A STUDY OF VISUOMOTOR BEHAVIOUR IN NORMAL AND BRAIN LESIONED HUMAN SUBJECTS, WITH SPECIAL REFERENCE TO LINE BISECTION PERFORMANCE IN PATIENTS WITH HEMISPATIAL NEGLECT

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A Thesis Submitted for the Degree of PhD
at the
University of St Andrews

1994

A Study of Visuomotor Behaviour in Normal and Brain Lesioned Human Subjects, with Special Reference to Line Bisection Performance in Patients with Hemispatial Neglect

A Thesis Presented by

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to

THE UNIVERSITY OF ST. ANDREWS

In Application for the Degree of

Doctor of Philosophy

March 1993

Th B418

Zum Andenken an meinen Vater

Declaration for the Degree of Ph.D.

I, Monika Harvey, hereby certify that this thesis has been composed by myself, that it is a record of my own work, and that it has not been accepted in partial or complete fulfilment of any other degree of professional qualification.

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I was admitted to the Faculty of Science of the University of St. Andrews under Ordinate General No 12 on the first of October 1989 and as a candidate for the degree of Ph.D. on October 1990.

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Acknowledgements

First of all I would like to thank David Milner for his outstanding supervision of my thesis. He not only enabled me to work efficiently and independently (although dealing professionally with day to day problems) but provided a stimulating environment which made doing the research very exciting. I am very grateful to the neurologists Richard Roberts and Ronald McWalter who were very helpful in giving me access to their patient files and recruiting subjects. Further thanks goes to Richard Roberts for his proficient assessment of CT-scan data and to all subjects for repeatedly participating in the experiments. A big thank you also goes to Michael Oram for his computer programming over the last three years and more importantly for being amazingly adept in guessing what I needed doing from my (mostly incoherent) descriptions. I am also indebted to the workshop especially Malcolm McCandles, Ken Munro and Brian Kirk for providing me with all the necessary equipment. Moreover special thanks goes to Brian Kirk for putting extra hours into dealing with the hopelessly temperamental Pluto Graphics System. Another big thank you also goes to David Matthews for joining me in the recruitment of patients but also for creating (in quick succession) relaxed, stressed, happy, depressed, gossipy or silent atmospheres in the office which proved especially useful in the rather tedious writing up stage. In the same vein thanks goes to David Carey for providing me with useful literature but also making me realize how hopelessly little I know.

I am very grateful to George Ettlinger for encouraging me to go to Britain and at the same time like to thank all my German friends (especially Antje Rauscher and Manfred Stenzel) for putting up with my homesickness in endless telephone calls. I also feel very grateful towards my sister and 'Oma' but especially my mother for constant help and support in all my decisions. Finally a big thank you to my husband Andy for helping me with all the figures but most importantly for encouraging me in my work and putting up with all my depressions and tantrums.

CONTENTS

ABSTRACT

In Experiments 1 to 8 an attempt was made to examine the nature of the displacements found in the traditional line bisection test when applied to normal (right-handed), as well as brain lesioned subjects. The problem with this test is that it invariably confounds perceptual and motor components which might both contribute to the observed errors. However, use of the 'landmark task' enables an examination of perceptual effects in isolation. It was found that five out of six neglect patients judged the left half-line of a centrally bisected line as shorter than the right half-line. Moreover, it was consistently shown that cueing strongly influenced judgements in normal and left and right hemisphere lesioned subjects (without neglect) in that it caused them to overestimate the cued part of the line. It was argued that the perception of relative size is subject to systematic distortion as a function of this selective attention within the visual field. Neglect patients may present an abnormal example of this attentionally-induced illusion in that their attentional resources may be abnormally biased towards the ipsilesional space. The result of this imbalance may be to cause, quite directly, a gross abnormality of size perception. Nonetheless one of the neglect patients did not show spatial misperception but spatially misdirected actions, in line with what has been described as directional hypokinesia.

Experiments 9 to 12 were designed to demonstrate any possible contribution the right hemisphere might make to visuomotor control, but the data on normal subjects gave little indication of a specific right hemisphere involvement in such tasks. Neither use of a spatial bisection task, nor absence of visual feedback of the moving hand or arm seemed to produce left hand advantages on the dependent measures. On the other hand, RCVA patients proved to be impaired in their reaching behaviour in that they erred systematically to the right of the true target over all three spatial positions, in the absence of visual feedback. The bias was interpreted as a pure example of directional hypokinesia.

CHAPTER ONE

SYMPTOMATOLOGY OF UNILATERAL SPATIAL NEGLECT

Among the behavioural disorders found in patients with hemispheric dysfunction unilateral spatial neglect is one of the most striking. In its most extreme forms, a patient may deny that the involved limbs are his own and object to their presence in his hospital bed. Other patients may fail to shave or dress the neglected side (Kolb and Wishaw, 1980). Although the terminology varies among different authors (Milner, 1987) four major component clinical symptoms are generally distinguished in patients showing unilateral spatial neglect: hemispatial neglect, hemi-inattention, sensory extinction and hemiakinesia (Heilman and Valenstein, 1979; Heilman *et al.*, 1985a; Damasio and Geschwind, 1985).

Hemispatial neglect can be seen when patients are asked to perform a variety of tasks in space. Patients showing this symptom would neglect the hemispace contralateral to their lesion. The examples given before (failure to dress on the affected side or recognize the affected limbs as one's own) are the most dramatic behavioural consequences. Others are found in tasks such as drawing or copying a picture where the patient would omit details on the side contralateral to the lesion, i.e. drawing or copying only half the picture. The tests that are mostly used in a clinical context are cancellation tasks (Albert, 1973) where the patient is asked to cross out lines that are drawn randomly on a page. Failure to cross out on one side of the page would indicate hemispatial neglect. In the line bisection task, also commonly used, the patient is asked to bisect various horizontal lines in the centre. Patients with hemispatial neglect will usually make their mark to the side of the midline ipsilateral to their lesion. When asked to draw a clock-face and put the numbers on, patients with neglect will only write on one side of the clock: they may write in only the numbers that belong on that side or they may write all twelve numbers on one side. Recent research has demonstrated that hemispatial neglect is not only limited to the visual modality but occurs in the tactile and auditory modalities as well (De Renzi *et al.*, 1970; De Renzi *et al.*, 1989a; Chedru, 1976; Halsband *et al.*, 1986). The finding that hemispatial neglect also extends to internal representations was elegantly proved by Bisiach and colleagues (1978; 1981) in demonstrating that patients fail to retrieve the left-sided components of a reconstructed visual image of a familiar scene.

The second symptom group, *hemi-inattention*, refers to a lack of awareness and responsiveness to unilateral sensory stimuli presented to the side contralateral to the lesion, which cannot be accounted for in terms of a sensory loss (Milner, 1987). But unlike a patient with hemianesthesia or hemianopia, a patient with hemi-inattention is able to detect the stimulus when his attention is directed to that side. There seems to be a disorder in the ease with which a stimulus contralateral to the lesioned side is able to attract 'automatic' attention. Additionally, although patients are most inattentive to stimuli contralateral to their lesion, it is not unusual for them also to be inattentive to ipsilateral stimuli, although the ipsilateral neglect is less severe (Heilman *et al.*, 1985a). Testing for hemi-inattention involves presentation of single stimuli in the visual, auditory or somesthetic modality to the affected and unaffected side of the patients' body in random order. Ideally stimuli should be presented repeatedly, as some patients who initially do not show inattention may do so after repeated stimulation.

