
Selective, Non-lateralized Impairment of Motor Imagery Following Right Parietal Damage

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Abstract

Using variants of a visually guided pointing task, in which subjects make pointing movements towards targets of varying sizes, we explored motor imagery in a patient with visual neglect. When this patient actually pointed towards targets of different sizes he showed the normal correlation between movement duration (MD) and target size, such that MD increased as target size decreased. In contrast, his imagined movements did not show the same speed–accuracy trade-off observed for actual movements. This was true regardless of the hand used or the initial direction of movement (left versus right). The patient performed normally on several tasks of visual imagery, including size estimation, perceptual discrimination and localization of cities on an imagined map. This patient’s performance suggests that the networks in the right parietal lobe play an important role in the generation of internal models of motor movements regardless of the hand used to perform the task.

Introduction

Understanding the role of the parietal cortex in the control of movement is complicated by the fact that different kinds of movement show different patterns of hemispheric lateralization. Thus, lesions of the left, but not the right, inferior parietal cortex typically produce apraxia, characterized by deficits controlling sequential movements and complex gestures of both limbs (Leiguarda and Marsden, 2000). Lesions of the superior parietal cortex of either hemisphere lead to optic ataxia, a deficit in the visual control of pointing and grasping (Perenin and Vighetto, 1988). Lesions of the right, but not the left, parietal cortex commonly result in visuospatial neglect, but in addition, produce subtle deficits in the visuospatial control of goal-directed movements for both limbs (Goodale *et al.*, 1990; Duhamel *et al.*, 1992; Mattingley *et al.*, 1992, 1994; Harvey *et al.*, 1994; Hussain *et al.*, 2000). Unlike the lesions that produce the profound deficits observed in optic ataxia, the lesions that give rise to neglect and the associated visuomotor impairments are more often located in the temporoparietal junction (Rafal, 1998; Karnath *et al.*, 2001).

The control of imagined movements provides an interesting avenue through which processes of motor control, including the contribution of mechanisms in the parietal cortex, can be explored. Jeannerod and others have suggested that there is

substantial overlap in the neural structures involved in controlling both real and imagined movements [see Jeannerod (1997) for a review]. Functional neuroimaging studies have revealed common foci of activation in pre-motor and parietal cortices for real and imagined movements, although some controversy exists as to the amount of overlap in primary motor cortex (Decety *et al.*, 1994; Grafton *et al.*, 1996; Gerardin *et al.*, 2000). These results would suggest that patients with lesions in the parietal cortex might be expected to show deficits not only in their actual movements but also in their ability to generate imagined movements. Furthermore, the nature of any deficit of actual and imagined movements should depend on the location of the lesion within the parietal cortex. For example, lesions of the left inferior parietal cortex that result in apraxia should be accompanied by deficits in imagined movements of the same praxic tasks, while lesions in superior parietal cortex leading to optic ataxia, should result in accompanying impairments in the ability to imagine goal-directed movements, particularly in the visual periphery (Perenin and Vighetto, 1988). The important point to emphasize here is that any impairment in imagined movement control should mirror the impairments found for actual movements.

Indeed, the findings of a recent study of imagined movements in patients with parietal lesions provides some support

for this proposal (Sirigu *et al.*, 1996). Patients with left parietal lesions that extended into the inferior parietal lobule demonstrated a bilateral impairment in imagined movements across a range of motor tasks, including visually guided pointing. Because all the motor tasks the subjects were asked to imagine inevitably had some praxic component, the fact that they showed a deficit in imagining movements with either hand may reflect the apraxia that typically accompanies lesions in the left inferior parietal lobule. In contrast, the patients with right parietal lesions that were restricted to the superior parietal cortex, an area thought to play an important role in visually guided behaviour, showed a deficit only when they imagined using their contralesional limb. This was particularly evident when the patients imagined pointing to targets that varied in size (i.e. the duration of imagined movements of the contralesional limb did not exhibit the expected speed–accuracy trade-off). In other words, imagined movements made with the contralesional hand did not show any relationship to target size, despite the fact that such a relationship was evident for actual movements of both hands and imagined movements of the ipsilesional limb (Sirigu *et al.*, 1996).

It is somewhat surprising that the patients with superior parietal lesions in the Sirigu *et al.* (1996) study continued to show relatively normal movements with their contralesional limb, while at the same time showing impairments in imagined movements with that limb. Although these patients were not reported to have optic ataxia, one patient was described as having difficulty with visually guided movements. It is unclear whether or not this difficulty was greatest in the visual periphery, as is usually the case for optic ataxia patients (Perenin and Vighetto, 1988). The pointing task that Sirigu *et al.* used allowed free vision, which may have been beneficial to these patients with superior parietal lesions. Actual movements of foveated targets are often unimpaired following damage to this region, perhaps because patients can use kinesthetic and visual feedback of the moving hand to point to where they are looking, and they do not have to depend on internal models of the intended action (Duhamel *et al.*, 1992). Of course, there is no opportunity to do this with imagined movements. In fact, the imagined movements made by neurologically intact individuals must rely almost entirely on a forward model of the intended movement (Desmurget and Grafton, 2000). Thus, the failure to show a speed–accuracy trade-off for imagined but not actual movements in patients suggests that the parietal lobe may be crucial for generating an internal representation of intended movements.

As yet, motor imagery in patients with neglect from right cerebral lesions, including the inferior parietal lobule and the temporoparietal junction, has not been extensively studied. Given that impairments in actual motor control are observed for both the ipsilesional and contralesional limbs in such patients (Hussain *et al.*, 2000), we expected to see impairments in imagined movements for both limbs. The case reported here explored the control of actual and imagined

movements in a patient with neglect following a right hemisphere stroke.

Case report

LR is a 76-year-old, right-handed male who suffered a haemorrhagic stroke of the right middle cerebral artery in July 2000. Testing commenced in September 2000. On admission to hospital, LR presented with left-sided hemiplegia and somatosensory loss and a complete left visual field homonymous hemianopia. During his in-patient stay in a rehabilitation hospital, LR regained good use of both upper and lower limbs on his left side, although some somatosensory loss persisted. His hemianopic field defect was also confirmed with Goldman perimetry and has remained stable since testing began (Fig. 1A). A computed tomography (CT) scan demonstrated a large, high-density lesion affecting the right posterior temporal, frontal and parietal lobes (Fig. 1B). A higher-density component within this mass lesion was observed posteriorly, with lower densities inferiorly and anteriorly. In other words, the greatest density of his lesion lay in the posterior parietal lobe extending into the temporoparietal junction. At the time of the initial CT scan, considerable mass effect was observed with effacement of adjacent sulci, ventricular compression and a moderate midline shift to the left (Fig. 1B).

