

The influence of spatial coordinates in a case of an optic ataxia-like syndrome following cerebellar and thalamic lesion

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We report the case of a patient (S.C.) who, after a lesion involving the midbrain, thalamus, and cerebellum on the left side, was unable to reach a target at which he was not directly gazing. When attempting to do so with either hand, he showed an optic ataxia-like behaviour: A rightward deviation was manifest with respect to the real position of the target object, accuracy being worse for the right than for the left hand and for the right than for the left hemifield. To assess whether S.C.'s reaching accuracy was affected by the position of the target with respect to the retina, eyes, and/or head, he was asked to perform a pointing task in different conditions. By manipulating eyes and head position, the relative location of the target with respect to these body parts was altered. Further, to verify the relevance of the visual feedback for the accuracy of the reaching responses, the task was also performed either with or without vision of the performing hand (closed- and open-loop conditions). The results showed that the patient's reaching impairment reflects a deficit in spatio-motor coding mainly within head-centred coordinates. The lack of visual feedback about the hand spatial location worsened the reaching performance. This new pattern of reaching deficits is discussed in relation to the theoretical framework of both parietal optic ataxia and cerebellar ataxia.

INTRODUCTION

A motor reaching response deficit can be the consequence of a damage of the parietal cortex (Balint, 1909) or of the cerebellum (Holmes, 1922). A relatively common consequence of a parietal

lesion is optic ataxia (OA), whereas cerebellar ataxia may follow to a lesion of the cerebellum. Despite the fact that both optic and cerebellar ataxia are reaching disorders, they are different in many respects. Optic ataxia is a disorder of visually guided reaching that, in the most frequent form,

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We thank Alessandro Farnè and Giuseppe di Pellegrino for helpful comments on an early version of the manuscript and Drs. McIntosh, Pisella, and Rossetti for their suggestions. This work was supported by grants from MURST (COFIN) and SERINAR to Elisabetta Làdavas.

only affects movements executed towards targets that are not foveated (nonfoveal OA), whereas in the most unusual form it affects movements to visual targets in all circumstances, even when they are directly foveated (foveal OA). Recently, Pisella et al. (2000) have demonstrated that even in patients with “nonfoveal optic ataxia”, a deficit of automatic visuo-motor guidance could be demonstrated for target reaching in central vision in a target jump paradigm. Cerebellar ataxia is a reaching disorder characterized by a nonlinear trajectory of upper limb movement and by dysmetria.

This study presents data from a patient, S.C., who exhibited a reaching disorder following a left-sided lesion involving the midbrain, the thalamus, and the cerebellum. When asked to pick up objects presented in peripheral vision, S.C. tended to reach rightwards off the target, especially when grasping objects with his right hand in the right hemifield. The reaching responses of this patient are interesting for two reasons: First, it can contribute to clarifying the way in which the position of a visual target is coded in space for a reaching response; second, it may add important information on the role played by the cerebellum and other subcortical structures, like the thalamus, in this function.

Concerning the first point, reaching to an object depends upon precisely coordinated spatio-motor activity of the eye, head, and hand and can be performed within different reference frames (Andersen, 1995), whose relative contribution needs to be taken into account, as it might be differently affected in reaching disorders.

Visual targets are initially encoded in a *retinotopic* frame of reference whose origin is at the subject's fixation point. Another representation useful for visually guiding action is *oculocentric* (eye-centred) coding, in which the stimulus is mapped with respect to the geometric centre of the eye (Stein, 1992). In this reference frame, the location of a visual stimulus that maximally excites an eye-centred neuron changes as the eye position changes. This pattern of neural responsiveness as a function of eye position occurs even when stimuli are presented at the same retinal locus—that is, when the stimuli are moved in

correspondence with the amount and direction of eye movement (Andersen, Essick, & Siegel, 1985), or at the same location with respect to the head. Furthermore, eye-centred neurons fire even when there is no retinotopic target position information, as when the eyes are moved in the dark or in response to an auditory stimulus (Bracewell, Barash, Mazzoni, & Andersen, 1991).

The convergence of both eye and retinal position information allows representation of the location of a visual target with respect to the head—that is, in *head-centred* coordinates.

The coding of stimulus location with respect to the body—that is, *body-centred* coordinates, requires one's knowing not only where the eyes are looking, but also the orientation of the head on the body. There are at least two possible sources for the head position signal: neck proprioceptive signals generated by changes in the orientation of the head on the trunk, and vestibular signals generated by head movements. The neck proprioceptive signals provide information about the location of the head with respect to the trunk and thus can contribute to the representation of body-centred locations. The vestibular signals provide information about the orientation of the head in the world and thus, combined with the orientation of the eyes in the orbits and the stimulus on the retina, can code locations in *world-centred coordinates* (Andersen, Snyder, Bradley, & Xing, 1997).

Other coordinates are implemented if the task requires an arm movement. More precisely, to reach an object, it is important to be able to compute the location of the object relative to our arm and hand (*arm- and hand-centred coordinates*). Thus, the arm-centred frame is likely to be particularly important in planning and performing reaching movements to targets (Caminiti, Johnson, Galli, Ferraina, & Burnod, 1991; Flanders, Tillery, & Soechting, 1992; Kalaska & Crammond, 1992; Soechting, Tillery, & Flanders, 1990; Tipper, Lortie, & Baylis, 1992).