Most patients suffering from a stable lesion later improve in their behaviour. So although they might initially ignore stimuli presented contralateral to their lesion they eventually detect these stimuli correctly. When given bilateral simultaneous stimulation, however, they often fail to report the stimulus presented on the side opposite the lesion. This phenomenon is called *sensory extinction* and apart from occurring in the visual modality can also be found in the tactile and auditory modalities (Loeb, 1885; Oppenheimer, 1885; Bender, 1952; Heilman *et al.*, 1970), and is reported even across different sense modalities (Denny-Brown *et al.*, 1952). This seems to suggest that sensory extinction includes all instances where attention drawn to one side prevents detection of the stimuli on the other (Milner, 1987). Indeed Posner *et al.* (1980) demonstrated an extinction like effect when attention is misdirected using a central symbolic cue. Testing for extinction is similar to tests used for inattention, but to test for extinction, unilateral stimuli should be randomly interspersed with bilateral simultaneous stimuli. Patients would then fail to report the stimulus presented to the contralesional side under the latter conditions.

The symptoms grouped under *hemiakinesia* can be described as a reluctance or failure to make a movement, or as a delay in initiating a movement, in the absence of any clinical evidence for weakness or paralysis (Milner, 1987). Heilman and Valenstein (1979) claim that hemiakinesia is not limited to the extremity contralateral to the lesion but may be seen for any response originating in the hypoaroused (lesioned) hemisphere i.e., a deficit to respond with either limb (or head or eyes) towards the contralateral side of the lesion. They later refer to this as 'directional hypokinesia' (Heilman *et al.*, 1985b).

Apart from not attending (hemi-inattention) or not showing a motor response (hemiakinesia) towards a stimuli contralateral to the lesioned side some patients also tend to mislocate a contralesional stimuli as ipsilateral. For example a tactile stimulation to one half of the body would be perceived by the subject to be on the other half, usually in a somewhat symmetrical region. This symptom has been reported by a number of authors (Bender *et al.*, 1949; Hecaen, 1972; Heilman and Valenstein, 1979) and is referred to as *allaesthesia*.

It has also been found in the auditory and visual modality where an auditory and/or visual stimulation to the affected side will be reported, or pointed to, on the other side (Brain, 1941; Bender *et al.*, 1949; Joanette and Brouchon, 1984).

HISTORICAL BACKGROUND AND THE ISSUE OF LATERALITY

Regarding the historical background, unilateral spatial neglect has been widely described since the early twentieth century. Although initially observed by Oppenheimer (1883), Holmes (1918) and Riddoch (1935), it was first discussed in detail by Brain (1941; 1945). In 1941 he reported three patients with large right parietal lesions and a disorder of route-finding which he attributed to '...an inattention to, or neglect of the left half of visual space.' He also suggested that this '...agnosia for the opposite half of space' was largely restricted to patients with minor (usually right) hemisphere lesions (Brain, 1945). However, he also pointed out that as the syndrome was a consequence of parietal lobe damage, the apparent absence of the same symptoms in patients with lesions to the dominant (usually left) hemisphere might be due to masking from other effects such as severe aphasia, disorientation or different types of agnosia.

Since this early work of Brain the issue of laterality has been a prevailing theme: does neglect for one side of space occur more frequently with right- than with left- sided lesions, and if so, what significance can be attributed to such a bias (Halsband *et al.*, 1985)?

Brain's view that unilateral visuo-spatial neglect is predominantly a manifestation of right hemisphere damage was supported by subsequent findings of McFie and Zangwill (1960) and Hecaen (1962; 1969). Hecaen (1962) detected the syndrome in 33.8 per cent of 154 right hemisphere lesioned patients but only in 1.9 per cent of 206 left hemisphere lesioned patients. Similarly McFie and Zangwill (1960) compared cases of constructional disability due to left hemisphere damage with a group of previously reported right hemisphere lesions (Paterson and Zangwill, 1944; 1945; McFie at al., 1950; Ettlinger *et al.*, 1957). They found that left-sided visuo-spatial neglect had been present in 14 of the 21 right hemisphere lesioned patients but right-sided neglect only in one of the eight left hemisphere lesioned patients. However, in contrast to these studies Battersby *et al.* (1956) who specifically looked for evidence of visuo-spatial neglect in 85 patients with space-occupying lesions found no significant difference as to the side of the lesion. Although they found the syndrome in 29 per cent of patients with non-dominant lesions and only in 9 per cent of patients with dominant lesions they concluded that this difference was due to the fact that severe aphasia had precluded adequate testing in a further 29 per cent of the patients with dominant hemisphere lesions. So looking at it the opposite way round, they judged 62 per cent of the left hemisphere cases and 59 per cent of the right hemisphere cases to be without neglect (in the remaining 12 per cent of right hemisphere cases the diagnosis of neglect was uncertain). Gainotti (1968) then attempted to study the same problem by means of a battery of tests simple enough to be administered to all patients, including severe aphasics. He found that unilateral spatial neglect is not only significantly more frequent, but also definitely more severe in patients suffering from lesions of the right hemisphere. This was only partly confirmed by Costa *et al.* (1969) who also found a higher incidence of neglect in right hemisphere lesioned patients, but contrary to Gainotti reported that severity and patterns of deficit were alike in both left and right lesioned groups.

Various factors may underlie these diverging findings. Especially in the older studies, authors failed to specify their criterion for the diagnosis of unilateral spatial neglect, so some differences must have been due to case selection. Also Oxbury *et al.* (1974) point out that the two hemisphere groups of McFie and Zangwill differed in the incidence of both visual field defect and papilloedema, suggesting that the right hemisphere lesions may have been bigger than the left. Both Battersby *et al.* (1956) and Hecaen (1962) claimed that unilateral spatial neglect was associated with widespread cerebral dysfunction and in both series neglect was associated with a high incidence of hemianopia. A second critical factor regards the locus of the responsible lesion. Halsband *et al.* (1985) note that during the period of 1941-1957 a consensus emerged that '...parietal damage was sufficient to give rise to the manifestions of neglect, although the advantages of modern computer-based radiological methods were not then available to exclude additional damage elsewhere'. In more recent research it has been reported that neglect also arises after temporo-occipital lesions (Battersby *et al.*, 1956), frontal lesions (Chedru *et al.*, 1973; Van der Linden *et al.*, 1980) and subcortical lesions such as the striatum (Healton *et al.*, 1982; Stein & Volpe, 1983), the thalamus (Henderson *et al.*, 1982) and the claustrum (Ettlinger, 1984). Vallar and Perani (1986) carried out an extensive CT-scan study on 110 patients with right hemisphere stroke lesions. They found that in patients with purely cortical lesions neglect was more frequently associated with retrorolandic rather than frontal lesions. The inferior parietal lobule seemed to be the area most frequently involved. Regarding subcortical damage neglect occurred more often when grey nuclei (such as the basal ganglia or thalamus) were damaged, whereas lesions to the subcortical white matter were rarely associated with neglect. Similarly Heilman (1983) pointed out from CT-scan evidence that the right inferior parietal lobule - together with the temporo-parieto-occipital junction - is a critical area for inducing neglect.

Finally Gainotti *et al.* (1972; 1986) were able to demonstrate that task is also an important factor regarding the differences between right and left hemisphere damage on neglect. For example data obtained by Gainotti *et al.* (1972) and Colombo *et al.* (1976) showed that when the task required attention to be focused on small portions of space, then neglect for one half of the stimulus was almost only observed in right hemisphere damaged patients. On the contrary, when the task required exploration of large displays, no difference was observed between right- and left hemisphere damaged patients, i.e. contralateral neglect was shown in both groups. Similarly Gainotti *et al.* (1986) reported that whilst both left- and right hemisphere damaged patients showed an asymmetric exploration of space in a 'Searching for Animals test', on the other hand only right hemisphere damaged patients showed a clear tendency to omit figures lying on the left side of the composite pattern in an 'Overlapping Figures test'.

In conclusion, although the issue of laterality is by no means solved most authors now consider unilateral spatial neglect to have a higher incidence and greater severity following right rather than left hemisphere lesions (Critchley, 1953; Gainotti, 1968; 1986; Oxbury *et al.*, 1974; De Renzi, 1982; Heilman, 1983).

