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# Reaching movements may reveal the distorted topography of spatial representations after neglect

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## Abstract

It has been proposed that patients with spatial neglect fail to respond appropriately toward stimuli opposite their brain lesion because they have an impairment of directing attention. However, a disorder of 'intention' — or movement initiation — has also been demonstrated in this condition. Recently, the paths of neglect patients' reaches have been shown to be abnormally curved, but it is unclear whether this impairment is visual or motor. Here, we show for the first time that reaches to and from *identical* positions executed by three patients recovering from neglect are significantly more curved to visually defined targets compared to when the same targets are defined proprioceptively. These findings indicate that abnormal hand paths in neglect result from an impairment in the visual representation of space used to guide reaches but without any general failure of spatial representation of target position. Furthermore, the curved hand paths reveal how the topography of that representation is distorted in spatial neglect. © 2000 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

During reaching movements, sensory signals must be transformed into an appropriate set of motor commands. For visually guided movements, this involves transforming visual information signalling the spatial position of the target, into a motor plan specifying the sequence of postural changes required to bring the hand to the target [1]. In neurologically normal individuals, unconstrained reaching movements produce almost straight hand paths that are very gently curved [2]. The reason for this mild curvature has assumed theoretical importance as a means of differentiating between two general models of trajectory planning [2–6]. The first holds that hand paths are curved due to the *motor* constraints of limb dynamics [3,5] or limb kinematics [2,6,7]. The second, that hand paths are curved because the topography of *visual space* is curved [4,8–13]. Determining between these accounts has proven difficult.

Neurophysiological studies in the monkey, together with functional brain-imaging studies in humans, suggest that the sensorimotor transformations associated with the planning and control of visually guided action are mediated by cortical circuits linking the occipital and posterior parietal cortices, with motor regions of the frontal lobes [14–18]. A frequent consequence of damage to these circuits is the behavioural syndrome of visuospatial neglect. While neglect can occur following damage to a variety of brain regions, it is chiefly associated with damage to the inferior parietal lobule (IPL), most frequently involving the occipito-temporo-parietal junction of the right hemisphere [19].

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Neglect patients fail to respond appropriately to stimuli or events occurring within their contralesional hemispace, and may restrict eye and hand movements to objects or events occurring within ipsilesional space. Such behaviours are generally thought to result from an impairment in the ability to construct an appropriate representation of extrapersonal space [20–22], or, as a consequence of an attentional bias which favours the processing of ipsilesional stimuli [23,24]. Neglect patients may also suffer from a disorder of 'intention' however, experiencing difficulty initiating movements towards targets in the neglected hemispace [25–28]. Recently, neglect patients have also been found to produce abnormally *curved* hand paths when executing reaching movements [29–30]. Furthermore, abnormalities in reaching kinematics may frequently *persist long after the perceptual impairments associated with neglect are no longer evident* [29–31]. Consequently, the relationship of abnormally curved hand paths after right hemisphere brain damage and visuospatial neglect remain controversial and in need of clarification. The present study addresses this question by asking the following question: are abnormally curved trajectories in neglect the result of a motor impairment or due to a distortion in the visual representation of space used to guide reaches?

## 2. Methods

### 2.1. Case reports

Patient LC is a 77 year old woman who sustained a right-hemisphere infarct in February 1996. A computerised tomography (CT) scan given shortly thereafter revealed a lesion involving the right occipito-temporal cortex, together with a separate, deeper lesion involving the basal ganglia. Behavioural assessment immediately prior to our tests (May 1997) revealed a left hemiparesis, left hemianopia, and a severe left spatial hemineglect. LC was severely impaired on a range of cancellation and line-bisection tasks taken from the Behavioural Inattention Test [36]. Her cancellation errors consisted of the omission of items presented on