Clinical examination demonstrated dense left spatial neglect on line bisection, figure copying and various cancellation tasks (Fig. 1C). Because the experiments presented here were conducted over several months, LR was examined for the presence of neglect at each testing session using various combinations of the following tasks; Albert's lines, shape cancellation (multiple versions), line bisection, the baking tray task and figure copying (multiple versions). At the final testing session, LR demonstrated neglect on star and letter cancellation tasks, figure copying and on the baking tray task. For line bisection, LR demonstrated a relative rightward displacement of 16% of the total line length (for lines of 240 mm). Cognitive assessment of LR revealed an average level of intelligence with impairments on tasks requiring spatial processing. His language and higher cognitive functions were all within a normal range. LR is of German origin, but has lived in Canada for approximately 30 years. His previous occupation was as a teacher and a draughtsman.

Methods

Control subject

For all tasks presented here, data were collected from an age- and education-matched control subject who was a 76-year-old neurologically healthy, right-handed female (subject MR). Informed consent was obtained from both subjects prior to the commencement of testing and the protocol was approved by the University of Western Ontario Ethics Review Board.

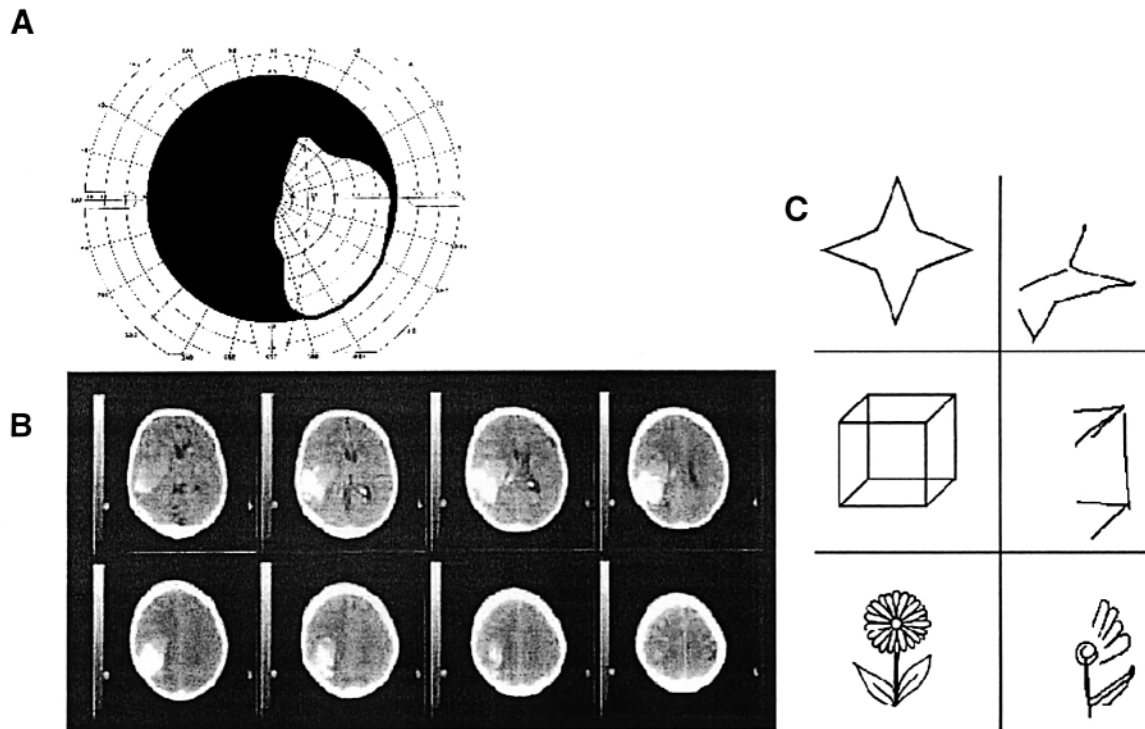


Fig. 1. (A) Goldman perimetry showing LR's complete left visual field homonymous hemianopia. (B) An early computed tomography scan showing the haemorrhagic bleed in LR's right temporoparietal region (note the left of the scan shows the right hemisphere as is neuroradiological convention), with ventricular compression and midline shift. (C) LR's copy (to the right) of a star, cube and flower, September 2000.

Apparatus and procedure

A visually guided pointing task (VGPT) was used to explore both actual and imagined movements. The format chosen for the task replicated the stimuli used by Sirigu *et al.* (1996). The patient was required to make five repetitive pointing movements to targets that varied in size, as quickly and accurately as possible (Fig. 2). All tests were conducted at the bedside with free vision allowed. LR was asked to make five pointing movements with either his right (ipsilesional) or left (contralesional) hand to targets of different sizes (Fig. 2). All movements were made with a stylus held in the patient's hand (a standard ink pen) so that the endpoints of movements could be recorded, as the task required 95% accuracy of pointing movements in order to calculate a reliable speed-accuracy trade-off (Fitts, 1954). The targets consisted of open squares with sides of 1.9, 3.7, 7.5, 14.9 and 30 mm in length. The centre of each target appeared 3 cm to the right or left of a vertical line of 8 cm in length (Fig. 2). This was done so that any differences in performance due to the initial direction of movement could be analysed [a manipulation absent in the Sirigu *et al.* (1996) study].