THEORETICAL EXPLANATIONS OF UNILATERAL SPATIAL NEGLECT

So assuming that neglect for one side of space does occur more frequently and more severely with right hemisphere lesions, what significance can be attributed to such a bias? The nature of the defect in unilateral spatial neglect has preoccupied authors as far back as the early work of Brain (1941; 1945). Halsband *et al.* (1985) point out that he and also Duke-Elder (1949) implied a selective cognitive disorder *independent* of both sensory and general intellectual disturbances. This position was essentially accepted by Zangwill and his co-workers (McFie *et al.*, 1950; Ettlinger *et al.*, 1957) and also by Hecaen and co-workers (Hecaen *et al.*, 1956; Hecaen, 1969), but a different view was taken by Bay (1950) and by Battersby *et al.* (1956). They claimed that a combination of sensory defects and intellectual deterioration could account for the disorder. However Ettlinger (1956) failed to obtain evidence for a strong association between various measures of visual efficiency and spatial defect. Critchley (1949) also found that, although extinction was often (but not always) accompanied by some primary sensory deficit, it was disproportionate to it. Moreover, directing a patients 'attention' to the source of stimulation could influence the perceived sensation. He argued that 'inattention' was a better term than 'extinction'. Direct evidence that extinction is not purely a sensory disorder was provided by Volpe *et al.* (1979), who demonstrated accurate perception of 'extinguished' (neglected) material when patients with right parietal damage, were required to make same/different comparisons of stimuli, presented simultaneously to the intact and extinguished hemifields.

Although Critchley's contention that a failure at the sensory level is not a sufficient explanation of the symptomatology of neglect has not been consistently confirmed, the belief that attention rather than lack of sensory information is the basis of unilateral spatial neglect has widely influenced the literature.

For instance Bisiach and Luzzatti (1978) convincingly demonstrated unilateral spatial neglect on purely conceptual tasks, i.e. tasks that are soluble without sensory inflow and which contain an inbuilt control condition indicating the availability in memory of all necessary information. They asked patients with unilateral spatial neglect from right hemisphere damage to describe from memory a highly familiar scene. In one condition they were to take the perspective of facing a cathedral located at the end of the major piazza in Milan. In a second condition they were to take the perspective of facing away from the cathedral. In the patients' descriptions of the piazza, left sided details were omitted *depending on the perspective taken*. From these findings and a subsequent study (Bisiach *et al.*, 1981) the authors concluded that mental representation of the environment is structured topographically and seems to be mapped across the brain (representational map hypothesis); the processes by which the visual image is build up may be split between the two hemispheres and with right hemisphere damage there is a representation disorder for the left half of this image. This conceptual form of neglect described by Bisiach and colleagues poses difficulties for those investigators who argue for a direct association between unilateral spatial neglect and oculomotor disorders (Chedru *et al.*, 1973; Girotti *et al.*, 1983; Johnston and Diller, 1986). Smith and Latto (1982) for example, proposed that left- and right- sided cerebral lesions are equally likely to be associated with neglect; the left parietal patients however can compensate for their neglect by recourse to scanning, whereas the right parietal patients fail to compensate in the same way because their eye movements are disordered. Indeed eye-movement studies of visual search, line bisection and picture inspection (Ishiai *et al.*, 1987; Huber *et al.*, 1988; DeRenzi *et al.*, 1989b; Gainotti *et al.*, 1989) have shown that, in neglect patients, fixations tend to be crowded to the right of the stimulus. Moreover, a recent experiment by Hornak (1992) revealed further that even in the dark, fixations of neglect patients are confined almost entirely to the right hemispace. However, impaired scanning patterns cannot account for conceptual neglect unless one assumes that such patients are impaired on internal scanning movements as well. The representational hypothesis however has difficulties in explaining the findings of Lavadas *et al.*, (1990). They reported that patients with left spatial neglect, when being presented with stimuli that occupy left-right relative positions in the ipsilesional field, respond to the rightmost stimuli quicker than the left. Bisiach and Vallar (1988) have made an attempt to account for this finding by suggesting a representational gradient, whose strength would go from a maximum in the extreme position of the ipsilesional field to a minimum in the extreme position of the contralesional field .

Ladavas *et al.* (1990), however, consider their findings in full agreement with Kinsbourne's attentional hypothesis: Kinsbourne (1977; 1987) postulated that each hemisphere is responsible for shifting attention in a contraversive direction, either in the ipsilateral or contralateral half of space. Damage to one hemisphere would consequently unbalance the attentional system in favour of shifts contraversive to the intact side. He assumes that in intact humans the rightward bias caused by the left hemisphere is stronger than the leftward bias caused by the right hemisphere, reporting that newborn babies orient about four times as frequently to the right as to the left in their spontaneous behaviour (Siqueland and Lipsitt, 1966; Turkewitz *et al.*, 1968). This asymmetry in turning tendency has two consequences. First the right hemisphere would exert a more balanced control over both sides of space. Secondly, a right hemisphere lesion would release a stronger contraversive bias from the left hemisphere. For this view it must be accepted that in normal brain function, the hemisphere contralateral to the stimulus will inhibit the ipsilateral hemisphere from acting to the stimulus. Thus, the presence of a unilateral lesion would imbalance this reciprocal inhibition and result in an increase in the activity of the intact hemisphere (Kinsbourne, 1970). Kinsbourne's hypothesis has been supported by a number of authors (Ladavas, 1987; Ladavas *et al.*, 1989; Altman *et al.*, 1979; Bisiach *et al.*, 1984; Corin and Bender, 1972; De Renzi *et al.*, 1989b) but has also been opposed by others (Leicester *et al.*, 1969; Chain *et al.*, 1979; Joanette and Brouchon, 1984; Kashiwagi *et al.*, 1990).

These investigators favour Heilman's 'directional hypokinesia' hypothesis. According to Heilman and his colleagues (1979; 1985a;b; 1987) each side of the brain possesses its own activating system and, when one of these two systems is lesioned, the corresponding hemisphere cannot properly process sensory information and organize motor responses. So with the damaged hemisphere being hypoaroused there is a selective loss of the orienting response to the space contralateral to the lesion and the hemisphere cannot prepare efficiently for action, i.e. is hypokinetic. To explain why unilateral spatial neglect occurs more frequently following right than left hemisphere lesions, he postulates that the left hemisphere controls orienting to stimuli on the right side of space only, whereas the right hemisphere controls orienting towards both sides. Consequently the right hemisphere can compensate for left hemisphere damage but the left hemisphere cannot compensate for right hemisphere damage (regarding processing of sensory information). This claim was confirmed in an experiment by Heilman and Van den Abell (1980) where they presented lateralized visual stimuli to 12 normal subjects and recorded their electroencephalograms. They reported that although the left parietal EEG desynchronized most after right-sided stimuli, the right parietal EEG desynchronized *equally* after right or left stimuli.

Consistent with this theory is the finding that patients with right hemisphere lesions show ipsilateral as well as contralateral neglect in visual and manual exploration tasks, whereas left hemisphere lesioned patients do not show ipsilateral neglect (Weintraub and Mesulam, 1987). Similarly Leicester *et al.* (1969) and Chain *et al.* (1979) have shown that the severity of neglect is generally greater when the ability demanded by the task has to be carried out by the damaged (right) hemisphere (e.g. a visuospatial rather than a verbal task).