Moreover, two main reaching situations can be classically considered: The first has been characterized as the “open loop” and the second as the “closed loop” depending, respectively, upon the

absence and presence of visual feedback about the ongoing movement. Evidence concerning which type of reference frame may be used in the open-loop and in the closed-loop condition is controversial. While some authors (Soechting & Flanders, 1989a, 1989b) have demonstrated that the “open-loop” component is programmed in a shoulder-centred coordinate system, others (Blangero, Rossetti, Honoré, & Pisella, 2005; Khan et al., 2005b) have demonstrated that neurologically intact subjects do programme their movements in an eye-centred reference frame even in an open-loop condition.

The aim of the present study was to verify which of the above-mentioned components of visuo-motor control were impaired and which were spared in patient S.C. and to functionally relate his altered reaching behaviour with the lesioned anatomical substrates. Thus, in order to verify whether patient’s reaching deficit is a deficit in reaching for the position of the target with respect to a specific coordinate system—that is with respect to the retina, the eyes, and/or the head, he was asked to perform a series of pointing tasks, while the position of the eyes and/or the head was systematically varied. More precisely, to assess patient’s spatial coding in retino-centred coordinates, he was asked to point to a visual target with eyes either free to move or fixed at midline. If the patient’s defective reaches are programmed in retino-centred coordinates, the position of the stimulus on the retina will influence the patient’s reach; the responses should be more inaccurate when the patient is reaching a visual target presented in a specific spatial position according to the retino-centred coordinates. This hypothesis can be verified only if the patient looks at a central fixation point, and the visual target is presented in different retinal positions, by varying its spatial location. In contrast, if the patient can freely move his eyes, a change of eye position in the orbit also changes the position of the target’s projection on the retina.

Moreover, to assess patient’s spatial coding in head-centred coordinates, he was asked to perform the pointing task with different head orientations: fixed at midline, steadily turned to

the left or to the right, and without constraints—that is, with his head free to move. If the patient’s reaches are programmed in head-centred coordinates, the position of the target with respect to the head will influence the patient’s pointing accuracy, and it should be more inaccurate when a visual target is presented in a specific spatial position with respect to the head. This possibility can be verified by asking the patient to hold his head in a fixed position and by varying the target position in space with respect to the head. When the eyes and/or the head are fixed at the midline, it is not possible to disambiguate between a possible impairment in retino-centred or head-centred coordinates. However, when the head is turned to the left or to the right, and the eyes are fixating centrally, the two coordinate systems do not coincide. For instance, when the head is turned to the right, visual target can be coded as “left” according to the head-centred coordinates, but they are still “left” and “right” according to the retino-centred coordinates.

Finally, to assess the effects of the visual feedback on the ongoing movement, the patient was asked to perform the reaching task both with (closed loop) and without (open loop) the vision of the hand. If the patient’s performance is modulated by the vision of the pointing hand, it is possible that shoulder- or eye-centred coordinates may also contribute to the patient’s deficit.

CASE HISTORY

S.C. is a 54-year-old right-handed enterpriser with 8 years of schooling who was in good health until 4 months prior to the investigations reported here, when he suffered an ischaemic stroke.

On admission to the hospital he presented a straight-ahead gaze, a limitation of the amplitude of vertical eye movements, diplopia when looking down, *anisocoria* (left > right), right homonymous hemianopia and paresis of the right arm and leg, dysarthria, and dysphagia. A computed tomography (CT) scan revealed an ischaemic lesion

involving the left occipital lobe, the left midbrain, and the left thalamus.

Neurological examination 4 months after the vascular accident, when he came to our attention, revealed normal eye movements in all directions, normal visual field, and normal strength of right hemisoma. Diplopia also resolved, but he showed dysarthria. He spontaneously complained about reaching problems: He was sometimes unable to reach objects, and, for example, during lunch, he could have difficulties in reaching to a bottle or a glass of water.

A magnetic resonance imaging (MRI) scan of the brain performed at the time of investigation revealed a reduction of midbrain and thalamic lesion and a small damage to the left cerebellum, the latter not being visible at the previous CT scan. More specifically, the lesion involved the red nucleus, the thalamus, and the superior part of the left hemisphere of the cerebellum. The occipital lesion was no longer visible (see Figure 1).

The patient appeared fully oriented in time and space and was very cooperative throughout the testing period. Neurological examination did not show any hemiparesis, somatosensory deficit, or visual field deficit. There was no sign of intention tremor and hypermetric errors in the classical clinical testing of finger–nose pointing. Proprioception was evaluated by asking the patient (blindfolded) to point to one of his hands

with the other one. The patient's target hand was passively moved by the experimenter alternately in the right and in the left hemisphere and the patient was asked to point to the target hand with his other hand. Ten trials (five per hemisphere) were executed with each hand. The patient was accurate in pointing proprioceptively to either hand in both hemispaces.

Concerning the examination of higher cognitive functions, his spontaneous speech was fluent, and his language comprehension was good as well as his reading and writing. The ability to imitate with the right hand different gestures performed by the experimenter was normal. In a line cancellation task (Albert, 1973), in the Bell cancellation test (Gauthier, Dehaut, & Joannette, 1989), and in a line bisection test there was no evidence of right visuospatial neglect. There were no clinical signs of contralesional extinction on visual and tactile bilateral stimulation.