Target stimuli were presented on a sheet of A4 paper that was stabilized on a table in front of the patient. LR was instructed before beginning the task to emphasize both speed and accuracy equally. The five pointing movements always began behind the vertical line in the display. For targets with an initial rightward movement, this meant that movements

began with the stylus placed to the left of the vertical line. Conversely, for movements with an initial leftward movement towards targets, movements began with the stylus placed to the right of the vertical line (Fig. 2). All movements were made towards the centre of the target and back behind the vertical line, with each sequence of five movements always ending behind the vertical line (Fig. 2). On each trial LR was given a verbal signal to commence his movements by the experimenter. LR completed three trials for each of the five targets, with each hand and for each initial direction of movement (60 trials in total). The target size was randomized throughout each block. However, the hand used and the initial direction of movement were varied randomly between blocks. LR was given brief rest periods between each trial. For imagined movements, LR was asked to imagine making the same movements as he had in the actual movement conditions. The trial sequence and stimuli were identical to those used for the actual movement condition, with the exception that for imagined movements, LR gave a verbal signal to the experimenter when he had completed imagining all five movements within a trial. Thus, imagined movement duration (MD) was measured by the experimenter from the time of the 'go' signal to commence the imagined movements to the time at which LR signalled verbally that he had completed the five imagined movements. The experimenter was always blind to the display of the stop watch during each trial for both actual and imagined movements.

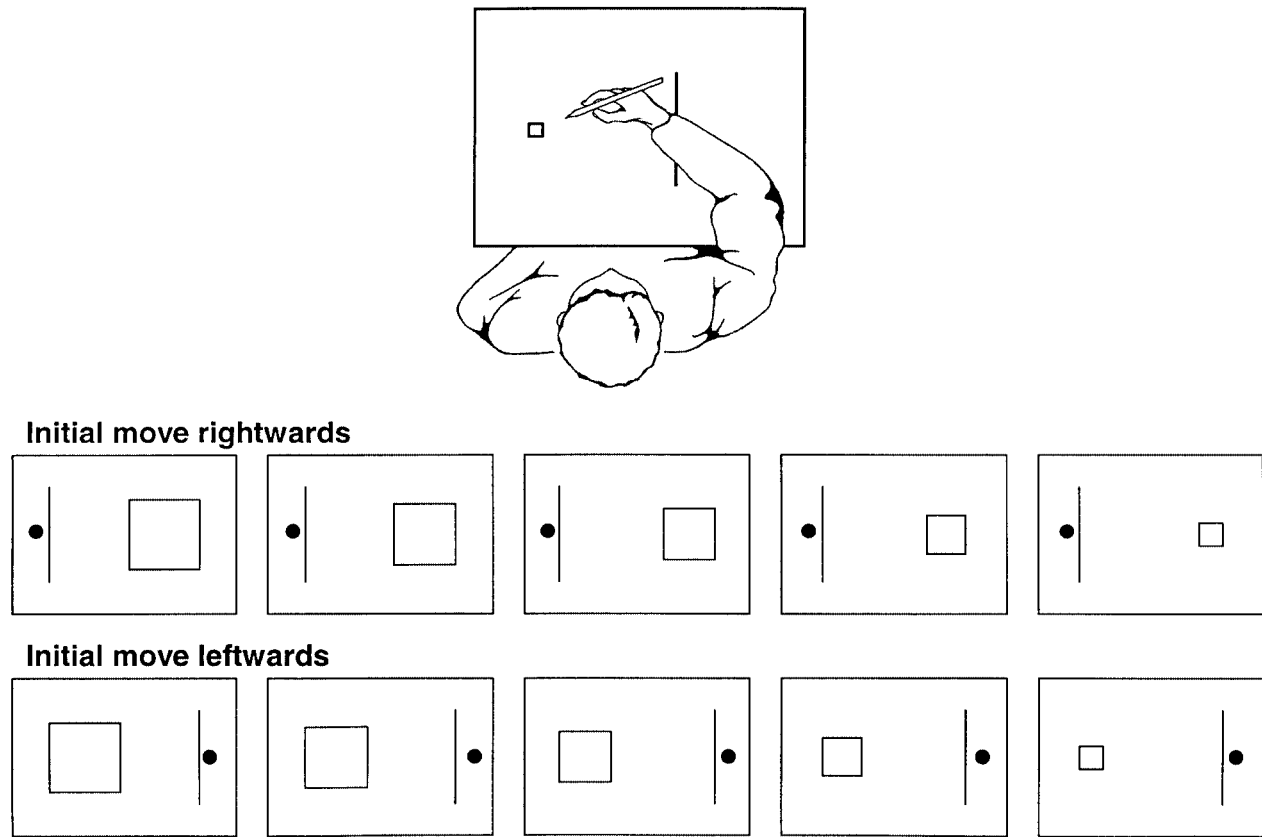


Fig. 2. The stimulus set up for the visually guided pointing task. The upper panel shows the general set up. The lower panels represent the different target sizes from large to small (moving from left to right) with either an initial move made towards targets on the right side of the page (upper panel) or an initial move made towards targets on the left side of the page (lower panel; see Method section). The black dot to the left or right of the vertical line (depending on target location) represents the start and endpoint of movements (note that no physical dot was present in the displays).

Data analysis

The mean MD of the three trials conducted for each target under each condition (i.e. hand versus initial movement direction) was first calculated. The data were then organized according to an index of difficulty (ID) as calculated by Fitts' Law (Fitts, 1954). Fitts' Law states that MD will be a function of the combination of the amplitude of movements (A) and the width of targets (W), expressed as ID according to the following logarithmic law:

$$ID = \log_2 (2A/W)$$

According to Fitts' Law, MD should increase linearly with increases in ID. This effect has been shown to be robust, requiring small numbers of subjects and very few trials per subject (Maruff *et al.*, 1999a, b; Danckert and Goodale, 2001). Least squares regression was then used to model the relationship between MD and ID in each condition (actual and imagined movements) separately. To investigate the extent to which imagined performance mirrored actual performance, MDs in the two conditions were correlated (Sirigu *et al.*, 1996). For healthy controls, previous research has demonstrated a high correlation between imagined and actual MD, further supporting the proposition that actual and imagined movements share much of the same neural circuitry.