The approaches of both Heilman and Kinsbourne have typically been applied to data obtained with overt motor response measures, such as eye-movements or pointing responses. However Posner and his colleages (Posner, 1980; Posner *et al.*, 1980) adopted a 'covert orienting' paradigm in which spatial attention is manipulated by presenting subjects with visual cues that specify to-be-attended locations, followed by targets that appear either at the cued (primed) location, or targets that appear at unattended locations. The spatial cue is termed *valid* when cue and target locations are coincident and *invalid* when they are not. Posner and his colleages found that in normal subjects response latencies are significantly faster on the valid than on the invalid cue trials. It was argued that the *validity effect* (benefit) is the difference between valid and neutral RT's whereas the cost is the difference between the neutral and invalid RT's. As the validity effect is obtained even when the eyes remain fixed in the central position throughout the trial it seems to be a measure of the cost of *covert* orienting. When using this paradigm in a clinical context Posner *et al.* (1982; 1984) found that patients with right parietal damage showed little impairment in the detection of a left visual field stimulus when the spatial cue was also directed towards the left visual field. There was also no impairment (beyond the 'normal cost') at detecting right visual field stimuli when their attention had been directed to the left visual field. However, when a spatial cue directed attention to the right visual field, patients often failed to detect a subsequent left visual field stimulus or if they did, showed abnormally long response latencies. So despite relatively intact sensory capacities in both visual fields, right parietal damage biases attention towards the right visual field and produces a profound reluctance to redirect attention to the left visual field. However, in a further experiment Posner *et al.* (1987) found that patients with parietal lobe damage are worse in redirecting their attention in a contralesional than in a ipsilesional direction in *either* visual field. So it seems to be the case that there is a difficulty in reorienting to targets contralateral to the current focus of attention. This hypothesis may also explain the findings that right parietal patients sometimes neglect the left side of objects even when they are presented to the ipsilesional hemifield (Driver and Halligan, 1991; Young *et al.*, 1992). If leftward covert scans are difficult for the patients one would expect to find problems with the left side of objects, no matter where they are presented.

So the theoretical explanations for unilateral spatial neglect given so far can be summarized as the sensory hypothesis proposed by Battersby *et al.*, the representational hypothesis put forward by Bisiach *et al.*, the attentional explanations (overt and covert) by investigators such as Kinsbourne and Posner (and colleagues) and finally the 'directional hypokinesia' hypothesis by Heilman *et al.*.

FINDINGS ON LINE BISECTION PERFORMANCE IN NEGLECT PATIENTS

Additionally to the findings presented above, there has been a whole range of experiments carried out on line bisection performance of patients with unilateral spatial neglect. As a task, line bisection was first introduced by Axenfield (1894) who took it from psychology (Kund, 1863) into neurology, as he considered it to be an easy tool to study asymmetries of spatial perception in hemianopic patients. Subsequently, the task of bisecting a horizontal line became a standard 'bedside' method for diagnosing the presence and severity of unilateral spatial neglect in patients both with and without visual field deficits. Schenkenberg *et al.* (1980) applied the line bisection test to groups of brain damaged patients, and found that patients with right hemisphere damage erred towards the right of the true midpoint and differed from all the other patient groups when the horizontal lines were presented in left and central space (space defined with reference to the patient's head and trunk). There was no difference between the groups for the set of lines presented in right space.

A year earlier, Heilman and Valenstein (1979) used the line bisection task on six patients with unilateral spatial neglect to test their theory of hemispatial hypokinesia. They argued that if neglect is due to hemispatial hypokinesia, patients with this syndrome should show less neglect when the lines are placed in the right rather than the left hemispace (hemispace again defined with reference to the patients' head and trunk). If however neglect is due to a failure to process the information from the left hemispace, the imposition of a strategy that ensures the processing of the left side should alleviate neglect. Accordingly they investigated whether neglect in a line bisection task was influenced by two factors: hemispace of stimulus presentation and cueing patients to process the neglected end of lines. In their task, each line that had to be bisected by the patient had a letter at each end. On half the trials patients were cued to look at the left end of the line and to report the letter at that end; on the second half of trials they were cued to look at the right end of the line and to report the letter at that end. There were three blocks of trials in which lines where presented to the left of the subject's midline, to the right of the subject's midline and centrally (i.e., directly in front of the patient). Neglect was measured in terms of magnitude of error. Their results showed that cueing had no effect on performance: the amount of neglect was equivalent whether patients had to report the letter on the left or the right end of the line. There was, however, an effect of hemispace: patients showed bigger rightward bisection errors when the lines were presented in left space than when presented in the centre or in right space. Heilman and Valenstein took this as support for their hemispatial hypokinesia hypothesis as the patients neglected primarily in hypokinetic (left) hemispace and as this effect was not altered by cueing. They mention however that their results might possibly be due to hemispatial memory defects in that although the patients explored the line they perhaps '...forgot the left side of the line and performed as if they had not seen it.' (Heilman and Valenstein, 1979). This explanation however was not available in a later experiment (Heilman *et al.*, 1983) where five patients with hemispatial neglect were instructed to point to an imaginary point in space perpendicular to the midline of the chest. These patients deviated *more* into the hemispace ipsilateral to their lesion than left hemisphere damaged controls. Heilman *et al.* interpreted this finding along their hemispatial hypokinesia hypothesis as the task could not have been affected by impaired memory. It is obvious that the findings of Heilman and his colleages are in contrast to Posner *et al.'s* experiments (1982; 1984) whose patients showed large cueing effects (see above).

In order to elucidate the issue Riddoch and Humphreys (1983) carried out two more line bisection experiments on patients with neglect syndrome. In one experiment apart from cueing both ends of a line, they also cued either just the right or the left end of the line and found that neglect was significantly reduced in the single left cue condition. There was no effect of space. In the other experiment lines were cued at both ends and the patients were asked to report *either* the left letter only or the right letter only. This time neglect was reduced whenever the patients were forced to report a left side cue irrespective of whether other cues were present or not. These data fail to support the hemispatial hypokinesia hypothesis, as cueing could be clearly demonstrated. The authors explain their data in agreement with Posner's theory: patients with unilateral spatial neglect fail to orient automatically to the signals on the side contralateral to their lesion. Nevertheless some ability to orient consciously remains intact, so neglect is reduced when the patients are instructed to orient and to report stimuli on the neglected side.

Halligan and Marshall (1989a) note that one possible problem with these traditional cueing studies is that the cue-task (report the letter) is not intrinsically linked to the experimental task (line bisection). The patient may thus perform the first task correctly (naming the cue) but then disregard it upon switching to the second quite different task (bisecting). To avoid this they presented lines on a computer visual display unit with a small bisection arrow appearing at either the leftmost or rightmost point of the line. The position of the arrow was under direct, continous control of the patient as he moved a mouse which in turn moved the arrow along the line. Cueing and bisecting thus emerged into one task. Although only reporting the results of a single patient with unilateral spatial neglect they found that left cueing was highly efficient in reducing left neglect. On the other hand they also report a patient with severe unilateral spatial neglect who showed better line bisection performance when using the left as opposed to the right hand (Halligan and Marshall, 1989b) which might appear to demand a motor-based explanation. However in a later experiment, Halligan *et al.* (1991) then demonstrated that this pattern of performance could be modified by changing the starting position of the patient's hand in crossing the hands over the midline: when the left hand commenced the task on the right side, performance was very similar to when the right hand commenced on that side, similarly when the right hand was positioned on the left side performance was similar to that shown with the left hand on that side. The results are thus again in favour of Riddoch and Humphreys' findings (1983) in suggesting that cueing has a more profound effect upon task performance than hand.