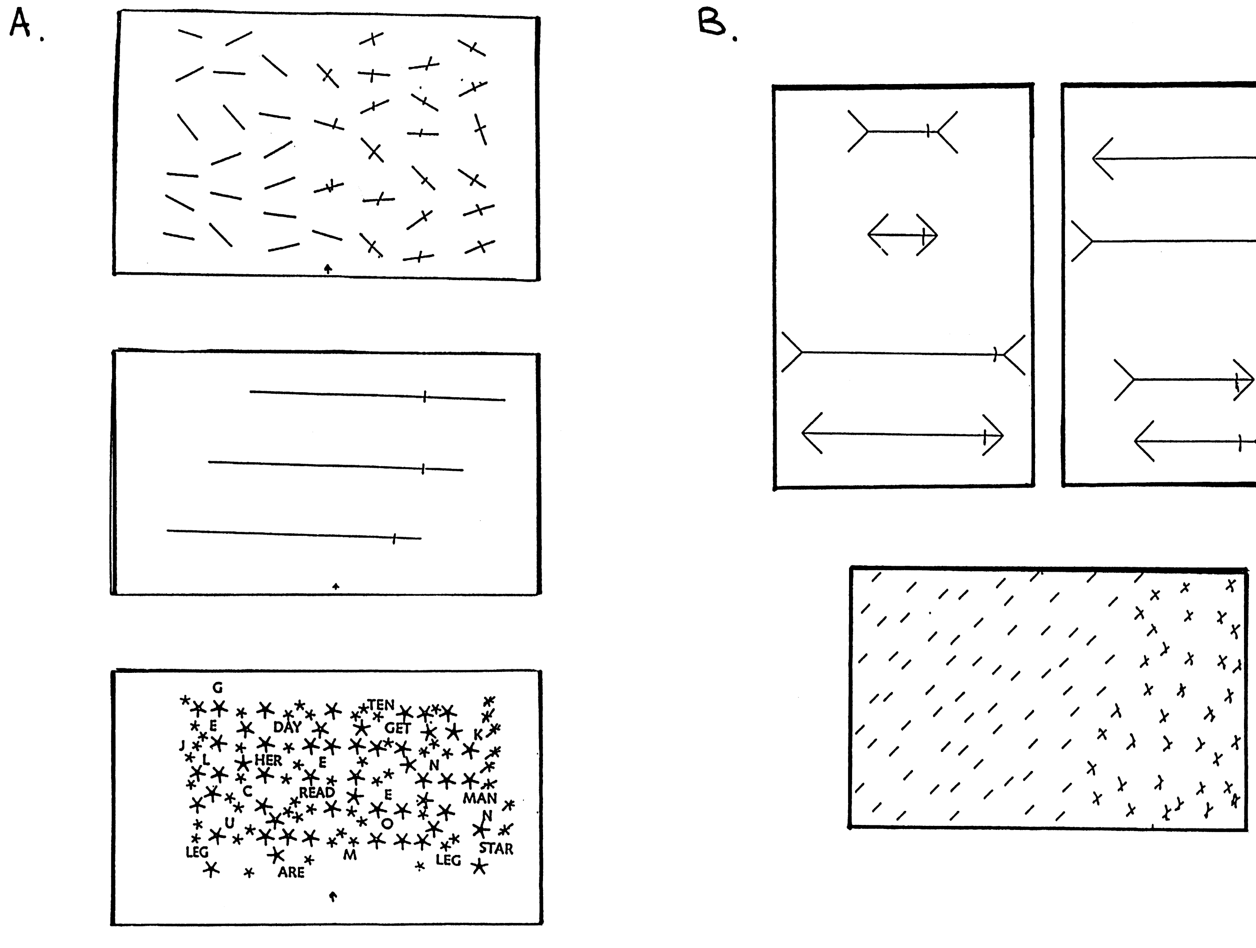

Fig. 1. (A) Representative examples of patient LC's line cancellation (upper left panel); star cancellation (bottom left panel) and line bisection (middle left panel) performance. (B) Representative examples of patient RB's line cancellation and line bisection performance.

the left. Her line bisection performance showed a consistent rightward bias. Examples of LC's performance are presented in Fig. 1. LC showed a preserved ability to draw from memory, and was unimpaired on a range of neuropsychological assessments including both memory and verbal intelligence. LC was right handed.

