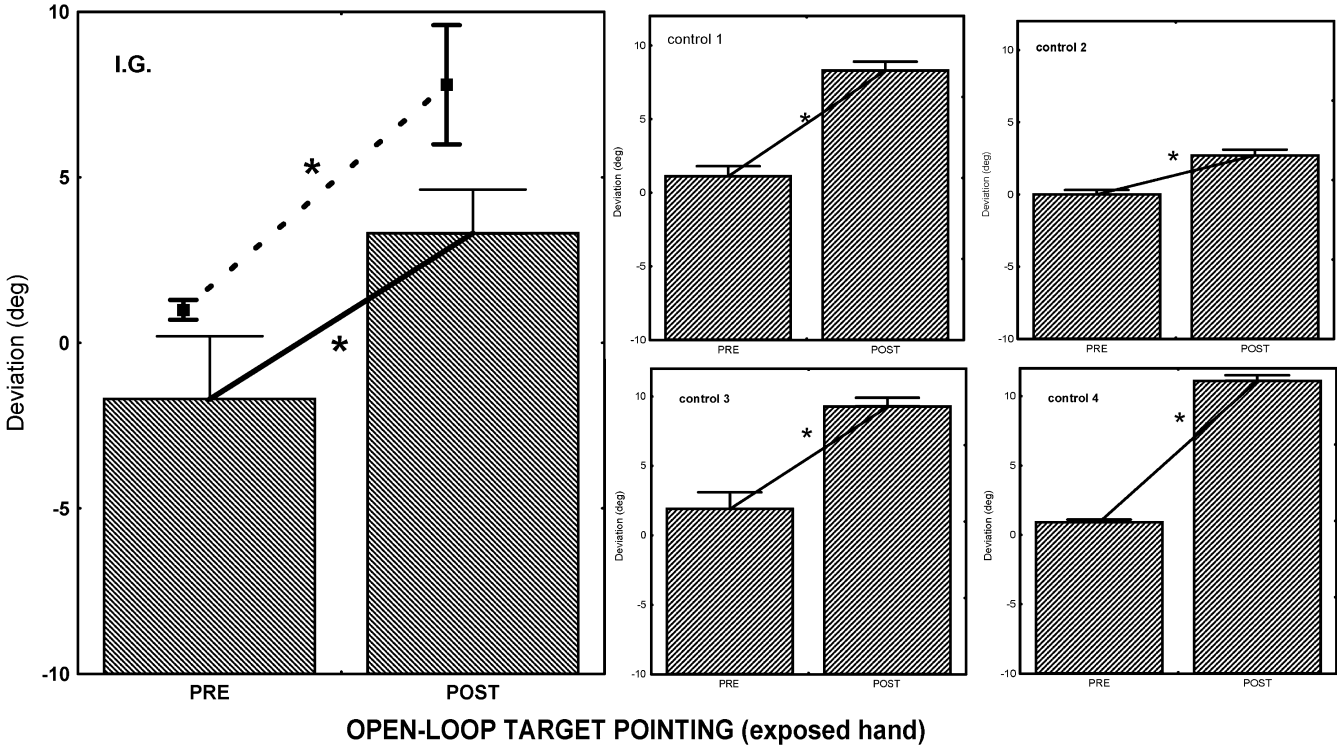

Fig. 3 Checking adaptation by open-loop target pointing with the exposed (right) hand. *Columns* represent the means and standard deviations of the errors observed for each subject before (*pre*) and after (*post*) the prism adaptation procedure with the right hand. In the *top left panel,* the mean values and inter-individual standard deviations of the group of four control subjects' performance are illustrated (*broken line*) for a comparison, in addition to the patient's performance (*continuous line*). For all the four control subjects and the patient, the mean pointing values are significantly modified between the pre-test and the post-test sessions (see Table 1). The data in the *top left panel* show a parallel aftereffect for the control subjects and the patient

Table 2 Transfer (unexposed hand)

Task	Subjects	Mean shift (deg)	Transfer rate	*F*-value	*p*
Visual pointing (open-loop)	**I.G.**	**2.7**	**54%**	$F_{(1,10)}$=19.13	**<0.01**
	Controls	**0.9**	**13%**	$F_{(1,3)}$=11.85	**<0.05**
	Control 1	1.7	23%	$F_{(1,10)}$=10.64	<0.01
	Control 2	0.5	18%	$F_{(1,10)}$=0.98	0.35
	Control 3	0.6	8%	$F_{(1,10)}$=1.67	0.23
	Control 4	1.1	10%	$F_{(1,10)}$=5.60	<0.05

studies (Redding and Wallace 1993, 1996). Therefore the *visuo-manual adaptive processes of I.G. can be considered as normal* despite patient I.G.'s bilateral lesion of the PPC.