Although most of these findings tend to contradict the hypokinesia hypothesis, Coslett *et al.* (1990) suggest that both a directional hypokinesia and an attention deficit may each be a primary determinant of neglect. They tested four patients with neglect syndrome on the line bisection task but prevented direct viewing of the line in using a video-camera and monitor, each of which could be moved independently into right or left hemispace. They report that two patients performed in a manner consistent with the hypokinesia hypothesis and the other two consistent with the attentional hypotheses. Similarly Bisiach *et al.* (1990) asked neglect patients to bisect a line with a pully device. In the congruent condition patients moved a pointer directly to the centre of the line. In the incongruent condition a rectangle on the bottom string was moved thus advancing the pointer in the opposite direction. It was reported that patients demonstrated substantially smaller rightward displacements in the incongruent as opposed to the congruent condition, although only two patients actually showed leftward displacements. The authors suggest that both directional hypokinesia and perceptual components may coexist in the same patient but that for most of their patients perceptual factors prevailed. Interestingly, Tegner and Levander (1991a) also reported the same pattern when neglect patients were tested on a line cancellation task either in normal view or through a 90 degree mirror. In the mirror conditions half of their patients cancelled lines only in right space (hypokinesia) whereas the other half cancelled lines only in left space (attentional hypothesis).

Apart from cueing, line length has also been found to affect the performance of patients with neglect syndrome. Although in the early studies (Bisiach *et al.*, 1976; Schenkenberg *et al.*, 1980) no effect of line length on the relative degree of rightward displacement of the point set by the patients was found, Bisiach *et al.* (1983) claim that this was due to an improper interpretation of the results. They point out that rather than the observable subjective midpoint, the deduced left endpoint of the line should be the informative dependent variable (although it might be argued that these two measures should be linearly related). They assume that a patient with neglect of the left hemispace has an adequate representation of the right extremity of an *objective* horizontal line and they further assume that the left extremity of the *represented* line can be deduced from the right endpoint of the objective line and from the subjective midpoint. Testing 12 patients with neglect syndrome they demonstrated an increase of the rightward displacement of the subjective midpoint as a function of the length of the lines. However, looking at the individual data they found two types of behaviour: some patients showed a right displacement that seemed independent of line length, other patients produced a far larger rightward displacement the longer the lines presented were. Halligan and Marshall (1988) concluded from this second finding that, if one extrapolates this performance to even smaller lines, the subject's subjective midpoint should cross over from a rightward to a leftward displacement. They demonstrated this 'crossover' in a patient who showed a linear increase of the rightward displacement with line length and also a consistent leftward displacement at lines as short as 2.5cm. Halligan and Marshall then interpreted these findings in terms of an 'attentional boundary' placed slightly to the left of the objective midline of space. The 'crossover' to the left was explained through perceptual completion, i.e. the patient incorporates the space up to the attentional boundary into his representation of the line. Nonetheless in a later study (Halligan and Marshall, 1989c) they fail to confirm their theory of an attentional boundary as errors of three neglect patients, tested on varying lines, proved too great to be accounted for by this model which predicts that a line's extension to the left of the 'boundary' is neglected and the rightward extent bisected correctly. But, in yet another single case study Marshall and Halligan (1990) explain bisection errors through the size of the Weber fraction. They argue that in psychophysical terms, a bisection task requires one to place a mark such that one line is divided into two lines whose respective lengths differ within one 'just noticeable difference'. Moreover the larger the original magnitude of the stimulus, the greater the range of transections that cut the initial stimulus length in two equal segments (Wolfe, 1923 cited by Marshall and Halligan, 1990). The authors then argue that if standard deviations are regarded as a metric for the 'indifference zone' of bisections it seems that this value of the Weber fraction has greatly increased in their patient. Control subjects were not discussed in this study (a control group was mentioned in Experiment 1 only) and an investigation performed by the same group on normal subjects (Manning *et al.*, 1990) suggested that normal subjects show the *same* behaviour pattern, i.e. the variability and the mean displacement of the transections both correlate positively with line length. So it seems that an increase in magnitude and variability for transections of longer lines, occurs in normal subjects as well as neglect patients. Consequently to explain why neglect patients show a greater magnitude of errors than normal controls, Marshall and Halligan (1990) argue that, with longer lines, patients with neglect approach the line from the right, and make rightward errors, whereas with smaller lines, they approach from the left and accordingly produce leftward errors.

Tegner and Levander (1991b) who also demonstrated leftward bisection errors for very short lines in 24 out of 25 neglect patients, disagree with Halligan and Marshall's idea of an increased Weber fraction for neglect patients. They point out that this explanation is difficult to reconcile with their findings, as it would predict that absolute errors should be as large for marking the centre of circles as for bisecting lines. Nonetheless the authors report near-normal accuracy for circles. It seems that so far no satisfactory explanation can be given as to why neglect patients bisect very small lines to the left of the true midpoint. A different line of argument could be that the leftward errors produced by neglect patients on very short lines simply resemble 'normal' bisection behaviour: Marshall and Halligan (1990) report leftward bisections for their control subjects on lines varying in length from 1 inch to 11 inches (Experiment 1). In other words it may be that the 'reversed' bisection errors found in neglect patients with short lines, are not a symptom of disordered behaviour at all, and therefore not in need of special explanation. This point will be substantiated in chapter three.

VISUOMOTOR FUNCTIONS OF THE LEFT AND RIGHT HEMISPHERE

Although (as outlined above) there have been numerous findings that right-hemisphere lesioned patients with or without neglect (Bisiach *et al.*, 1976; Schenkenberg *et al.*, 1980) tend to misbisect a horizontal line, there have also been a range of studies indicating the importance of the left hemisphere for motor control. As one of the first Liepman (1908) suggested that apraxia was primarily a movement disorder, a manifestation of the disturbance of a system in the left hemisphere, which has to do with the control of '...purposive movements i.e., those learned connections of elementary muscle actions' (Liepman, 1908). Liepman's interpretation differed from other widely held viewpoints which regarded apraxia as due to some inability to employ a conventional sign to stand for another object or event, or an impairment in the ability of the word to invoke the act it names (Head, 1926; Geschwind, 1967). However Kimura and Archibald (1974) argued that a difficulty with the asymbolia interpretation is that patients who have problems in producing the required manual acts to command, also have difficulty imitating them. This is inconsistent with asymbolia as imitation could be done without reference to symbolic content, and should therefore be little, if at all, affected by asymbolia. Consequently Kimura and Archibald (1974) attempted to give a more precise description of the nature of the defect in apraxia by studying several kinds of manual activity, from isolated flexion of a finger to more complex sequences, including unfamiliar as well as familiar sequences. The main finding was that left hemisphere damaged patients were particularly impaired on sequential manual tasks involving transitions from one hand posture to another, suggesting that the impairment is a disorder of motor control, unrelated to representational content. Moreover, aphasic patients were found to be relatively more impaired than nonaphasic patients. This association between deficits in speech and manual praxis following left hemisphere damage has been used by Kimura (1982) to argue that mechanisms within the left hemisphere play a special role in the sequential organization of complex movements in a variety of effector organs (articulatory musculature, musculature of hands and upper limbs). However, she also emphasized (1977; 1982) that the left hemisphere system seems not to be responsible for the ordering of the movement *per se* but rather for selecting the correct movement or effecting an efficient transition from one movement to another.

In a more recent study, however, Fisk and Goodale (1988) found direct evidence for a left hemisphere involvement in the much simpler task of visually guided reaching: they required 17 left hemisphere damaged patients, 11 right hemisphere lesioned subjects and 13 controls to reach quickly and accurately to one of four different visual targets as soon as they appeared on the screen in front of them. They reported that while the left hemisphere damaged patients did not differ from the control group with respect to movement initiation latency, they did require a greater period of time to execute the reach once it had been initiated. This difference proved primarily attributable to a prolonged terminal (deceleration) phase of the movement. The authors argue that although the patients might have had difficulty selecting the appropriate motor program when one of the four targets was illuminated (Kimura 1977; 1982), it is also possible that they were less able to make quick use of visual, proprioceptive and/or efference copy information therefore failing to monitor and correct the movement during its execution.