Experiment 1. The effect of hand and initial direction of movement on real and imagined movements

The first experiment explored imagined movements in LR using both the ipsilesional and contralesional limbs under conditions in which either rightward or leftward movements were made to targets. Given that lesions of the inferior right parietal cortex lead to impairments in motor control of both the contralesional and ipsilesional limbs, we hypothesized that LR would demonstrate an impairment for imagined movements of both limbs. That is, when asked to imagine making movements with either hand, we expected that the normal relationship between imagined MD and ID would not be evident. The initial direction of movement was manipulated to test the possibility that LR would show a greater degree of impairment for leftward versus rightward movements. Although there were five continuous pointing movements involved in each trial, the accuracy requirements were always limited to one direction of movement (i.e. within a given trial targets appeared only to the right or left of a vertical line, thereby requiring accuracy for only rightward or leftward movements; Fig. 2). Although we expected imagined movements to be impaired for both limbs compared with the control subject, this manipulation allowed us to investigate any possible differences for LR due to the initial direction of movement.

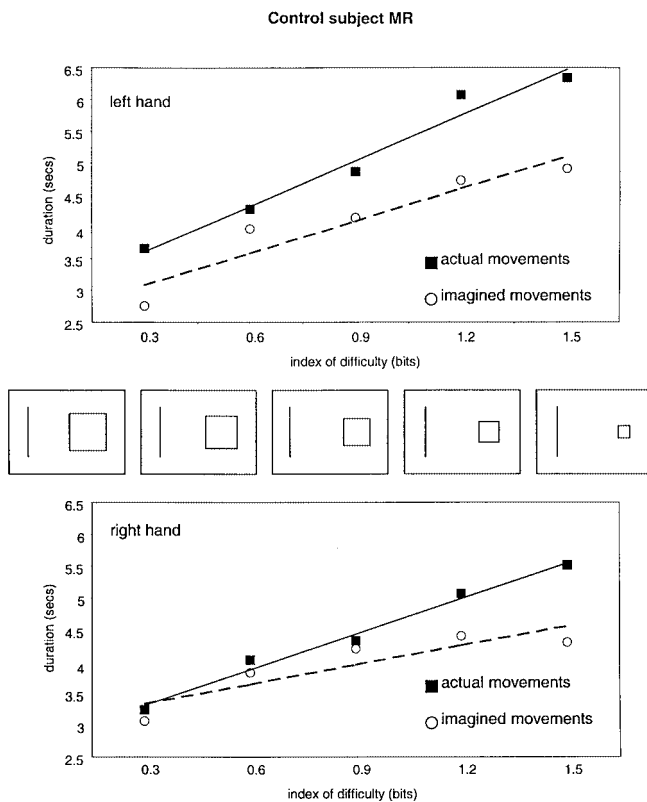


Fig. 3. Mean movement duration for actual (filled squares and solid lines) and imagined (open circles and dashed lines) movements for control subject MR, collapsed across the initial direction of movement. The upper panel shows movements made with the left hand, while the lower panel shows movements made with the right hand (see Table 1 for regression equations). A schematic representation of the targets shows which target size corresponds to the index of difficulty shown (note that this schematic representation depicts only the condition in which the initial direction of movement was rightwards).

Results

Less than 1% of the trials were excluded for either the patient or the control due to a lack of endpoint accuracy. For the control subject MR, no difference was observed in MD with respect to the initial direction of movement. Therefore, regression lines were fitted to data collapsed across this factor. For actual movements, overall MD demonstrated an effect of handedness with durations being somewhat slower for movements made with the left hand [see also Maruff *et al.* (1999a)]. Despite this slowing, there was a strong linear relationship between MD and ID for movements made with both the left and right hands (Table 1, Fig. 3). That is, MD increased in a linear manner as ID increased.

As expected, MR also demonstrated a strong relationship between imagined MD and ID for both her left and right hands (Table 1, Fig. 3). That is, her imagined MD increased linearly as ID increased. A high correlation was also observed between imagined and actual MD for MR, indicating that she performed imagined movements in much the same manner as she did actual movements (Table 1).

For patient LR, actual movements made with either the contralesional or ipsilesional hand showed a good relationship with ID, such that MD increased linearly with increases in

ID (Fig. 4). As expected, the duration of his imagined movements did not conform to this relationship. That is, when he was asked to imagine making movements with either his left or right hand, the MD of the imagined movements did not show a strong relationship with ID. This was true irrespective of the initial direction of the imagined movement (Fig. 4, Table 1). The clear dissociation between actual and imagined movements for either hand, and either initial direction of movement, was further confirmed by non-significant correlations between actual and imagined MD (Table 1). This result suggests that LR has a generalized impairment in the ability to imagine making motor movements independent of the hand used or the initial direction of movement.

Experiment 2. Imagining the target: exploring the role of visual feedback in the VGPT

When asked to imagine making pointing movements, subjects are obviously unable to benefit from visual or kinesthetic feedback of the moving hand. The role of visual and kinesthetic feedback in the control of skilled actions has been studied extensively (Desmurget *et al.*, 1997, 1999; Vindras *et al.*, 1998). One crucial role that visual feedback plays in the control of skilled movements is in providing online information about target position relative to the hand (Desmurget *et al.*, 1997; Vindras *et al.*, 1998). For saccadic eye movements, it is well known that following an initial saccade directed towards a peripheral target, corrective saccades are made to account for minor errors in amplitude of the initial saccade. Similarly, the endpoint accuracy of movements of the upper limb rely to some degree on feedback for updating the position of the limb relative to the target (e.g. Prablanc *et al.*, 1986). For this reason, we asked LR to complete a version of the VGPT in which he was required to imagine a previously viewed target while actually making pointing movements. That is, LR was given a view of the target for approximately 2 s and was then asked to make five pointing movements on a blank page while imagining the target he had just been shown (see Fig. 5).

In this way we could examine the possibility that LR showed a generalized impairment in the ability to imagine making visually guided pointing movements simply because visual and kinesthetic feedback were unavailable to him.