Patient RB is an 83 year old right handed man who sustained a right-hemisphere stroke in December 1997. A CT scan revealed an extensive haemorrhage involving the right temporo-parietal cortex, together with a partial obliteration of the right lateral ventrical. Behavioural assessment immediately prior to our tests (May 1998) revealed a severe left spatial hemineglect. RB showed no evidence of hemianopia, but was severely impaired on a range of cancellation and line-bisection tasks. As with LC, RB's cancellation errors consisted of the omission of items presented on the left, and his line bisection performance showed a consistent rightward bias. Examples of RB's performance are presented in Fig. 1. RB was unimpaired on a range of neuropsychological assessments including both memory and verbal intelligence.

Patient MH is a 72 year old right handed man who sustained a right-hemisphere infarct involving the territory of the right middle cerebral artery in February 1997. Behavioural testing shortly thereafter revealed a moderate to severe left hemineglect. However, an assessment immediately prior to our tests (May 1997) revealed no evidence of any residual neglect. Thus, MH completed identical cancellation and line-bisection tasks to those completed by LC and RB. All were completed by MH without error or rightward bias. MH was also unimpaired on a range of neuropsychological assessments including both memory and verbal intelligence.

## 3. Procedure

The patients and six right-handed, adult volunteers were each seated at a table on which rested a raised wooden board (painted matt black) containing eight holes each 6 mm in diameter. Subjects executed pointing movements, using the index finger of their right hand (the patient's *ipsilesional* hand), from a starting position on the saggital axis, to each of the eight target locations. In each case, reaching movements were made approximately 5 cm *above* the raised board. The height of subjects' reaches did not differ across conditions. Throughout the experiment subjects wore a 6 mm hemispherical passive infra-red reflective marker on the index finger of their right hand, and movements were recorded using a MacReflex optoelectronic recording device (see [10] for details). The study consisted of three pointing conditions as follows: (1) During vision/vision (VV) trials, target locations were defined *visually* by placing a small wooden 'target' dowel (coloured white) into the appropriate hole for that trial. Subjects pointed with their eyes open and were allowed to move their head and eyes freely. During V/V trials subjects' left arms were positioned beneath the target locations but were *not* in contact with the target array. (2) During vision/proprioception (VP) trials, the target array was covered by a matt black board so that there were no longer any visual cues as to the location of the target. Instead, target locations were defined *proprioceptively* by passively placing the index finger of the subject's *unseen* left hand onto the relevant drilled hole on the underside of the raised board. Subjects pointed with their eyes open so that visual information about the moving limb was available throughout the trial. (3) Proprioception/proprioception (PP) trials were identical to V/P trials with the exception that subjects were blindfold throughout. The order of presentation of the three conditions was randomised for controls, and presented in a randomised ABCCBA design for each patient. All subjects made four pointing movements to each target location in each condition making a total of 96 trials in all.

## 4. Results

We examined hand path curvature in two patients (LC and RB) who, following right hemisphere strokes, presented with severe left visuospatial neglect (Fig. 1), and a patient (MH) who had also sustained a right-hemisphere stroke producing left visuospatial neglect, but who at the time of testing, no longer showed any trace of visuospatial neglect (as assessed by clinical examination and standard neuropsychological testing). These patients were compared with a group of matched healthy control subjects. We distinguished between visual and motor components of hand path curvature by comparing reaching movements directed to visually-defined target locations against reaching movements directed to proprioceptively-defined targets (Fig. 2). As in each case, movements commenced from *identical* starting postures, and were directed to *identical* locations within peripersonal space, it follows that hand paths should not differ across these conditions if they are primarily planned in a motoric (joint- or muscle-based) coordinate system.