A complementary study performed by the same authors on normal right-handed subjects (Fisk and Goodale, 1985) seems to confirm the latter explanation: when asking subjects to reach out and put their index finger on small targets which appeared either to the left or right of a central fixation point, smaller constant and absolute errors were found for the right as opposed to the left hand. Moreover, right-hand reaches achieved a higher peak velocity and were completed in a shorter period of time than left-hand reaches. Most importantly, most of the difference between the duration of left- and right handed reaches was accounted for by a longer deceleration phase for left-hand reaches. Goodale (1989) argues that it is this portion of the reaching movement where most of the error corrections in the trajectory take place. Indeed authors studying repetitive aiming movements (Flowers, 1975; Roy, 1983) have interpreted the preferred (right) hand's superiority as a left hemisphere advantage in the processing of visual feedback information, thus allowing more efficient execution of error corrections. Roy (1983) argued further that then one would predict that in pointing at a target, a greater loss of accuracy should be experienced by the nonpreferred (left) hand as the speed of the movement increases. He examined this hypothesis in a serial pointing task in which right-handed subjects pointed at a series of target circles with a pencil held in their right or left hand. In one condition subjects were encouraged to point as quickly as possible while attempting to be accurate (speed condition); in the other condition subjects were encouraged to be as accurate as possible without being concerned for speed (accuracy condition). The results basically confirmed the hypothesis as, relative to the accuracy condition, in the speeded condition the left (nonpreferred) hand experienced a loss of about 80% in accuracy, whereas the right (preferred) hand lost only about 43%.

A different interpretation of the right-hand advantage was given by Annett and co-workers (1979) who claim that the left hand is simply more variable in its motor output. In their study, which examined subjects placing small pegs in a series of holes, they found that the left hand missed the hole more often and so had to make more corrective movements. This inaccuracy in placement leading to more corrective movements was, they suggested, due to greater variability in force used in initiating the aiming movements with the left hand. This argument was criticized by Todor and Cisneros (1985) who point out that Annett *et al.*'s data cannot rule out hand differences in error correction. Moreover in their own study, in which they asked subjects to hit circular targets with a stylus tip, the left hand exhibited a higher error rate, a finding which could possibly be interpreted as a greater variability in motor output. However, in the second experiment in which movements of maximum speed were obtained with a 20% or 0% error rate, hand differences existed only in the deceleration phase. From this finding the authors argue that the primary difference between the hands apparently lies in the speed or efficiency with which error corrections, which supposedly occur in this portion of the movement, can be effected. Consequently if there are hand differences in motor output variability, differences in error correction/sequential processing seem to be a major contributor to this variability.

Goodale (1989) argues that studies on eye movements accompanying limb movements add further evidence to the assertion that the left hemisphere plays a special role in the sequential organization and also the timing of movements involved in prehension: Fisk and Goodale (1985) demonstrated that aiming movements made with the right hand were initiated more quickly than those with the left hand (see also Carson *et al.*, 1990; Haarland and Harrington, 1989). More interesting though, the latency of the eye movements accompanying the limb movements was also shorter for right-handed as compared to left-handed reaches. This was despite the fact that the eye movements typically preceded the limb movements by 50 milliseconds or more.

So it seems that the left hemisphere participates in the control of visually guided reaching in at least two ways: first in the initial programming of the movement, since both the eye and limb movements are initiated more quickly in right- than left handed reaches. Secondly in amending the program in flight, since right- hand reaches are not only more accurate but also show shorter error correction phases. But is it really only the left hemisphere which has a specialized role in visuomotor control? In 1909, Balint described a patient in whom he had identified a psychic paralysis of gaze, optic ataxia and a spatial disorder of attention. When asked to reach for objects the patient behaved differently with either hand: although movements with the left hand were normal and easily reached the target, those with the right hand erred in all directions. Balint noted that the disorientation of the movement with the right hand was due to a problem with visual control for that hand. Post mortem examination of the patient revealed that the main lesion was located in the posterior parietal areas on *both* sides. Similarly Holmes (1918) reported six patients with a 'disturbance in visual orientation': again when asked to touch an object placed in front of them they would project their arms in the wrong direction. In the same patients Holmes also reported an inability to determine the relative position of objects within their field of vision, i.e. the patients could not describe the position of one object with respect to another. Post mortem examination of two of these patients showed again that the lesions were located in the posterior part of the parietal lobes on both sides. In later years authors noticed that some of the aspects of visual disorientation appeared to be specifically related to lesions in the right hemisphere. Brain (1941) reported three patients with lesions to the right parieto-occipital junction, who all showed inattention for the left half of space. These patients contrasted with another group of three who showed defective visual localization, limited to the visual field contralateral to the lesion. In these cases the lesions were on the right side in one patient and on the left in the other two patients. From this Brain concluded that visual localization is not a function to which dominance applies whereas 'agnosia for the left half of space' was specifically related to right-sided lesions. The predominance of right-sided lesions in visuospatial cognitive disorders was subsequently confirmed by a number of authors (Patterson and Zangwill, 1944; McFie *et al.*, 1950; Hecaen *et al.*, 1956). From this evidence Jeannerod (1988) argues that parietal lesions within the right hemisphere produce both spatial disorientation at the cognitive level and an impairment in orienting behaviourally within the left hemispace. On the contrary, symmetrical lesions of the left parietal lobe produce only the behavioural disorientation.

Evidence for a right hemisphere involvement in visuospatial tasks can be found in Fisk and Goodale's study (1988) in which right hemisphere lesioned patients showed a substantial increase in movement latency for both ipsi- and contralateral targets when compared to the control group. This was not the case for patients with damage to the left side. The authors argue that this delay could have been due to a difficulty in determining the position of the target in extrapersonal space. Because the patients could not establish the position of the target as efficiently as normal control subjects, they required a longer period of time to access the neural systems responsible for programming a movement to that position. This interpretation is consistent with the older work implicating the right hemisphere in visuospatial processing. Nonetheless the authors mention that these increased reaction times could also reflect a dominance of this hemisphere for motor action or intention. This interpretation was offered by Heilman and colleagues (Heilman *et al.*, 1985b) who tested the ability of patients with left-sided hemispatial neglect to move a lever toward or away from the side of their (right hemisphere) lesion in response to a central visual stimulus. They demonstrated that the neglect patients needed more time to initiate movement toward the neglected left hemispace than the right hemispace, an asymmetry which was not found in brain-damaged controls without neglect. Nonetheless Goodale (1989) points out that only two of the right hemisphere lesioned patients in their study (Fisk and Goodale, 1988) showed symptoms of hemispatial neglect and that, in another experiment, they were only slightly slower than the control group, when an auditory stimulus to begin moving was provided and the movement was to a constant spatial location. This adds further evidence to the argument that the delay was due to a deficit in visuospatial processing rather than a general problem in motor activation. Somewhat earlier Kimura (1969) provided tachistoscopic evidence for a right hemisphere involvement in visuospatial localization: normal subjects were asked to locate a dot on a spatial map depicting all of the dot locations presented. The point could be more accurately located when it had been presented to the left rather than the right visual field. This difference between the fields could not be attributed to differences in the ease with which the dot could be seen, as there was no demonstrable difference between the fields in the detectability of a dot. In conjunction these findings could suggest a right hemisphere involvement in tasks that require accurate visual localization. This was argued by Guiard *et al.* (1983) who pointed out that '...despite the fact that the predominant role of the right hemisphere in processing spatial information has been widely acknowledged, there is surprisingly little experimental evidence that normal motor performance of the left hand benefits from the dominant processing mode of this hemisphere.' When testing normal right- handed subjects, they managed to demonstrate a higher accuracy of the aiming movement of the left hand, under circumstances where vision of the responding limb was not available. Bracewell *et al.* (1990) investigated whether differences in accuracy between hemifields could be demonstrated in another type of visuomotor behaviour, the directing of saccadic eye movements. Again they could demonstrate that most right-handed subjects showed a left visual field advantage when asked to make saccades to the remembered position of visual targets, i.e. without the aid of visual feedback.