For this experiment both LR and MR completed three conditions of the VGPT. The actual and imagined conditions used in experiment 1 and a third condition in which they made pointing movements to imagined targets (Fig. 5). A trial sequence for this condition was as follows: a target was displayed for approximately 2 s. The target was then replaced by a sheet of paper with a vertical line to the left of the page. Five pointing movements were then made from behind the vertical line to an imagined target towards the right of the line. All movements were performed with the right hand (ipsilesional hand for LR) holding a stylus, as in the actual condition. This allowed us to record the endpoints of each

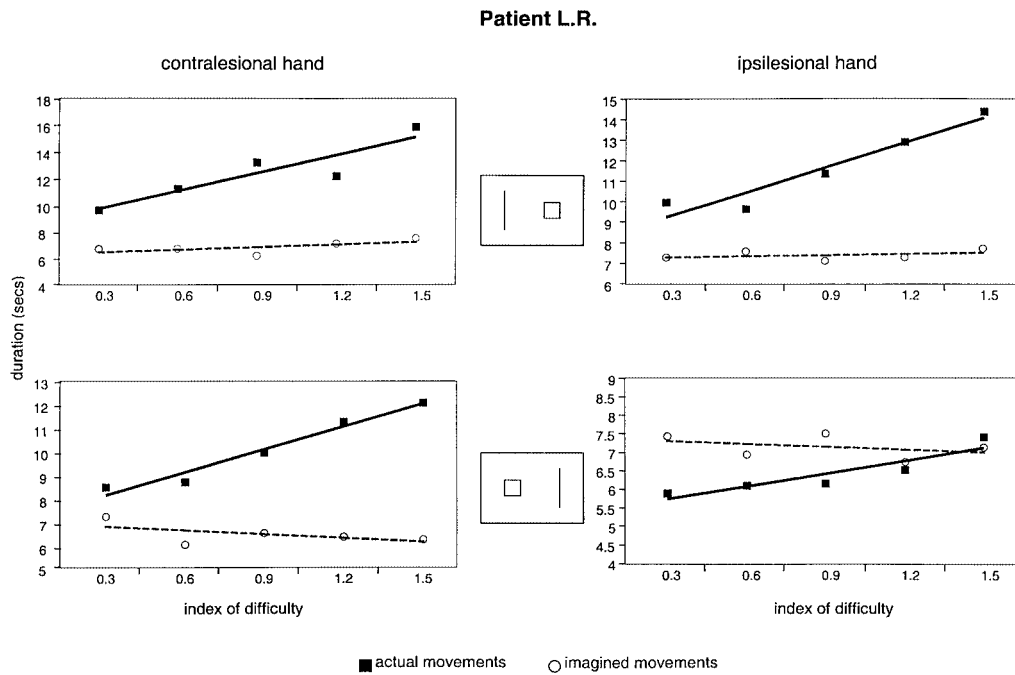


Fig. 4. Mean movement duration for actual and imagined movements for patient LR (symbols are identical to those in Fig. 3). Movements made with the contralesional (left) hand are presented on the left, while movements made with the ipsilesional (right) hand are presented on the right. For both contralesional and ipsilesional hands, conditions in which the initial movement was rightwards are presented in the upper panels, while conditions in which the initial movement was leftwards are presented in the lower panels (as indicated by the schematic diagrams). See Table 1 for regression equations.

Table 1. Linear regression equations for actual and imagined movements for both control subject MR (data collapsed across the initial direction of movement) and patient LR (the initial direction of movement is shown in parentheses). The correlation between imagined and actual movement duration is also shown

	Actual	Imagined	Correlation
Control subject MR			
Left hand	$y = 0.72x + 2.89, r^2 = 0.97$	$y = 0.51x + 2.58, r^2 = 0.89$	0.89*
Right hand	$y = 0.56x + 2.77, r^2 = 0.99$	$y = 0.3x + 3.04, r^2 = 0.78$	0.88*
Patient LR			
Left hand (move left)	$y = 0.99x + 7.37, r^2 = 0.96$	$y = -0.16x + 7.19, r^2 = 0.32$	-0.34
Left hand (move right)	$y = 1.35x + 8.63, r^2 = 0.83$	$y = 0.19x + 6.25, r^2 = 0.4$	0.25
Right hand (move left)	$y = 0.35x + 5.22, r^2 = 0.83$	$y = -0.08x + 6.11, r^2 = 0.15$	-0.33
Right hand (move right)	$y = 1.21x + 8.04, r^2 = 0.92$	$y = 0.06x + 7.24, r^2 = 0.14$	-0.36

*Significant correlation at $P < 0.05$.

movement, which were used to determine whether or not movements of similar amplitude were made within and across trials. A mean amplitude for movements made within each trial was then calculated. Trials in which the amplitude of any given movement fell outside two standard deviations of the overall mean were excluded from the analysis. For LR this meant that only one trial was excluded, while no trials were excluded for MR. In addition, a measure of the spread of endpoints was taken along the x -axis. This spread was also investigated across trials to ensure that both LR and MR were complying with the task instructions (i.e. imagining the targets and attempting to make accurate movements towards those imagined targets). Once again, trials in which the spread of endpoints fell outside two standard deviations of the mean were excluded from further analysis. No trials were excluded due to this criterion for either LR or MR (Table 2).

Results

For the control subject MR there was a strong relationship between ID and the duration of both actual and imagined movements, as seen in experiment 1 (Figs 3, 5). In addition, when MR actually made movements towards imagined targets she continued to demonstrate a strong relationship between MD and ID in the expected direction (Fig. 5, Table 2). There was a high and significant correlation between the duration of imagined movements and movements made while imagining the target for MR (Table 2).

For LR, actual movements again showed the expected relationship to ID, with MD increasing as ID increased. For imagined movements he demonstrated an opposite trend. That is, linear regression analysis showed that as ID increased MD decreased (Fig. 5, Table 2).