Transfer

Individual data showed that only control subjects 1 and 4 exhibited a significant rightward shift in the open-loop target pointing task with the unexposed left hand after prisms one-way ANOVA (p<0.01 for control 1 and p<0.05 for control 4; see Table 2, Fig. 4) corresponding to 23 and 10% of intermanual transfer, respectively. Control subjects 2 and 3 did not exhibit any significant prismatic aftereffect with the left hand (p>0.2; see Table 2, Fig. 4). The group of control subjects thus exhibited a low mean rate of 13% intermanual transfer, which did, however, reach significance (p<0.05 repeated measures ANOVA; see Table 2, Fig. 4). Surprisingly, a high intermanual transfer of 54% was observed in patient I.G., which was highly significant (one-way ANOVA p<0.01; see Table 2, Fig. 4). After prism removal, pointing performance with patient I.G.'s left hand was shifted by an average of 2.7 deg to the right (p<0.01; see Table 2, Fig. 4).

This result shows that the *intermanual transfer rate of prism adaptation is strikingly large for the patient* with a bilateral lesion of the PPC.

Discussion

The present paper raises the issue of the processes and the neural substrates involved in prism adaptation. We had the opportunity to test the adaptation ability of patient I.G. who suffered from an impairment of on-line automatic

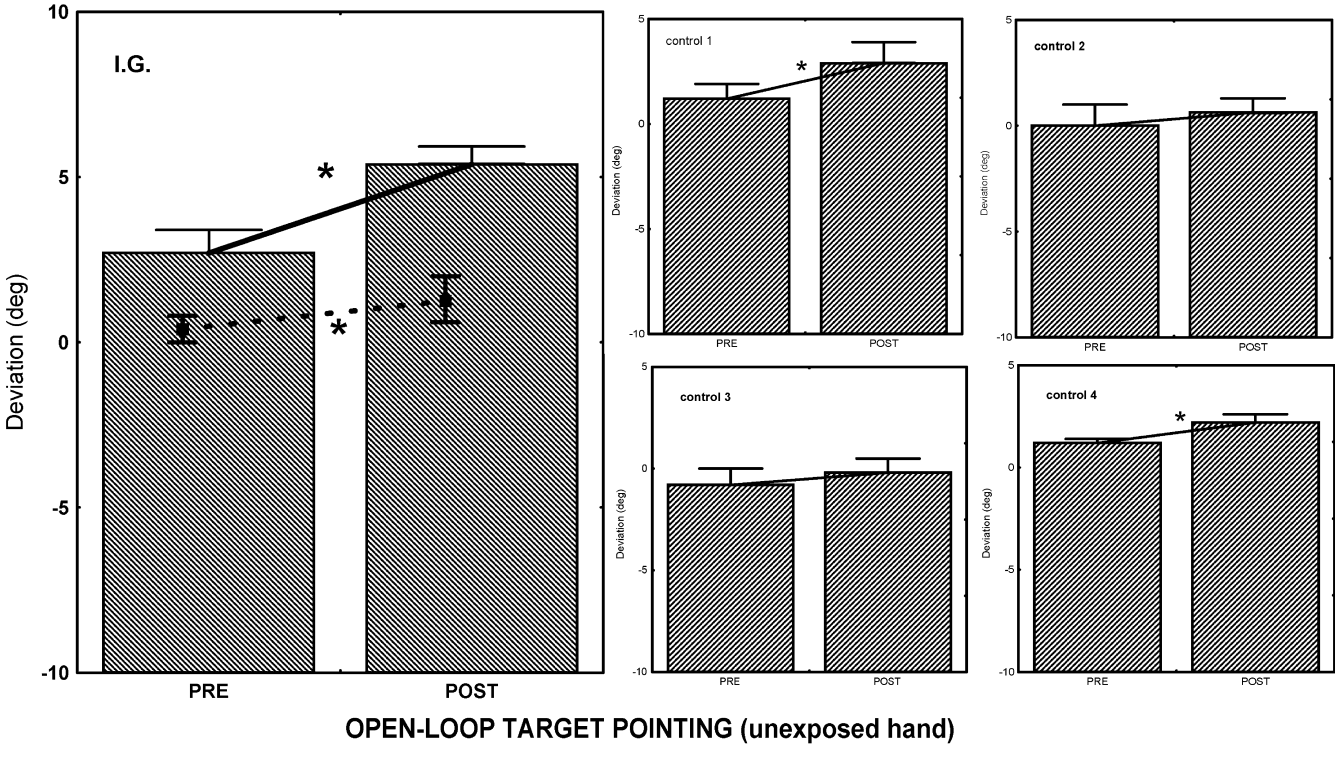

Fig. 4 Checking intermanual transfer by open-loop target pointing with the unexposed (left) hand. *Columns* represent the means and standard deviations of the pointing errors observed for each subject before (*pre*) and after (*post*) the prism adaptation procedure with the left hand. In the *first panel,* the mean values and inter-individual standard deviations of the group of four control subjects' performance are illustrated (*broken line*) for a comparison, in addition to the patient's performance *(continuous line*). A significant transfer was observed for patient I.G. and control subject 1 and 4 (see Table 2). The *top left panel* shows a larger rate of intermanual transfer for patient I.G. (54%) than for the control subjects (only 15%)

visuo-motor guidance (bilateral optic ataxia) following bilateral lesion of the PPC.

In the hypothesis presented in the introduction, we proposed that the PPC and the cerebellum are responsible for the strategic and adaptive components involved in reaction to a prism, respectively. Both components contribute to the error reduction, but the strategic component is not involved in the development of adaptive aftereffects. In addition, the strategic component involved in the error reduction seems to share the same mechanisms as those involved in the cognitive monitoring of other types of optical deviations and has been shown to activate the PPC in recent imaging studies (Bonda et al. 1996; Inoue et al. 1997; Sugio et al. 1999). Therefore, we predicted that the lesion of the PPC may partially affect the pattern of error reduction. However, the integrity of the PPC should not be crucial to observe negative aftereffects and hence an intact adaptation rate should be observed in patient I.G.