Clinical observation indicated that S.C. was unable to reach to a target at which he was not directly gazing. Thus, while gazing the examiner's nose, S.C. could identify objects presented in the periphery, but could not point exactly to these objects. When attempting to do so, he showed a rightward deviation with respect to the real position of the object, which was more evident when he had to point with the right hand to stimuli located in the right visual field. When he

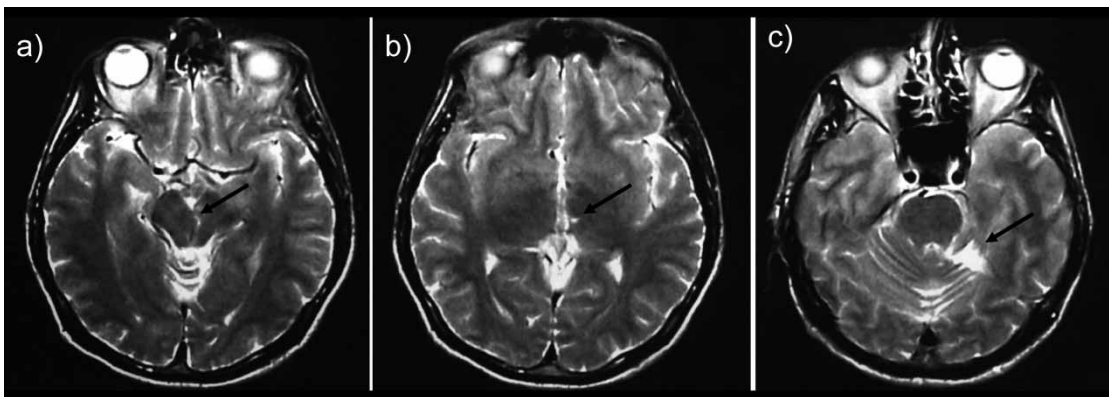


Figure 1. Brain magnetic resonance imaging scan showing the left ischemic lesion involving the red nucleus (a), the thalamus (b) and the superior part of the left hemisphere of the cerebellum (c).

was allowed to shift his eyes and head to gaze at the object, he was able to reach the target. To assess S.C.'s reaching accuracy, he was asked to perform a series of pointing tasks in different conditions (see below).

The performance of S.C. was compared with that of 6 healthy participants, as well as a control neurological patient. The control patient, M.A., was a 69-year-old right-handed man with an ischaemic cerebral lesion of the left thalamus that had occurred 9 months before the assessment session. Neurological examination showed no evidence of motor or somatosensory deficits of both limbs and an intact visual field. Formal neuropsychological assessment revealed no signs of OA or other cognitive deficits. A total of 6 healthy participants, who had no history of previous neurological disease, served as age-matched controls (mean age 52 years; range 46–64).

Method

The apparatus consisted of a wooden box (height 30 cm, depth 34 cm at the centre, and 18 cm at the periphery, width 72 cm). The box was open on the side facing the patient and on the opposite side facing the experimenter. On the side facing the experimenter there was a vertical transparent plastic support (height 30 cm, length 72 cm), arranged in semicircle and fixed to the table surface by means of four metallic stands (see Figure 2).

The visual target, a pen, was presented by the experimenter randomly in one of three possible positions: in a central position (0°), coincident with the fixation point, and in a lateral position, to the left or right of the patient's body midline (-21° and $+21^\circ$, respectively). The plastic support was graduated (in centimetres), and the experimenter could therefore ascertain and quantify the patient's spatial accuracy in pointing.

Procedure

The patient sat at a table in front of the apparatus at a distance of 57 cm, with his body midline aligned with its centre. He was asked to reach to targets that were presented through a pointing

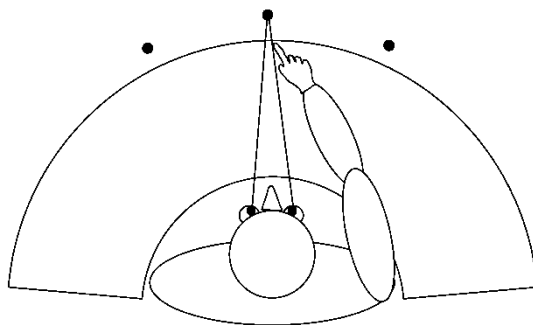


Figure 2. Bird's-eye schematic view of the apparatus. The visual target could be presented in one of three possible positions (black circles).

movement. The patient was instructed to keep his hand on his chest, at the level of the sternum (hand starting position), and to point, as fast and accurately as possible, with the index finger of the same hand towards the visual target. The pointing task was performed in the following six experimental conditions.

Condition 1: Eyes and head free (Efr-Hfr). In this condition the patient's eyes and head were unconstrained.

Condition 2: Eyes and head fixed (Efx and Hfx). In this condition, the patient was instructed to fixate a central point. Eye position was monitored to ensure fixation by the examiner, seated in front of the patient, just before initiating each reaching trial. Moreover, the patient's head was held in a midline position by a chin-rest and by one of the examiners. This manipulation enabled us to assess whether S.C.'s reaching accuracy was affected by the retinal position of the target with respect to his head (retinal and head coordinates).

Moreover, even if in everyday life we generally merge these two frames of reference (retinal and head coordinates), it is theoretically possible that reaching problems due to cerebral lesions may selectively affect motor responses for one reference frame. Thus, to verify separately the contribution of each coordinate system in the patient's deficit, he was submitted also to Conditions 3 and 4.