This trend is difficult to interpret, and in the context of

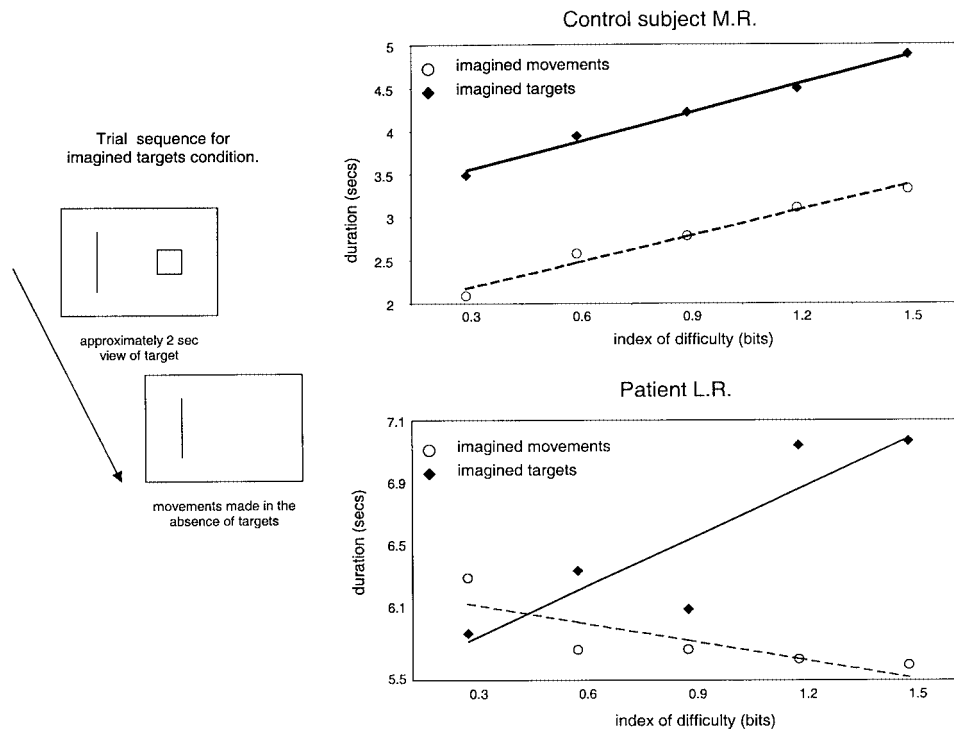


Fig. 5. Mean movement duration in seconds for both imagined movements (open circles and dashed lines) and movements made while imagining a previously presented target (filled diamonds and solid lines). Control subject MR’s data are shown in the upper panel and patient LR’s data are shown in the lower panel. A schematic representation of the trial sequence for movements made while imagining a previously presented target is shown to the left of the figures. See Table 2 for regression equations. Note that actual movements to visible targets are not depicted here but showed the expected relationship between movement duration and index of difficulty for both LR and MR.

Table 2. Linear regression equations for imagined movements and for actual movements made while the subjects were required to imagine previously viewed targets (see Method section). Note that mean amplitude and endpoint spread figures are for the imagined targets task only (see Methods section)

	Control subject MR	Patient LR
Imagined movements	$y = 0.31x + 1.87, r^2 = 0.97$	$y = -0.11x + 6.08, r^2 = 0.67^a$
Imagined targets	$y = 0.33x + 3.2, r^2 = 0.99$	$y = 0.31x + 5.42, r^2 = 0.78$
Correlation between imagined movements and imagined targets	0.87*	-0.002
Correlation between imagined targets and actual movements	0.89*	0.82*
Mean amplitude \pm SD (mm) within trials	59.9 (7.1)	50.93 (5.1)
Mean endpoint spread \pm SD (mm) within trials	5.9 (1.8)	4.1 (1.4)

^aThis equation indicates a negative slope in contrast to the expected positive relationship between movement duration and index of difficulty.

*Significant correlation at $P < 0.05$.

SD, standard deviation.

his previous performances (see Fig. 4) may be due to chance. Interestingly, when he was asked to make movements towards previously viewed targets, he demonstrated a strong relationship between MD and ID in the expected direction (Fig. 5, Table 2). That is, when LR made movements to targets that he had to imagine, his MD was sensitive to the size of those imagined targets, such that MD increased as ID increased. Although there was no correlation between the MD for completely imagined movements and the MD for actual movements made to imagined targets (Table 2), there was a significant correlation (Pearson’s $r = 0.82, P < 0.05$) between the MD for actual movements made to real targets and the MD for actual movements made to imagined targets (Table 2).

These results suggest that LR did in fact rely on visual

feedback of the moving limb in order to demonstrate a speed–accuracy trade-off on the VGPT. To test this further, LR was asked to complete one final version of the VGPT in which vision of his moving hand was occluded. In this condition, target displays were placed on a board raised approximately 15 cm from the surface of the table. The board was covered with black cloth, which allowed LR to move his hand underneath the board without actually seeing it. In this case, LR made the pointing movements with his index finger rather than a stylus, because of the limited space underneath the board. We knew from unpublished kinematic data that LR had no difficulty making accurate pointing movements to targets on the VGPT using his index finger alone. Yet when LR was asked to make movements without

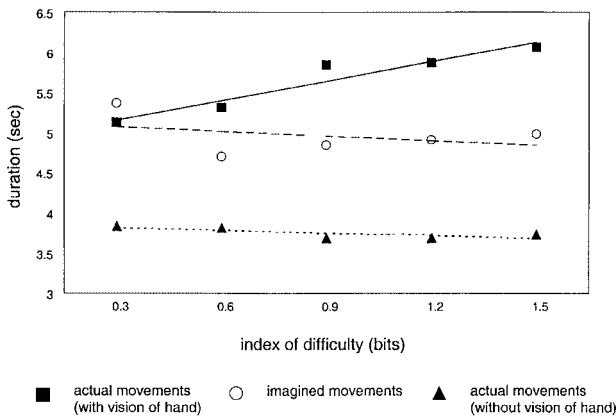


Fig. 6. Mean movement duration for actual movements with vision of the moving hand (filled squares), actual movements without vision of the hand (filled triangles) and imagined movements without vision of the hand (open circles). The only significant trend was observed for actual movements with vision of the hand (i.e. movement duration increased linearly as index of difficulty increased).

vision of the moving limb, his MDs did not show the expected speed–accuracy trade-off function (Fig. 6). We also asked LR to perform imagined movements with his limb in the same starting position (i.e. occluded underneath the board on which target stimuli were presented) as for the actual movements of this condition. As expected, his imagined MD failed to show any relationship to ID. Overall, LR has failed to show any speed–accuracy trade-off for imagined movements in five of the six conditions of the VGPT presented here. In this context, the unexpected result for imagined movements in the previous task, where he appeared to show the opposite of a speed–accuracy trade-off (see Fig. 5), appears to have been due to chance.