All these findings might support a right hemisphere role for localizing stimuli in space, without excluding a left hemisphere role in the utilization of visual feedback (when available) and the timing and sequential organization of the movement. However, a recent study by Goodale *et al.* (1990) might modify these assumptions. In their experiment the search for a possible right hemisphere participation in motor control was widened by using a spatial 'bisection' task. Right hemisphere lesioned patients and matched controls were asked to point either directly onto a single target or midway between two targets. It was found that the patients made bigger rightward directional errors than matched controls at the outset of the reach. These initial errors were observed for simple pointing as well as bisection. However, they were poorly corrected in bisection, such that the final rightward errors remained much larger than for pointing. These findings could argue for a right hemisphere role in programming initial heading direction in visual reaching in general, but also suggest a more specific role in feedback correction which becomes more obvious in a spatially demanding context, such as in the bisection task.

GENERAL OUTLINE OF THE EXPERIMENTS IN THIS THESIS

Consequently there are two main issues discussed in this thesis: firstly to further illuminate the relative contributions of the right and left hemisphere to visuomotor control especially in a task intended to model line bisection. Secondly, by testing a new task (the 'landmark test') an attempt is made to examine the nature of the errors found in brain lesioned and normal subjects when applying the traditional line bisection test.

In general, the bisection errors of normal subjects are smaller in magnitude and if anything opposite in direction, relative to those of right-hemisphere patients (Bowers and Heilman, 1980; Bradshaw *et al.*, 1985; 1987a), and this tendency to err leftwards in normal subjects is generally attributed to a right-hemisphere dominance in determining bisection responses. Furthermore, there is now evidence that subjects make bisection errors towards whichever end of a line is explicitly cued (Dudgeon, 1988; Nichelli *et al.*, 1989) suggesting that the distribution of spatial attention has differential effects on bisection judgements in normal subjects too. The subjects may perceptually overestimate line length on the side to which attention has been drawn, relative to the other side.

Thus the experiments in chapter two were designed to examine further the nature of this cueing effect on the bisection judgements of normal subjects, and also to re-examine the effect of spatial location, as the bisection bias can be influenced not only by cueing asymmetrically, but also by varying the spatial location of the line (Bradshaw *et al.*, 1987a; Riddoch and Humphreys, 1983).

A special attempt was made to decide between two schools of thought: Heilman and colleagues (1979; 1985a, see also **Theoretical Explanations of Unilateral Spatial Neglect**, above) explain the rightward deviations of neglect patients in terms of a *motor* error, a leftward 'directional hypokinesia'. The other school of thought places the error on the *perceptual* side and suggests that patients under-scale the leftward extent of the line (Milner, 1987) perhaps as a result of paying inadequate 'automatic' attention to it (Riddoch and Humphreys, 1983). The same logic could be applied to the findings of the normal subjects in that the subject's tendency to bisect left of centre, could either reflect a relatively magnified percept of the leftward part of the line (perhaps due to an attentional bias toward the left), or it could reflect a response bias in the form of a predominantly leftward orienting tendency (perhaps due to an activated right hemisphere). A critical test can, however, be attempted by using a task which requires no explicit *act* of bisection, or even which would demand an act *opposite* in direction to an erroneous bisection response. This is to use a 'landmark' task (cf. Pohl, 1973). In this task, the subject is given a pre-transected line, and is required to indicate, either manually or verbally, the end that is nearer to the transection mark (i.e. the 'landmark'). If the line is in reality centrally bisected, but the left half appears longer to the subject (the perceptual hypothesis), then a *right*ward response should be made. If instead there is no perceptual asymmetry but only a motor bias towards the left, then the subject should, if responding verbally, indicate either end randomly, or, if responding manually, indicate the *left* end. In short, the motor bias and the perceptual bias accounts of performance in the standard bisection task predict *opposite* response preferences in the manual landmark task. Analogous logic can be applied to an analysis of the effects of cueing or of spatial location: if the independent variable causes a bisection error in a given direction, then the manual landmark task will always place the two alternative accounts of that error in opposition.

Consequently by testing young and elderly subjects with the 'landmark task', it was hoped to decide whether errors found in the traditional line bisection test are due to perceptual or motor biases.

In chapter three the landmark task was also applied to patients with unilateral brain lesions (with and without symptoms of unilateral spatial neglect). Again an attempt was made to decide whether the rightward bisection errors found in neglect patients are due to directional hypokinesia (Heilman *et al.*, 1979; 1985a) or whether neglect patients might experience a distortion of their subjective space. That is, the subjective space might be compressed, but progressively more so in more leftward parts of space. According to this view, the space occupied by the left half of a line would literally appear shorter to a neglect patient than the right half, therefore bisection would tend to be performed in a rightward direction. This idea would predict rightward bisection errors, but can only account for the increased errors in left space and the lesser ones in right space if it is assumed that the gradient of distortion is steeper in the leftward parts of ego-space than in the rightward parts (Milner, 1987).

Again by use of the landmark task an attempt was made to decide between the 'motor' and 'perceptual' schools of thought. Additionally by testing RCVA patients with and without hemispatial neglect and comparing them to LCVA and normal control subjects it was hoped to clarify whether the observed effects are specific to neglect patients or rather to right hemisphere damage *per se*. It is also established in the literature that varying the length of lines length affects bisection performance of patients with neglect syndrome (Bisiach *et al.*, 1983; Halligan and Marshall, 1988) and that some patients actually show leftward bisection errors for very short lines (crossover). But it is possible that these leftward errors produced on very short lines simply resemble 'normal' bisection behaviour: a number of authors (Bisiach *et al.*, 1976; Bradshaw *et al.*, 1985; 1987a) reported this pattern for normal subjects. However the subjects in these older experiments were all tested on rather long lines (15 - 30 cm) so, in chapter three, all subjects were tested again, on lines with varying length, to confirm that leftward displacements can be found for very short as well as longer lines. It could possibly then be argued that the 'reversed' bisection errors found in neglect patients with short lines, are not a symptom of disordered behaviour at all, and therefore not in need of special explanation.

The second part of the thesis is designed to demonstrate any possible contribution the right hemisphere might make to visuo-motor control. Various studies have shown that this hemisphere is important for localizing stimuli in space (Kimura, 1969; Fisk and Goodale, 1988). Moreover, the findings of Goodale *et al.* (1990) suggest a right hemisphere role in programming initial heading direction in visual reaching in general, and a more specific role in feedback correction when the reaching task is performed in a spatially demanding context. So the experiments of both chapter four and chapter five were designed to detect possible visuospatial influences on hand asymmetries during reaches. By using a spatial 'bisection' task under 'open loop' conditions, i.e. asking the subject to point midway beween two targets, in the absence of visual feedback of the reaching hand, it was hoped to demonstrate a left hand advantage not only for movement onset time but for terminal accuracy as well. This could then be interpreted as further evidence for a right hemisphere involvement in feedback correction. In another type of visuomotor behaviour, the directing of saccadic eye movements, Bracewell *et al.* (1990) demonstrated that most right- handed subjects showed a left visual field advantage when asked to make saccades to *briefly* presented visual targets. They interpreted this finding as a right hemisphere advantage for visuomotor localization. Similarly in the experiment presented in chapter five it was hoped to find hand differences in accuracy between targets which disappeared immediately after movement onset and those which remained illuminated throughout the reach. It could be argued that presentation of brief targets under open loop conditions should produce left hand advantages as visuomotor localization is hardest in this condition.

With the experiment presented in chapter 6 an attempt was made to investigate the involvement of the two hemispheres more directly, by testing right and left hemisphere damaged patients and by choosing tasks that should presumably affect the performance of these two groups differently. Presenting the spatial 'bisection' task in the presence of visual feedback is likely to increase the complexity of visual feedback processing, as the finger's position has to be compared on-line to two as opposed to a single stimulus as the finger approaches the target. According to the findings of various investigators on normal subjects (Flowers, 1975; Roy, 1983; Todor and Cisneros, 1985) and those of Goodale and co-workers on brain lesioned subjects (Goodale, 1989; Fisk and Goodale, 1988) one might therefore expect an impairment in patients with left hemisphere lesions during closed loop performance (i.e. with the hand visible). The efficiency of these patients in error correction and/or sequential processing of the movement should be affected.