Condition 3: Eyes fixed and head free (Efx-Hfr). In this condition, the patient was instructed to fixate a central point, and the head was free to move. This manipulation enabled us to assess whether S.C.'s reaching accuracy was affected by the retinal position of the target independent of head position (retinal coordinates).

Condition 4: Eyes free and head fixed (Efr-Hfx). In this condition, the eyes were free to move whereas the patient's head was held in a midline position. This manipulation enabled us to assess whether S.C.'s reaching accuracy was affected by the position of the target with respect to his head independent of retinal position (head coordinates).

Finally, to verify the role of head- with respect to retinal-coordinate systems, two further conditions were introduced (see below).

Condition 5: Eyes fixed and head turned to the right (Efx-H + 30°). In this condition, the patient fixated a central point, and his head was turned 30° to right (+30°). This manipulation enabled us to disambiguate whether S.C.'s reaching accuracy was affected by the position of the target with respect to retinal or head position. Indeed, in this condition the retinotopic information coming from the right target location (+21°) could be coded as left with respect to head coordinates.

Condition 6: Eyes fixed and head turned to the left (Efx-H - 30°). In this condition, the patient fixated a central point, and his head was turned 30° to the left (-30°). Similarly, this manipulation enabled us to disambiguate whether S.C.'s reaching accuracy was affected by the position of the target with respect to retinal or head position. Indeed, in this condition the left retinotopic spatial information (-21°) could be coded as right, according to head-centred coordinates.

The pointing task, in each condition, was performed alternately with the ipsilesional and contralesional arm, either with (closed loop) or without (open loop) visual feedback. When the task was performed under visual guidance, the patient could see the pointing movement of

his arm. By contrast, in the no-vision condition the hand pointing movement was hidden below the top face of the response apparatus.

For each condition there were 30 trials, 5 executed with the right and 5 with the left hand for each of the three possible target positions. The total number of trials (360 trials, half open and half closed loop) was equally distributed in four experimental blocks (90 trials each) given in a random order and run in two sessions. Each session lasted approximately 1 hour and was run the same day. Patient S.C. and the control patient M.A. were submitted to the experimental conditions three times in three different days.

A supplementary follow-up session was further run in two consecutive days for patient S.C. after one month (see below).

Results

1. Effect of coordinates systems

In this section, we report data collapsed across the three testing sessions. Data from the follow-up session are not included in this first set of analyses and are presented later (Results 2).

To assess whether S.C. showed a failure of spatial coding in a specific coordinate system, the mean pointing deviation (expressed in degrees of visual angle) in each condition was submitted to analysis of variance (ANOVA). A two-way ANOVA was conducted with group (S.C., M.A., and C) as between-subject factor, condition (Efr-Hfr; Efx-Hfx; Efx-Hfr; Efr-Hfx; Efx-H + 30°; Efx-H - 30°) and loop (CL = closed loop and OL = open loop) as within-subject factors. Pairwise comparisons were conducted with the "Tukey honest for unequal N" test when necessary. Only the significant interactions with group are reported.

The interaction Group \times Condition, $F(10, 45) = 12.5$; $p < .0001$, was significant. Compared to M.A. and controls, S.C. showed a larger rightward deviation in the following conditions: eyes and head fixed (S.C. = 3.4°, M.A. = 0.4°, C = -0.5°, $p < .0002$, in both comparisons), eyes fixed and head free (S.C. = 2.1°, M.A. = 0.4°, C = -0.2°, $p < .03$ and $p < .001$, respectively),

eyes free and head fixed (S.C. = 2.6° , M.A. = 0.2° , C = 0.3° , $p < .0004$ and $p < .0007$, respectively), and eyes fixed and head turned to left (S.C. = 5.7° , M.A. = 0.3° , C = 0.1° , $p < .0002$ in both comparisons). In contrast, the three groups did not differ in two conditions: eyes and head free (S.C. = 0.4° , M.A. = 0.3° , C = -0.3°) and eyes fixed and head turned to right (S.C. = 0.6 , M.A. = -0.7 , C = -0.6). Moreover, S.C.'s performance in the condition with eyes fixed and head turned to left was worse than that in all other conditions ($p < .01$, in all comparisons). No significant difference was found between M.A. and controls in any condition.

The interaction Group \times Loop was significant, $F(2, 9) = 36.5$; $p < .00005$. S.C. showed a larger rightward deviation than did M.A. and controls, in both closed ($p < .02$ in both comparisons) and open loop ($p < .0002$ in both comparisons). Moreover, S.C. showed a larger rightward deviation in open (3.8°) than in closed loop (1.2° , $p < .0002$), whereas M.A. did not show any difference between open (0.3°) and closed loop (-0.03°), and nor did controls (-0.3° and -0.01° , respectively).

Finally, the interaction Group \times Loop \times Condition, $F(10, 45) = 3.3$; $p < .003$, was significant. Under visual guidance (closed loop), compared to M.A. and controls, S.C. showed a larger rightward deviation only in two conditions: with eyes and head fixed and with eyes fixed and head turned to left ($p < .007$ in all comparisons; see Figure 3a for mean values).