Prior to statistical analysis, subjects' hand paths were spatially resampled and translated, and a hand-path-curvature-index (HPC-index) computed [32]. Spatial resampling was carried out to produce hand paths which each contained 100 equally spaced spatial segments, thereby allowing comparisons between movements. It should be noted that

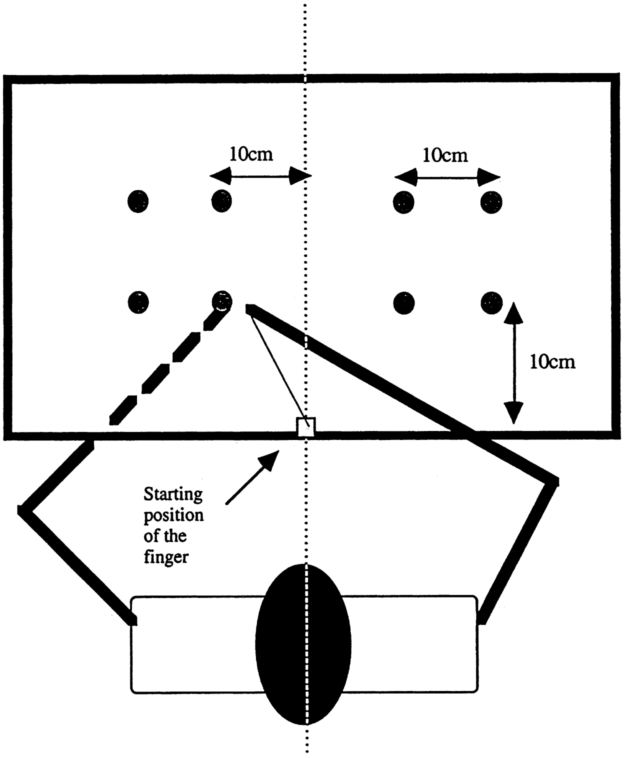

Fig. 2. Diagram illustrating the dimensions of the reaching task.

spatial resampling did not change the shape of each individual hand path, and did not result in the normalisation of movement amplitude. Hand paths were also translated spatially so that movements to different target locations within the workspace could be compared. This procedure resulted in a set of hand paths aligned along a single axis as shown in Fig. 3. This procedure is similar to that used by Haggard and Richardson [2] to compare reaches with different start and end points within the workspace. Finally, the HPC-index consisted of the *ratio* between the magnitude of the maximum lateral deviation achieved at any point during the movement (mm), and the straight line joining the kinematically-determined start and end positions of the movement (mm). Note that the HPC-index produces a measure of hand path curvature that is (1) *independent of movement amplitude*, and, (2) in which all values, regardless of whether the hand path curved leftwards or rightwards, are positive.

As leftward and rightward movements can often show a roughly mirror symmetric curvature, we carried out preliminary analyses to examine the sign of hand path curvature (HPC) in both controls and our patients, assigning positive values for rightward curving hand paths and negative values for leftward curving hand paths. In each case, data were analysed using a 3 × 2 repeated-measures ANOVA in which condition (VV, VP, and PP) and side of reach (left targets vs right targets) were factors. These analyses revealed that for the control subjects, that there was no main effects of condition ($F(2,10) = 1.3$, $P > 0.1$), or side of reach ($F(1,5) = 0.3$, $P > 0.1$). The analyses did, however, reveal a significant condition × side of reach interaction effect ($F(2,10) = 11.1$, $P < 0.01$). Planned comparisons using linear contrasts revealed that there was a significant effect of side for reach during reaches to visually-defined (VV condition) targets ($F(1,10) = 25.0$, $P < 0.0025$). Furthermore, the analysis confirmed that during VV reaches, hand paths curved in *opposite directions* for reaches directed with the right hand toward right (mean = 0.03; rightward curvature) and left (mean = −0.03; leftward curvature). There were no significant effects of side of reach during VP ($F(1,10) < 0.1$, $P > 0.1$) or PP ($F(1,10) = 2.4$, $P > 0.1$) reaches.