Three aspects of the present results that support our hypothesis should be summarised here. First, the pattern of pointing errors appeared slightly affected in patient I.G. Second, the patient significantly adapted to prisms despite a bilateral lesion of the PPC. Her amount of adaptation, as measured by the open-loop pointing task, did not differ significantly from that of healthy subjects. Third, the amount of transfer to the unexposed hand was about three times that of healthy subjects.

First, the initial pointing error of patient I.G. was close to the total optical displacement produced by the prisms, which confirms a reduced ability to modify her pointing movement on-line (Pisella et al. 2000; Gréa et al. 2002). She could, however, compensate for the prismatic deviation from the fifth pointing trial. Further studies should specifically investigate the contribution to this error compensation of the strategic modification of initial movement direction, the slow intentional feedback control and the adaptive realignment.

Second, patient I.G. significantly adapted to prisms despite a bilateral lesion of the PPC. The amount of aftereffect found in I.G. is about one third of the optical deviation, which is within the classical range of prism adaptation aftereffects (e.g. Redding and Wallace 1993, 1996; Rossetti et al. 1998). This result confirms previous reports made on patients with unilateral lesion of the parietal lobe (Weiner et al. 1983; Rossetti et al. 1998). Weiner et al. (1983) reported that patients with a right parietal lesion showed a normal *negative aftereffect* (using right prisms and right hand exposure). In these previous studies, it could be argued that the preserved contralateral parietal lobe of these patients was responsible for the normal visuo-motor adaptation. With a bilateral damage, the present case therefore provides a stronger demonstration that areas of the PPC included in the lesion are not crucial for prism adaptation. Most of the patient's lesioned areas are damaged symmetrically in both hemispheres: areas 19, 18 and the posterior part of the intraparietal sulcus, as well as areas 7 and 39 (in terms of Brodmann (1909); see Fig. 1a) or areas PEp and PEG (in terms of Eidelberg and Galaburda (1984); see Fig. 1b). However, the current data are not sufficient to exclude a putative role in the adaptation of the supramarginal gyrus and of the anterior part of the intraparietal sulcus remaining intact in patient I.G. (see Fig. 1c).