Experiment 3. Visual imagery and motor imagery: self as actor versus self as spectator

Given that LR did not show any systematic relationship between imagined MD and ID on the VGPT, we felt it was important to assess his ability to perform other types of imagery tasks. That is, it was important to exclude the possibility that LR was unable to generate internal images of any kind. Therefore, we asked LR to perform a range of different imagery tasks that would assess perceptual and visual imagery skills, size estimation and praxic motor imagery.

Procedure and apparatus

LR is German in origin but has spent the past 30 years living in Canada, giving us an opportunity to use two variants of a visual imagery task previously used in patients with neglect (Rode and Perenin, 1994; Rode *et al.*, 2001). Rode *et al.* (2001) asked a patient with neglect to imagine a map of France and to name all the cities he could think of on that map, a task that is thought to involve processes of mental

imagery. The patient predominantly named cities on the right half of the map, indicating a kind of imagined neglect. We asked LR to imagine a map of North America. He was asked to imagine standing in Mexico facing north and to name all the states of America and provinces of Canada he could. He was also asked to imagine a map of Germany in which he imagined standing in Munich facing north and was asked to name all the towns and cities in Germany he could. To assess visual imagery further, LR was asked to name all upper case letters that have curves in them (e.g. B, C, D, etc.) and all lower case letters that have tails (e.g. g, j, p, etc.). This task is also thought to require the use of visual imagery and has previously been used with neurological patients (e.g. Servos and Goodale, 1995). LR was also asked to complete a motor imagery questionnaire (Goldenberg *et al.*, 1989). The questionnaire consists of 50 true/false items that require the subject to imagine a series of complex motor acts. For example, the subject is told ‘a pencil is held between the thumb, index and ring fingers’ and is asked if this is true or false. Finally, previous research has shown that visual imagery is used to make size comparisons and that imagery becomes more necessary when such comparisons are difficult (Paivio, 1975; Kosslyn *et al.*, 1986; Servos and Goodale, 1995). This task was thought to be important in the context of LR’s impairment in imagined movements. That is, the question remains as to whether he was simply unable to imagine differences in target size in the VGPT as opposed to an impairment in the ability to imagine making movements to those targets. Although this question was answered somewhat by his performance when asked to make movements while imagining previously viewed targets, it was nevertheless important to determine whether LR has a generalized impairment in size estimation. The size estimation task used required LR to determine which of two items was bigger. The 40 pairs used were constructed from norms for size estimation collected by Paivio (1975) and have been used previously in neurological patients (Servos and Goodale, 1995). Twenty of the pairs were animals and 20 were common man-made objects. Within each category 10 pairs were denoted as difficult (with a mean size rating difference of less than 0.5), while 10 were denoted as easy (with a mean size rating difference of at least 2). More details regarding norms for this task can be found in Paivio (1975). The pairs of animals and objects, as well as the order of the larger versus smaller items within each pair, were randomized throughout.

Results

When LR was asked to imagine the states and provinces of North America he showed no laterality bias and generally recalled a large number of locations across the full extent of the continent. Similarly, when imagining cities in Germany, he showed no laterality bias and recalled a large number of cities and towns. Table 3 summarizes LR’s performances on the other tasks of mental imagery.

Generally he performed within a normal range on all tasks

Table 3. LR's performance on tasks of visual and motor imagery (first score indicates LR's performance, while the second score indicates the maximum possible score for that task)

Upper case letters with curves	11/11
Lower case letters with tails	6/6
Praxic motor imagery (Goldenberg <i>et al.</i> , 1989)	45/50
Size estimation	
Easy object pairs	10/10
Hard object pairs	9/10
Easy animal pairs	10/10
Hard animal pairs	9/10

of visual, perceptual and mental imagery. These tasks differ significantly from the VGPT in that LR was never required to imagine himself performing an action. Instead, these tasks involved visual imagery in which the self can be thought of as a spectator rather than an actor (Jeannerod, 1997). LR also performed within a normal range on the praxic motor imagery questionnaire (Table 3).

Discussion

Patient LR demonstrated a clear impairment in the ability to imagine performing visually guided motor actions (Figs 4, 5). Furthermore, his impairment was equivalent for both the ipsilesional and contralesional limbs. LR's impairment in motor imagery is in the context of actual movements that conform to expected speed–accuracy trade-off functions. That is, when LR actually performed pointing movements with either hand, the duration of those movements was closely related to ID, which in our case was solely determined by target size (i.e. amplitude remained constant throughout the experiments; Figs 4, 5). The only condition in which a speed–accuracy trade-off function was not observed for actual movements was when LR was denied vision of the moving limb (Fig. 6). This suggests that he relies heavily on visual feedback of the moving limb in order to control pointing movements of either limb accurately. For imagined movements, no relationship between MD and ID was evident irrespective of the hand used or the initial direction of movement (Figs 4, 5). Despite this obvious impairment in motor imagery, LR demonstrated preserved visual and perceptual imagery, suggesting that this is not a generalized impairment in the ability to generate internal images of any kind. Rather, these results suggest that LR has an impairment in the ability to generate internal models of goal-directed actions.

Interestingly, when LR was asked to point towards targets that he had previously viewed, the duration of these actual movements to imagined targets now conformed to the expected speed–accuracy trade-off (Fig. 5). That is, even though no target was present while LR made his pointing movements, the duration of those movements nevertheless showed a clear relationship to the size of the targets he had previously been shown. In the context of LR's performance on all previous tasks in which he was asked to imagine

making movements to visible targets, this result suggests that visual feedback of the moving limb is crucial for LR to demonstrate the expected speed–accuracy trade-off. That is, when asked to move to targets he had to imagine, he was able to make use of visual and kinesthetic feedback of the moving limb, in conjunction with stored information about the size of the recently viewed target, to demonstrate a normal speed–accuracy trade-off. Furthermore, the absence of a relationship between MD and ID when vision of the moving limb was denied (Fig. 6) suggests that LR relies more on visual than on kinesthetic feedback to control his actual movements to targets.