When visual feedback about the hand position was prevented (open loop), S.C. differed from M.A. and controls in all conditions ($p < .008$ in all comparisons), except in those whereby the task was performed with both eyes and head free, and with eyes fixed and head turned to the right (see Figure 3b for mean values). It is worth noting that S.C.'s performance was worse in the open than in the closed loop in all conditions, even if this difference was statistically significant in three conditions (Efx-Hfr; Efr-Hfx; Efx-H -30° ; $p < .003$ in all comparisons). The means show that also M.A.'s and controls' performance was less accurate in the open than in the closed loop in all conditions, but this difference was not statistically significant.

Since S.C.'s performance was compared with a small normative sample ($N = 6$) the same data were also analysed using a modified t test (Crawford & Garthwaite, 2002), which takes into account the size of the control group. The mean pointing deviations of the patient and of the control group were compared in each condition and loop. This analysis showed that S.C.'s performance significantly differed from controls' performance in all but two conditions: eyes and head free condition (Efr-Hfr) and eyes fixed and head turned to right condition (Efx-H + 30°), both in the closed and in the open loop ($p < .01$ in all comparisons).

By contrast, when the same analyses were performed comparing the performance of the control left brain-damaged patient (M.A.) with that of normal participants, no significant differences were found in any conditions, either in the closed or in the open loop.

2. Follow-up session: Effects of responding hand and target position

S.C. was submitted to a fourth session with only the conditions in which the eye and/or head position were constrained (Efx-Hfx, Efx-H + 30° , Efx-H - 30°), because these conditions are more informative about the contribution of eye/head coordinates to the patient's disorder. To assess whether S.C.'s reaching accuracy was affected by the hand used to perform the task and/or by the position of the target, a four-way ANOVA was conducted. The factors included in the analysis were: condition (Efx-Hfx, Efx-H + 30° , Efx-H - 30°), loop (CL = closed loop and OL = open loop), responding hand (right and left), and target position (left and right). Pairwise comparisons were conducted with the Newman-Keuls test when necessary.

The interaction Condition \times Loop \times Responding Hand was significant, $F(2, 18) = 3.68$; $p < .05$. Post hoc analyses showed a larger mean error in the condition Efx-H - 30° when S.C. was using the right hand in open-loop condition than in all the other conditions ($p < .04$ in all comparisons; see Figure 4a).

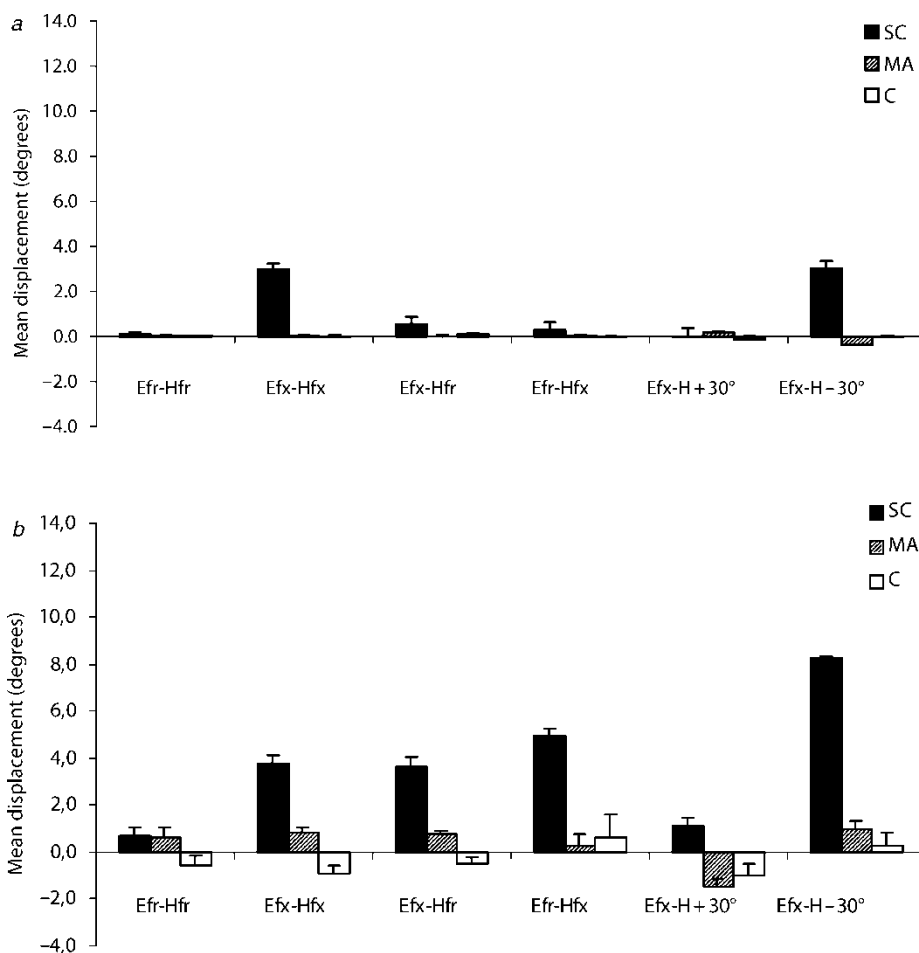


Figure 3. Effect of coordinate systems on pointing displacement. Mean pointing displacement (expressed in degrees of visual angle) and standard errors of S.C., M.A., and controls, in closed loop (a) and in open loop (b) in each condition: Efr-Hfr = eyes free, head free; Efx-Hfx = eyes fixed, head fixed; Efx-Hfr = eyes fixed, head free; Efr-Hfx = eyes free, head fixed; Efx-H + 30° = eyes fixed, head 30° turned to right; Efx-H - 30° = eyes fixed, head 30° turned to left. Bars represent SEM intersessions (S.C. and M.A.) and intersubjects (controls).