Similar ANOVAs were also carried out for each individual patient. These analyses revealed the following effects. Firstly, unlike controls, all three patients showed a clear difference in HPC for reaches directed toward rightward and leftward target locations (main effect of side of reach, minimum $F(1,15) = 31.3$, $P < 0.0001$). There was a significant main effect in the case of patient RB ($F(2,30) = 10.5$, $P < 0.0025$), whereas the condition × side of reach interaction effect was significant for patients LC and MH (minimum $F(2,30) = 19.5$, $P < 0.0001$). To understand the basis of these effects, planned comparisons examining the effect of side of reach for each condition were carried out. These results indicated that the hand path curvature of patients LC and MH looked like exaggerated versions of that seen for control subjects. That is, their hand paths curved in *opposite directions* for reaches directed with the right hand toward right and left target locations. In contrast to controls, reaches into left and right space were significantly different in all conditions (minimum $F(1,15) = 8.7$, $P < 0.01$). Patient RB who, based upon clinical assessment had the most severe neglect at the time of testing, showed a different pattern of results. The planned comparisons revealed that, unlike the controls and patients LC and MH, in the VV condition *only*, patients RB's reaches to leftward and rightward target locations curved in the same direction, both showing a clear *rightward curvature*. Furthermore, this curvature was greater for reaches directed to rightward targets ($F(1,15) = 5.8$, $P < 0.05$). For reaches executed to proprioceptively defined target locations (VP and PP conditions) reaches curved in *opposite directions* as was observed in controls.

The above results suggest that irrespective of sign, the hand paths of RH lesion subjects are more curved than for controls, and that curvature increases when reaching to visually defined targets. To test this, we translated all hand paths so that they were of the same sign. Our results confirmed that hand path curvature