To exhibit the same speed–accuracy trade-off for imagined movements as is shown for actual movements, the visuomotor system would have to anticipate the consequences of movements to targets of different sizes—without the benefit of any of the visual or kinesthetic feedback that would accompany a real movement. In other words, to show a speed–accuracy trade-off in imagined movements (such as that shown by the control subject, MR), the neural circuitry generating those movements would have to depend entirely on an internally generated movement plan or forward model of the intended movement. Such forward modelling is thought to involve a network of neural structures including pre-frontal and parietal cortex and the cerebellum (Wolpert *et al.*, 1998a, b; Desmurget and Grafton, 2000). Although the efference copy of an intended action may be generated in pre-motor and motor regions of the frontal cortex, the parietal cortex may be necessary for monitoring the efference copy to ensure the action being carried out matches the intended action. This might explain why LR, who has a large parietal lesion, did not demonstrate the expected speed–accuracy trade-off for imagined movements or for real movements in situations where no visual feedback was available. His lesion in the parietal cortex may have left him incapable of generating (or making use of) a forward model of his intended movement. This interpretation is also supported by a recent study showing that disruption of the parietal cortex using transcranial magnetic stimulation, results in an inability to correct pointing movements made to unexpected and rapid changes in target location during the performance of the movement (Desmurget *et al.*, 1999).

LR's deficit appears to be one that affects the imagining of visually guided hand or limb movements rather than the imagining of particular hand and limb postures. Thus, he performed within the normal range on a praxic motor imagery questionnaire, in which he was required to imagine a complex action or gesture and determine whether or not the description of this action and the component movements were correct (Goldenberg *et al.*, 1989). But then, LR's right parietal lesion would not have been expected to result in apraxia, or related deficits in imagining movements requiring praxis, which typically follow lesions of the left inferior parietal region (Sirigu *et al.*, 1996; Ochipa *et al.*, 1997). Indeed, previous research has shown impaired praxic motor imagery in patients following left parietal lesions (Ochipa *et al.*, 1997).

LR's deficit in motor imagery was not lateralized to the contralesional hand. Other studies of patients with right parietal lesions have demonstrated motor imagery impairments on the VGPT in which the deficit is limited to imagined movements involving the contralesional limb. In these cases, however, the lesions were in more superior regions of the parietal lobe than the lesion in LR (Sirigu *et al.*, 1996). As reviewed in the introduction, lesions in the more superior regions of the parietal cortex often result in unilateral impairments in the control of visually guided pointing movements, particularly to targets in the visual periphery (i.e. optic ataxia). Indeed, one patient with a right parietal lesion described by Sirigu *et al.* (1996) did have 'left sided difficulties with hand movements and visually guided reaching' (p. 1567), suggestive of optic ataxia. Thus, it is perhaps not surprising that the imagery impairments in such patients are also lateralized to the same limb or region of space. In short, once again, the deficit in imagined movements mirrors to some extent the impairment in actual movements.

Unlike the patients with right superior parietal lesions (Sirigu *et al.*, 1996), LR, who has neglect associated with a right inferior parietal lesion, showed a deficit in visually guided motor imagery involving both the left and the right hand. Previous research that has explored the kinematics of hand movements in patients with neglect from right parietal lesions has revealed deficits in the timing and trajectory of visually guided movements in both limbs (Goodale *et al.*, 1990; Harvey *et al.*, 1994). Thus, it is perhaps not surprising that LR demonstrated bilateral impairments in imagined movement control. Other studies have shown that patients with right parietal lesions show deficits in initiating movements in a leftward direction and in left hemispace, even with the ipsilesional hand (Mattingley *et al.*, 1992, 1994; Hussain *et al.*, 2000). Although we observed no difference in LR's ability to imagine moving to leftward versus rightward targets, the imaging task by its very nature may not be sensitive enough to pick up subtle differences in timing. Even his actual movements did not show evidence of any directional impairment. Given that we measured a speed-accuracy trade-off for total movement time, again any subtle differences in performance would be obscured. Recently, however, we tested LR's movements with an opto-electronic recording device which allowed us to explore his movement kinematics in more detail. Using this technique, we were able to demonstrate a directional bias in visually guided pointing movements, such that leftward movements with either hand showed longer deceleration periods (unpublished data). This suggests that a more detailed analysis of the kinematics of movements would reveal subtle and perhaps spatially lateralized impairments in visuomotor control following right parietal lesions (Goodale *et al.*, 1990). Nevertheless, these impairments are likely to be seen in both limbs.

A recent neuroimaging study using high-resolution functional magnetic resonance imaging (fMRI; Gerardin *et al.*, 2000) demonstrated only left parietal activation during motor imagery. Once again, however, the task the subjects were

asked to perform in this fMRI study appears to have put demands on the praxis system rather than on the visual control of movements. To reiterate our main point: different regions of left and right parietal cortex make quite different contributions to the control of skilled actions, and as a consequence are differentially invoked in different motor imagery tasks. We would argue that the right inferior parietal cortex plays a critical role in generating (and/or updating) forward models of visually guided movements of the limbs. Thus, lesions to this region would be expected to disrupt the ability to make use of such forward models, an impairment that would be particularly evident for imagined movements in which the visuomotor system has to rely solely on the forward models.

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Selective, non-lateralized impairment of motor imagery following right parietal damage

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Abstract

Using variants of a visually guided pointing task, in which subjects make pointing movements towards targets of varying sizes, we explored motor imagery in a patient with visual neglect. When this patient actually pointed towards targets of different sizes he showed the normal correlation between movement duration (MD) and target size, such that MD increased as target size decreased. In contrast, his imagined movements did not show the same speed–accuracy trade-off observed for actual movements. This was true regardless of the hand used or the initial direction of movement (left versus right). The patient performed normally on several tasks of visual imagery, including size estimation, perceptual discrimination and localization of cities on an imagined map. This patient's performance suggests that the networks in the right parietal lobe play an important role in the generation of internal models of motor movements regardless of the hand used to perform the task.

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Primary diagnosis of interest

Hemispatial neglect

Author's designation of case

LR

Key theoretical issue

- Motor imagery after damage to right parietal cortex

Key words: neglect; motor imagery; parietal lobe

Scan, EEG and related measures

Computed tomography

Standardized assessment

Behavioural inattention test, Goldman perimeter, motor imagery inventory, visual imagery tests

Other assessment

None

Lesion location

- Right temporal, parietal and frontal cortex with a greater focus posteriorly within the temporal and parietal cortices

Lesion type

Haemorrhagic stroke

Language

English