Also the interaction Condition × Loop × Target Position was significant, $F(2, 18) = 4.49$; $p < .03$. Post hoc analyses showed a larger mean error in the condition Efx-H-30° when S.C. was pointing to the right target in open-loop condition than in all the other conditions ($p < .01$ in all comparisons; see Figure 4b).

Since the factor that most influenced patient's performance was the head turned to the left,

independent of the eyes' position, these results confirmed that the space more affected by the lesion is the one coded as right according to the head-centred instead of the retino-centric coordinates. Moreover, this effect is modulated by the responding hand, since in the worse condition (Efx-H - 30° under open loop), the patient was more impaired when using the right hand.

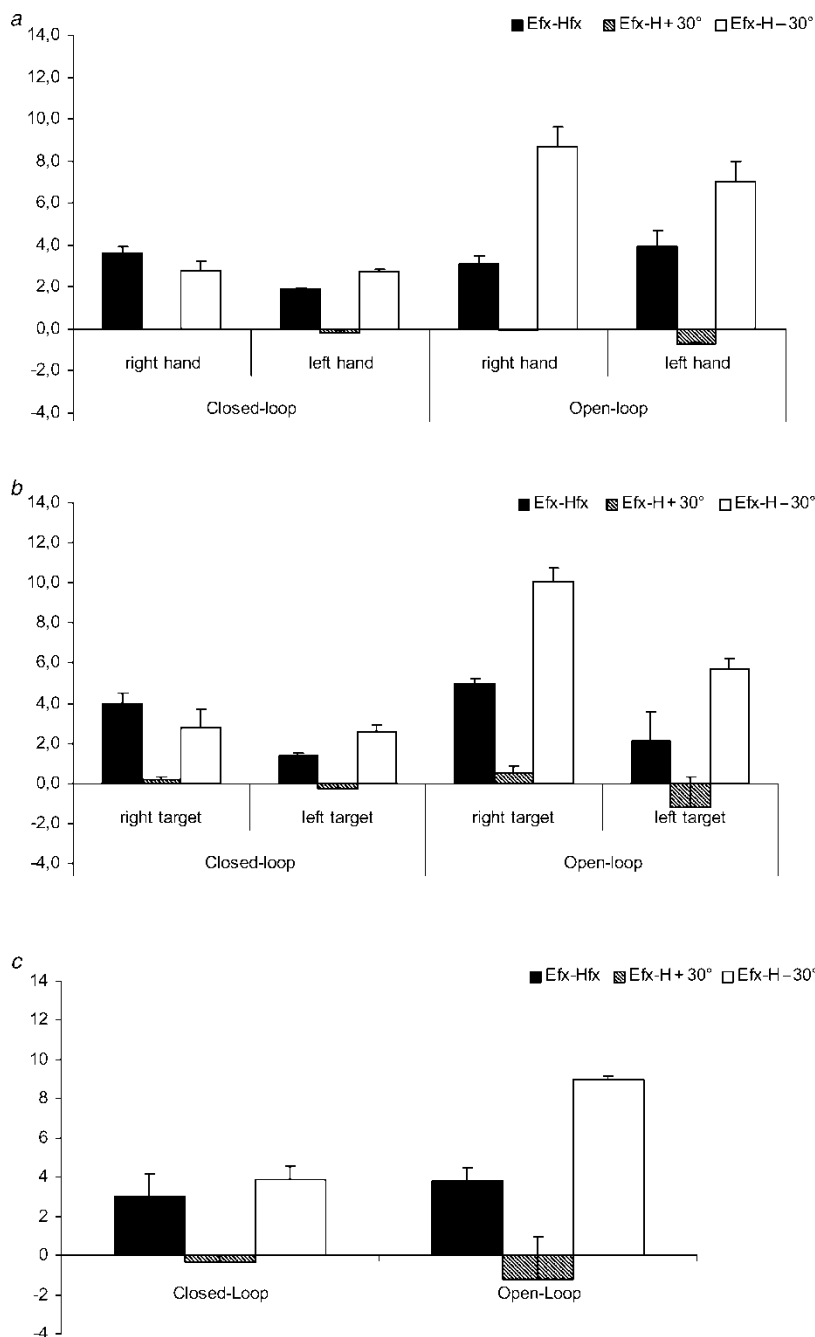


Figure 4. Effect of closed- and open-loop conditions on pointing displacement. Mean pointing displacement (expressed in degrees of visual angle) and standard errors of S.C. in the closed and in the open loop, with the right hand and left hand (a), for the right and left target (b), and for the central target (c) in the following conditions: Efx-Hfx = eyes fixed, head fixed; Efx-H + 30° = eyes fixed, head 30° turned to right; Efx-H - 30° = eyes fixed, head 30° turned to left. Bars represent SEM intersessions (S.C.).

To further disentangle between the relevance of retinal and head-centred coordinates in determining S.C.'s deficit, a three-way ANOVA was conducted on the mean pointing deviation towards central target (i.e., target located at fixation). The factors included in the analysis were: condition (Efx-Hfx, Efx-H + 30°, Efx-H - 30°), loop (CL = closed loop and OL = open loop) and responding hand (right and left). Again, pairwise comparisons were conducted with the Newman-Keuls test when necessary.