With respect to these two first results, it is interesting to note that I.G. has been previously shown to exhibit a specific impairment in automatic corrective processes (Pisella et al. 2000). When asked to perform corrections in response to visual targets that were displaced at the onset of her movement, she failed to produce the fast corrections found in normal subjects and instead performed slow intentional corrections (Pisella et al. 2000). According to theories of feedforward modeling (Desmurget and Grafton 2000), this suggested that the PPC was crucially involved in comparing on-line predicted and observed events. We showed elsewhere that this patient is still able to plan and execute movements with a quasi-normal kinematic pattern (Gréa et al. 2002). In addition, we show here that she is also able to integrate error signals and modify her visuo-motor correspondences off-line in order to adapt to prisms, probably by using proactive visuo-motor control. The present results therefore provide direct neuropsychological evidence for a dissociation between the processes involved in on-line visuo-motor control (*flexibility* of the pointing movement) and the processes involved in visuo-motor adaptation (*short-term plasticity* of the sensory-motor system). Both these processes are involved in accuracy maintenance, though they operate on two different time scales. This further confirms that the impairment of cerebellar ataxic patients in sensori-motor adaptation is not due to their inaccuracy (Martin et al. 1996).

Third, the rate of intermanual transfer showed by I.G. appears abnormally increased. In the literature, intermanual transfer has been described in two main situations (see Redding and Wallace 1988). First, intermanual transfer is reported when realignment is localised in the head-neck proprioceptive system; this type of adaptation is especially obvious when the head is free to move. Since we used a chin rest for all subjects, there is no basis in the present method to suppose more head shift for the patient than for controls. Second, intermanual transfer should be theoretically observed when realignment is visual rather than proprioceptive, as a consequence of subjects, and particularly patients, adopting different strategies of sensori-motor guidance, thus solving the task with different neural circuits. However, Redding and Wallace (1988) showed that visual aftereffects and intermanual transfer were unrelated.

Therefore, an alternative hypothesis must be proposed. The observation of adaptive aftereffects in patient I.G. provides a strong argument against a necessary involvement of the PPC in prism adaptation and indirectly suggests that the cerebellum is more likely to be the main substrate of adaptation. However, the second main result of our study shows that I.G. unexpectedly transferred more than 50% of the adaptation to the unexposed hand, while the group of healthy subjects exhibited low transfer (13% on average), as classically reported in the literature (Taub

and Goldberg 1973; Choe and Welch 1974). This abnormal transfer in patient I.G. suggests in turn that the PPC may participate in the adaptation. If the lesion of the PPC reduces the strategic component in this patient, adaptation would consequently be mostly achieved by recalibration processes (true adaptive component), hence more likely to be generalised. A large generalisation of the aftereffects was also suggested by results obtained in hemineglect patients where adaptation has been observed to improve neuropsychological testings (Rossetti et al. 1998), postural balance (Tilikete et al. 2001), wheel-chair locomotion (Rode et al. 2003) and even mental imagery (Rode et al. 1999, 2001). Both sensori-motor and perceptual aftereffects are observed after prism adaptation in neglect patients and these effects are more robust and durable than in normals (Pisella et al. 2002; McIntosh et al. 2002; Farnè et al. 2002). Strikingly, hemineglect patients do not notice the alteration resulting from the optical deviation. In normal subjects, when the deviation is not noticeable (e.g. about 3 deg) or when subjects are not informed of its direction, larger adaptive aftereffects are observed (Jakobson and Goodale 1989). These two results suggest that the lack of cognitive compensation facilitates the development of the true adaptive component (see Redding and Wallace 1993, 1997). The lack of strategic component would also be responsible for the important generalisation found in neglect patients. An important challenge for future prism adaptation research will be to determine whether spatial generalisation (e.g. Bedford 1993), inter-manual-transfer (Redding and Wallace 1988), and the cognitive effects of prism adaptation found in patients (Rossetti et al. 1998; Rode et al. 1999, 2001) and in normals (Colent et al. 2000; Berberovic and Mattingley 2003; Michel et al. 2003) all belong to an heterogenous group of unexposed conditions, possibly extending the aftereffects of a prism adaptation mostly achieved by recalibration processes.

Finally, recent imaging data showing an involvement of the PPC in the processes of adaptation (either exclusively: Clower et al. 1996; or in addition to a cerebellar activation: Hallett et al. 1997) also support our hypothesis. In these studies, the optical deviation was reversed (left to right) every five trials. It can therefore be argued that this paradigm did not involve the two components of adaptation in the usual way. Rather, this procedure would have selectively activated, or at least favoured, the main involvement of the strategic component (the subjects were continuously kept in an error reduction phase). It is thus not surprising that in these conditions the parietal lobe was shown to be activated exclusively or at least partially. This interpretation would also account for the lack of (or the non-exclusive) cerebellum activation found in these studies.

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