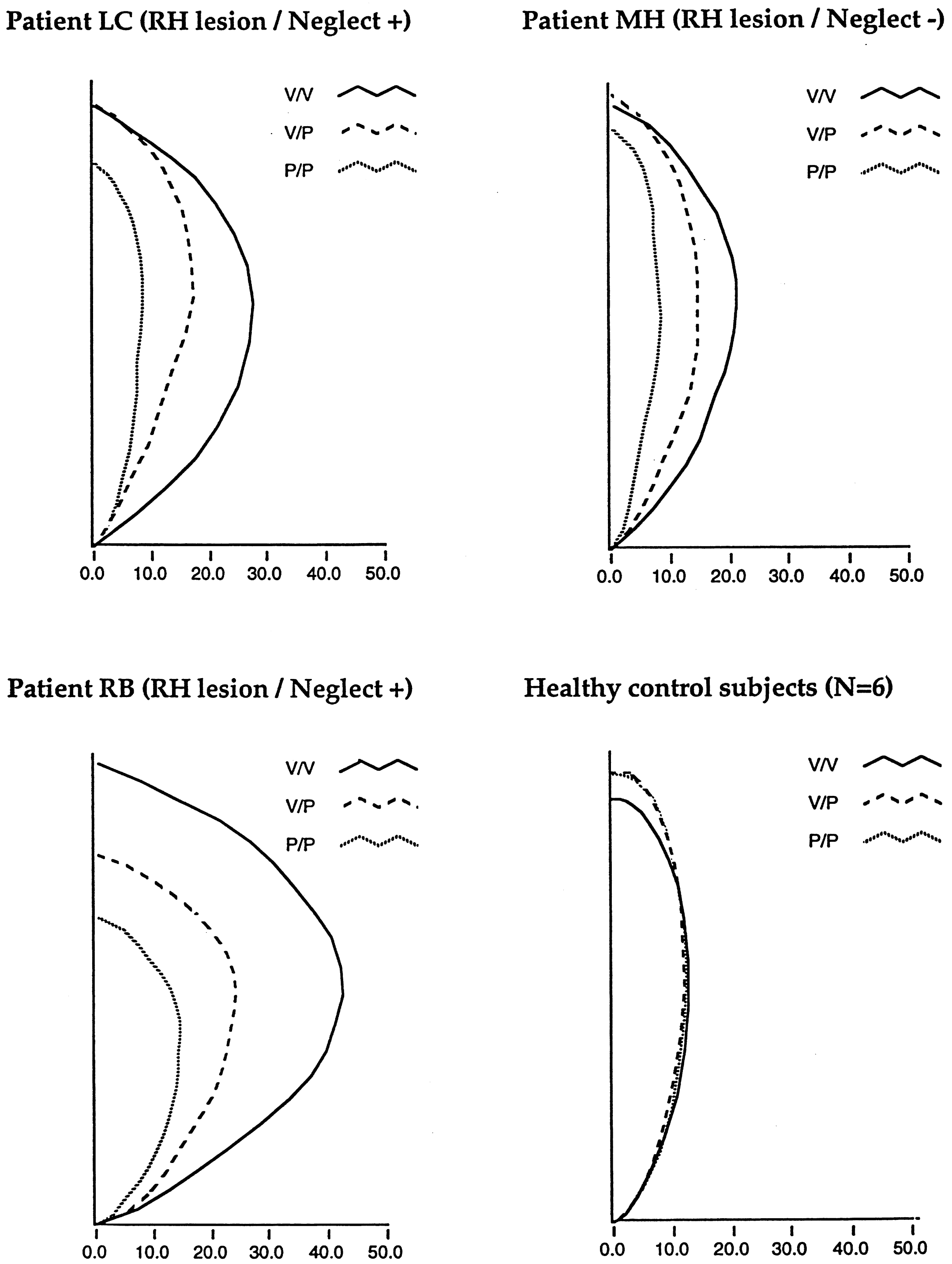

Fig. 3. Illustrates mean hand paths for control subjects and patients in each movement condition.

was significantly increased in each of our patients when vision was available. Mean hand paths for each condition are presented for comparison in Fig. 3. The mean HPC-index for each condition is presented in Fig. 4. For healthy control subjects, the mean hand path curvature did not differ across movement conditions ($P = 0.8$), and was not different for leftward compared to rightward reaches ($P = 0.1$). In contrast, for the right hemisphere lesion patients (LC, RB, and MH) hand path curvature increased significantly for visually defined reaches (V/V condition) compared to reaches made to proprioceptively defined targets (P/P condition) (patient LC: $F(1,15) = 100.8$, $P < 0.0001$; patient RB: $F(1,15) = 14.2$, $P < 0.001$; patient MH:

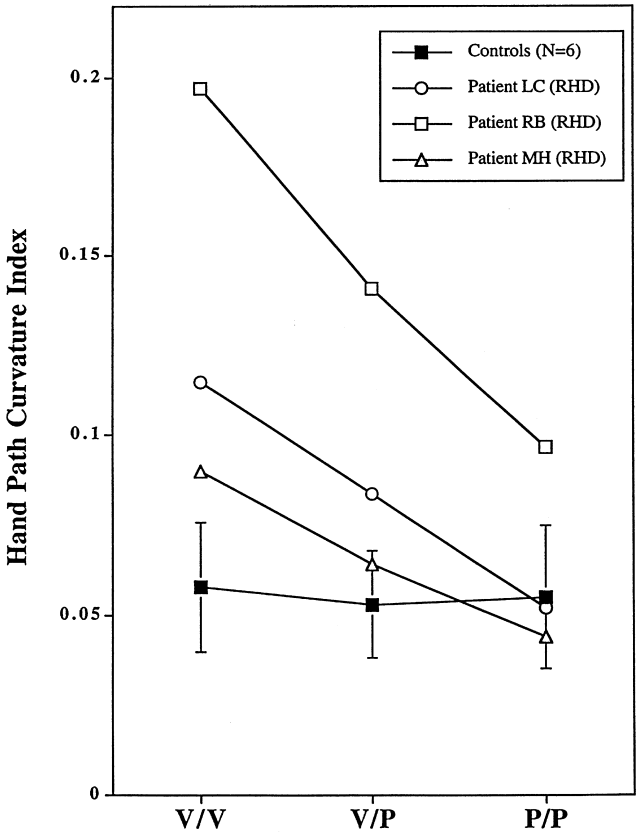

Fig. 4. The graph shows the mean hand-path-curvature-index (HPC-index) for control subjects and patients in each movement condition. The HPC-index is computed by taking the *ratio* between the magnitude of the maximum lateral deviation achieved at any point during the movement (mm), and the straight line joining the kinematically-determinined start and end positions of the movement (mm). This produces a measure of hand path curvature that is independent of movement amplitude, and in which all values, regardless of whether the hand path curved leftwards or rightwards, are positive. Error bars represent the standard error of the mean.

$F(1,15) = 26.7$, $P < 0.0001$). There was no significant difference in the degree of curvature observed for reaches executed in left and right hemispace.

Patients LC and MH also showed a significant increase in hand path curvature when reaching to proprioceptively defined targets when vision of the moving hand was available (V/P condition) (patient LC: $F(1,15) = 26.8$, $P < 0.0001$; patient MH: $F(1,15) = 5.2$, $P < 0.05$). While the right hemisphere lesion patients' hand path curvatures were significantly different from those of the controls in the VV condition (more than two standard deviations greater than that observed for controls), this was not the case for proprioceptively defined movements.

The differences in hand path curvature observed for visually guided reaches were not always accompanied by differences in movement end-point accuracy. Thus, patients LC and MH both produced end-point accuracy values that were comparable to those of controls (controls = 4.5 mm; LC = 5.8 mm; MH = 4.9 mm). However, it is of interest that, in contrast to control subjects who produce slightly hypermetric movements for reaches to proprioceptively defined targets (known as the 'overlap effect' [33,34]), each of the RH lesion patients produce *hypometric* movements when reaching to target locations defined by proprioceptive cues (see Fig. 3), and in some cases this hypometria was quite substantial (e.g., RB).

## 5. Discussion

These results demonstrate that reaches made under visual guidance are significantly more curved than those made without vision. As the starting position and target locations were identical in the proprioceptively-defined (PP) and visually guided (VP and VV) conditions, differences in hand path curvature cannot readily be explained by models of trajectory planning which hold that reaching movements are primarily planned in *intrinsic* (joint- or muscle-space) coordinates [2,4,6]. Therefore, the underlying cause of our patients' misreaching is not due to an impairment of motor control but rather to a spatial distortion in the visual representation of space used to plan movements.

Previous studies of neglect have suggested there is a distortion of the representation of space. For example, evidence in favour of a spatial compression [21] or egocentric rotation of this representation [35] have each been provided. We suggest that the hand paths of the patients we have studied may effectively 'trace out' the distorted topography of the visual representation used to guide reaching movements. Further investigation will be necessary to determine whether this topography coincides with the distorted representation of space used to make *perceptual* judgements in this condition.

But why should the visual representation of space used to guide reaching movements be distorted in neglect? Previous studies in healthy adults have shown that allocating visual attention to a non-target object or region of space produces deviations (increased hand path curvature) in the spatial paths of both hand [11] and eye movements [12]. It has, therefore, been suggested that visual mechanisms may normally operate to create a dynamic representation of peripersonal space which is sculpted by attentional mechanisms into selected (target) and inhibited (non-target) regions [7,10–12]. Our findings demonstrate that analogous (but more marked) changes in hand path curvature can occur in visuospatial neglect, and that such changes may persist long after clinical and perceptual indices of visuospatial neglect are no longer apparent. The relationship between the attentional and visuomotor deficits in neglect may therefore be closer than first supposed.