If the patient had a deficit in coding the position of an object in retinal coordinates, this deficit should have disappeared when the patient points to a target at fixation, independent of head position. Instead, if the patient had a deficit in coding the position of an object in head coordinates, this deficit should be present even for targets at fixation and should be modulated by the patient's head position.

The results of this ANOVA supported the second hypothesis. Indeed, the interaction Condition \times Loop was significant, $F(2, 18) = 27.88$; $p < .000003$. Post hoc analyses showed a larger error in the condition Efx-H - 30° in the open-loop condition than in all the other conditions ($p < .0002$ in all comparisons). More precisely, the condition with the head turned to the left is worse than the condition with the head turned to the right, both under closed and open loop ($p < .0002$); this suggests that the pointing to a central foveated target is modulated by head position. Moreover, the condition with head turned to the left was worse under open than under closed loop condition ($p < .0002$), thus demonstrating that the absence of visual feedback worsens an already present impairment (see Figure 4c). This analysis also confirms the role of the factor hand, $F(1, 9) = 20.02$; $p < .002$, since the patient's performance was worse with the right than with the left hand (3.8 vs. 2.3).

Discussion

The aim of the present study was to verify which frame of reference—that is, retino-centred and/or head centred—was used to reach for objects in

a brain-damaged patient presenting with a reaching deficit akin to optic ataxia, who was affected by an atypical, nonparietal lesion. The lesion involved left-sided structures—that is, the thalamus and the red nucleus, as well as the left anterior part of the cerebellum. While S.C. presented no signs of cerebellar ataxia, he consistently erred towards the right when pointing to peripheral visual targets.

To clarify which reference frames were impaired and which were preserved in S.C.'s behaviour, and to functionally relate his reaching deficit with the role potentially played by the damaged cerebral structures, S.C. was asked to perform a pointing task towards visual targets by systematically varying the patient's eyes and head position.

The results showed that S.C. consistently erred to the right in the pointing task when compared to a healthy group. This pointing error was not present in a control left brain-damaged patient and in healthy participants.

Moreover, the pointing error appeared to be more severe when the eyes and/or the head were stably oriented towards a central fixation point. Thus, patient's performance could be impaired in retino- or head-centred coordinates. In order to disambiguate the role played by each of these spatial coordinates, the head was tilted to the left or to the right, while the eyes were maintained fixed at the centre. When the head was turned to the right, all visual target locations fell on the left according to head-centred coordinates, but they were still on the "left" or "right" according to retinal coordinates. Instead, when the head was turned to the left, the target locations were either "left" or "right" with respect to the retinal coordinates, but were coded as "right" according to the head-centred coordinates. In these conditions, the patient's performance was most inaccurate when his head was turned to the left, whereas it was close to normal when his head was turned to the right. Therefore, reaching errors were evident when the patient had to point to stimuli coded as right according to head-centred coordinates.

Thus, it seems that head coordinates play an important role in determining S.C.'s hand

pointing errors, whereas retinal coordinates seem to be less important in determining the patient's defective performance. Indeed, irrespective of the relative (left/right or central) location of visual targets according to retinal coordinates, when targets were acted upon in the condition in which they were all coded as left sided with respect to the head, the patient's reaches were within normal limits.

In terms of cognitive architecture, this study can contribute to clarifying the way in which the position of a visual target is coded in space for a reaching response and the role played by brain structures, like the thalamus, in this function.

The present findings suggest that the head-centred coordinates are an important frame of reference in coding the spatial position for a pointing movement towards a visual object. A point that deserves discussion is why S.C. was less impaired under the closed-loop condition when the head was fixed, and the eyes were free to move (Efr-Hfx). In this closed-loop condition S.C. was actually still significantly impaired, when compared to controls, but his deficit was more severe in the open-loop condition. In this respect, it is worth noting that S.C.'s performance was overall worse in the open than in the closed loop in all conditions (see Figure 4). Similarly, the pointing performance of both the brain-damaged control patient (M.A) and the healthy control group was generally less accurate in open- than in the closed-loop conditions, although this difference was not statistically significant. As a consequence the difference between S.C.'s performance in closed and open loop when the head is fixed, and the eyes are free to move (Efr-Hfx) is most likely due to the general increased difficulty in performing a reaching action without visual feedback. This interpretation is also supported from the analysis of the foveated central target, whereby S.C.'s performance was selectively modulated by head rotation, additionally showing a worsening due to the lack of visual feedback of the pointing hand. The increase in task difficulty seems thus to be added to the patient's selective deficit in a specific head-centred coordinate system.

Two alternative explanations of the results can be considered. The first is that, since it has been suggested that in open-loop tasks reaching is programmed in shoulder- and hand-centred coordinate frames (Soechting & Flanders, 1989a, 1989b), the worsening of the patient's performance when visual feedback is not available is due to an impairment in programming arm and hand movements within *shoulder- and hand-centred coordinate frames*. Even if this coordinate system could have played a role in patient's impairment, this is not the only factor influencing patient's pointing, since the impairment is also modulated by a deficit in the head-centred coordinate system. Second, S.C.'s performance can be explained by a deficit in programming his movements within an eye-centred frame of reference, in which normal participants programme their movements also in the open-loop condition (Khan et al., 2005b; Blangero et al., 2005). However, this second possibility is less probable for two reasons. First, as we have seen before, the eye-centred frame of reference is not the one that is more impaired in this patient (Results 1). Second, the analysis conducted on central position showed a strong modulation of head position on the patient's performance also when the target was at fixation (Results 2).