One question raised by the findings of this and previous studies is why patients who show such marked curvature when reaching under visual guidance should nevertheless produce accurate reaching movements. That is, distortions in the hand path typically occur in mid-reach but decrease as the patient's hand approaches the target. One possible explanation for this pattern is that such movements are based upon an erroneous motor command signal which is then corrected, on-line, during movement execution and is based upon an error signal indicating the moment-by-moment changes in the hand relative to the target. Within this view movements are anchored at both the beginning and the end of the movement, but are less so during mid-reach when they may be maximally susceptible to visuospatial distortion.

We have recently found some support for this suggestion in a study of reaching movements after adaptation to rightward displacing prisms [37]. In that study, subjects initially underwent a period of prism adaptation in which they executed a large number of pointing movements while wearing rightward displacing prisms. After this adaptation period, we examined hand path curvature for reaching movements executed by subjects using their adapted hand under VV, VP, and PP conditions (in the latter two conditions movements of the adapted hand are directed to target locations specified by the non-adapted hand). While reaches with the adapted hand were spatially accurate when directed to visually defined (VV condition) targets (i.e., end-point errors were negligible), hand paths were nevertheless substantially more curved than reaches executed under PP conditions. Furthermore, maximum curvature occured during mid-reach.

A visual error signal indicating moment-by-moment changes in the spatial separation between the moving hand and the target cannot explain subject's performance in the VP condition. However, it could be argued that in this case subject's were able to compute an error signal indicating the spatial separation of the hand and target based upon the seen position of the hand and the felt position of the target (indicated by the unseen hand). The VP condition is extremely interesting for several reasons. Firstly, it is usually assumed that target detection is based on vision, or, when vision is not available such as in the PP condition, solely on proprioceptive cues. Recent studies indicate that this may not be the case however, as they demonstrate that somatosensory detection can be enhanced by visual cues in circumstances where vision cannot possibly convey task relevant information [38]. An analagous finding was obtained in the current study insofar as we found that end-point accuracy was substantially increased in the VP condition compared to the PP condition even though vision of the table surface could not possible cue the subject to the position of the target hand beneath the table surface (means for control subjects: PP = 37 mm vs VP = 27 mm; $F(1,10) = 9.1$, $P < 0.01$).

We recently obtained converging neuropsychological evidence demonstrating that vision can increase end-point accuracy in the VP condition [39]. We have now studied two patients who, following a stroke, had suffered unilateral somatosensory impairments to one of their upper limbs. Both patients were asked to execute reaching movements using their non-impaired hand to a target location defined by their impaired hand. In the PP condition patients were blindfold, whereas, in the VP condition patients see the table surface but not the target position signalled by the hand beneath the table. We found that end-point accuracy was substantially improved in both patients in the VP condition.

Finally, as Figs. 3 and 4 indicate, in the VP condition of the current study, hand path curvature was substantially reduced in the patients, but *not* to the same levels as for the PP condition. Instead, the curvature observed in the VP condition appears to approximate the mean of the VV and PP conditions combined. Convergent evidence for this finding was also obtained in the prism adaptation study described above [37]. In that study we also found that, for healthy subjects reaching with their adapted hand, the hand path curvature index for reaches executed under VP conditions was approximately mid-way between the means for the PP and VV conditions.

The ideas outlined above are preliminary, and much further investigation is required to work out the mechanisms leading to the abnormal hand path curvature observed in neglect. However, the data presented here indicate that our patients' misreaching is not inherently a 'spatial disorder', since they are clearly capable of planning and executing movements of comparable curvature to controls when such movements are planned and controlled proprioceptively. Consistent with this observation, investigations of monkey parietal cortex have demonstrated that different regions of parietal cortex are involved in directing either visually guided reaching movements or reaches executed to targets defined by proprioceptive cues [16].

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