After having considered the reference frame of the final pointing error and the open- and closed-loop difference in the pointing performance, other factors influencing patient's performance (hand and field effects) were analysed. In this respect it was found that S.C. was more impaired when he used the contralesional hand in the contralesional hemifield (right) to perform the task. This pattern of results was more evident in the most impaired conditions.

Thus, although the patient's symptoms are typical of OA in some respects (combined hand/field effect following left hemisphere damage; Perenin & Vighetto, 1988), they are not in others. First, the lesion observed in this patient is atypical for optic ataxia. Second, the bias away from the side of the lesion conflicts with the early reports of deviation towards the side of the lesion (e.g., Perenin & Vighetto, 1998) and with the more recently emerging view that the typical

pattern may be for errors towards fixation (e.g. Jackson, Newport, Mort, & Husain, 2005; Khan et al., 2005a, 2005b; Milner, Dijkerman, McIntosh, Rossetti, & Pisella, 2003).

Concerning the first point, whereas OA is a common consequence of damage to the posterior parietal cortex (Bálint, 1909; de Renzi, 1989; Holmes, 1918), S.C. did not show any structural lesion of the parietal cortex. The patient's brain damage was limited to subcortical structures, in the mesencephalus (red nucleus) and in the diencephalus (the ventral and posterior part of the thalamus), and to the cerebellum. The occurrence of reaching errors in S.C. may be explained if we consider the lesion of thalamus and the relationship between the ventral nuclei, the posterior part of the thalamus, and the parietal cortex. In detail, ventral nuclei are connected with the somatic sensory cortices, which include SI and SII, and, more important, the posterior part of the thalamus is connected with the somatic sensory association areas of the posterior parietal cortex (Kelley, 1994). Moreover, the lateral dorsal nucleus of the thalamus, which is most likely to be involved by the lesion, is directly connected with the superior parietal lobule (Brodmann area 5).

Thus, the symptoms observed in S.C. could be ascribed to the rich reciprocal connections between the thalamus and the parietal cortex. Moreover, the role potentially played by the lesion of the red nucleus in determining the pointing deficit in our patient needs to be considered. The red nucleus is part of a circuitry that involves the cerebellum and the spinal cord: the red nucleus of one side (i.e., left) is connected with the cerebellum and the spinal cord of the opposite side (i.e., right; Ghez, 1994). In our case the lesion involved the red nucleus and the cerebellum of the same side, and so this circuitry cannot explain the patient's impairment, but again we cannot exclude a role of the red nucleus or of the cerebellum *per se* in reaching deficit. A possible role of the cerebellum in producing this pattern of results is also suggested by some brain imaging (Desmurget et al., 2001) and neurological (Pisella et al., 2004) studies. However, patients

with a lesion of cerebellum or of the red nucleus often show dysmetria, whereas our patient, especially in the closed-loop condition, did not show pointing deviation—for example, when gazing at visual targets. Moreover, patients with a cerebellar lesion typically show dysmetria with the ipsilesional upper limb more than with the contralesional one, and there is no worsening of the performance in the open-loop condition (Haggard, Jenner, & Wing, 1994; Holmes, 1922; Schmahmann, 2004; Schmahmann & Pandya, 1997). Thus, the pointing deviation shown by S.C. is not compatible with a disorder of movement coordination following the cerebellar or red nucleus damage.

Finally, it remains to address the patient's deviation of the trajectory towards the side opposite to the lesion, which was observed irrespective of target location. Usually, in patients with OA the reaching deficits consist of a deviation of the trajectory towards the side of the lesion (Jakobson, Archibald, Carey, & Goodale, 1991; Jeannerod, 1986; Milner, Paulignan, Dijkerman, Michel, & Jeannerod, 1999; Perenin & Vighetto, 1988; Roy, Stefanini, Pavesi, & Gentilucci, 2004). In this respect, one possibility is that the left cerebellar lesion may be responsible for the unexpected rightward deviation. In favour of this interpretation, a case of right-side neglect in a patient with a right cerebellar lesion has been reported (Silveri, Misciagna, & Terrezza, 2001). Silveri et al. (2001) described the case of a patient who, after a right cerebellar lesion, showed a leftward deviation in line bisection, whereas neglect patients, after a right cerebral (supratentorial) lesion, usually show a rightward deviation in this task. The authors proposed that the side (right) of the neglect was the effect of crossed cerebello-cerebral diaschisis. However, the ipsilesional deviation pattern, formerly considered to be typical in OA, has also been challenged recently by evidencing errors towards fixation in OA patients (Khan et al., 2005a, 2005b; Milner et al., 2003). Therefore, the reason for S.C.'s contralesional deviation remains to be clarified.

In conclusion, the present results suggest that the headcoordinates may play a crucial role in guiding

pointing actions. A brain circuitry with specific structures, one of which might be the thalamus, seems to be devoted to coding visuomotor space within this frame of reference and could be functionally impaired after a selective lesion.

Manuscript received 21 April 2005
Revised manuscript received 1 February 2007
Revised manuscript accepted 9 February 2007

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