On the other hand, the results of the Goodale *et al.* (1990) study suggest that this effect may be outweighed by visuospatial demands that would tend to increase right-hemisphere participation. This should be particularly apparent under open loop conditions, where no visual information on hand/target discrepancy is available (cf. Guiard *et al.*, 1983). Consequently while the bisection task might maximize the expected impairment in left hemisphere damaged patients during closed loop reaching, it should also exaggerate the expected impairment of right hemisphere damaged patients during open loop reaching. Moreover, locating stimuli in the left half of egocentric space as opposed to central and right space, might maximize the possibility of detecting right-hemisphere influences on reaching (Heilman *et al.*, 1987).

Finally, in chapter seven, a preliminary reaching experiment was performed on two RCVA patients who displayed symptoms of hemispatial neglect at the time of testing. It was expected that these two patients would show longer latencies, movement times and greater overall errors than the RCVA group tested in chapter six. Especially use of the spatial bisection task in closed loop conditions should produce rightward deviations comparable to (or possibly larger than) the findings of Goodale et al. (1990). Moreover, there might be phenomena of extinction with the bisection task, especially for reaches into left hemispace and possibly more so in the absence of visual feedback. One of the neglect patients (B.W.), although demonstrating strong hemispatial neglect overall, showed atypical leftward errors when tested with the traditional line bisection test. Observing the patient during this test gave the impression that he approached the line from the right and then overcompensated into displaying a substantial leftward error. It was hoped that a detailed analysis of his reaching movements might substantiate this impression.

CHAPTER TWO

LINE BISECTION PERFORMANCE OF YOUNG AND ELDERLY NORMAL SUBJECTS

Apart from trying to explain the rightward displacement errors of patients with unilateral spatial neglect, various authors have also investigated the performance of normal subjects in the line bisection task. And interestingly, instead of finding an accurate performance with small random right or leftward displacements, a pattern which would be expected if there was no bias of any kind, investigators have often reported that normal subjects bisect to the left of the actual midpoint.

The first relevant study was carried out by Bisiach *et al.* (1976), who tested twenty-five right-handed subjects on individual lines centered with respect to body midline, and found that their subjects produced a leftward bisection displacement, regardless of hand used. Bowers and Heilman (1980) found the same result on a tactile line bisection task carried out by normal right handers. Bradshaw *et al.* (1985; 1987a) repeatedly demonstrated leftward bisection errors in normal right-handed subjects and although Scarisbrick *et al.* (1987) pointed out that their findings might result from an occlusion effect, in which the subject fails to compensate for the portion of the line hidden by her/his hand, they also noted that this explanation fails to account for similar errors in tactile tasks and would predict errors to the right of the centre when stimuli are bisected with the left hand. This is however not the case, subjects showing even larger leftward displacements when the left hand is used (Scarisbrick *et al.*, 1987). So the findings of Bradshaw, Scarisbrick and colleagues are generally explained in terms of a right-hemisphere advantage on visuo-spatial tasks (Bogen and Gazzangia, 1965; Nebes, 1971; Geffen *et al.*, 1972) in that tasks which involve the appreciation of visual space may selectively activate the right hemisphere with a resultant enhancement of the left visual field (Bowers and Heilman, 1976; Kinsbourne and McMurray, 1975; Tartaglione *et al.*, 1983). This enhancement of the left visual field might result in a leftward shift of the subjective midpoint relative to the objective midpoint. The findings that larger deviations occur, when the left hand is used for bisection, can then be explained as a consequence of the increased activation of the right hemisphere through the use of the left hand (Joanette *et al.*, 1986; Kinsbourne and Cook, 1971).

However, it has to be noted that apart from these findings there have been other reports showing no significant right or leftward displacements regarding bisection of centrally presented lines (Werth and Poeppel, 1988; Manning *et al.*, 1990; Halligan *et al.*, 1990; Nichelli *et al.*, 1989). On the other hand there may be some other support for Bradshaw and colleagues' explanation in that there is now evidence that normal right-handed subjects make bisection errors towards whichever end of a line is explicitly cued (Dudgeon, 1988; Nichelli *et al.*, 1989; Reuter-Lorenz and Posner, 1990). For example Reuter-Lorenz and Posner found that relative to the 'no cue' condition there was greater rightward deviation of the bisection response in the presence of a right cue and greater leftward deviation in the presence of a left cue. Thus there may indeed be perceptual overestimation of the line length on the side to which attention has been drawn, relative to the other side, as a consequence of the contralateral hemisphere being especially activated.

The present experiments were designed to examine further the nature of this cueing effect on the bisection judgements of normal subjects, and also to re-examine the effect of spatial location, as the results on this are ambiguous so far. Nichelli *et al.* (1989) found that subjects bisect to the left in right hemispace and to the right in left hemispace whereas Fukatsu *et al.* (1990) found no effect of spatial location.

Additionally an attempt has been made to decide between two schools of thought: Heilman and colleagues (1979; 1985a, see also chapter one) explain the rightward deviations of neglect patients in terms of a *motor* error; because of a leftward 'directional hypokinesia'. This is thought to weaken the leftward vector in spatially directed action, thus causing a net rightward error. The other school of thought places the error on the *perceptual* side and suggests that patients under-scale the leftward extent of the line (Milner, 1987), perhaps as a result of paying inadequate 'automatic' attention to it (Riddoch and Humphreys, 1983). Similarly the tendency in normal subjects to err leftwards could be conceptualized, once more, either in perceptual/attentional terms (Bradshaw *et al.*, 1987a; Scarisbrick *et al.*, 1987) or in motor/orienting terms (Heilman *et al.*, 1979; 1985a). In other words, the normal subject's tendency to bisect left of centre could either reflect a relatively magnified percept of the leftward part of the line (perhaps due to an attentional bias toward the left), or it could reflect a response bias in the form of a predominantly leftward motor orienting tendency (perhaps due to an activated right hemisphere).

A critical test can, however, be attempted by using a task which requires no explicit *act* of bisection, or even which would demand an act *opposite* in direction to an erroneous bisection response. This is to use a 'landmark' task (Dudgeon, 1988; Pohl, 1973; Reuter-Lorenz *et al.*, 1990). In this task, the subject is given a pre-transected line, and is required to indicate, either manually or verbally, the end that is nearer to the transection mark (i.e. the 'landmark'). If the line is in reality centrally bisected, but the left half appears longer to the subject (the perceptual hypothesis), then a *right*ward response should be made. If instead there is no perceptual asymmetry but only a motor bias towards the left, then the subject should, if responding verbally, indicate either end randomly, or, if responding manually, indicate the *left* end. In short, the motor bias and the perceptual bias accounts of performance in the standard bisection task predict *opposite* response preferences in the manual landmark task. Analogous logic can be applied to an analysis of the effects of cueing or of spatial location. A *perceptual* overestimation of the cued side should result in judging the side opposite the cue as shorter. A *motor* bias due to the presence of the cue however, would be expected to elicit responses toward the cued end of a line, due to activation of the contralateral hemisphere. Finally, presenting stimuli in left or right space should cause *motor* biases toward the lateral ends of the lines due to such activational effects, whereas a *perceptual* overestimation of the lateral part of the lines would result in a manual indication of the medial end as shorter. So if the independent variable causes a bisection error in a given direction, then the manual landmark task will always place the two alternative accounts of that error in opposition.

EXPERIMENT 1

The first experiment was performed in order to ensure that the particular stimuli, cueing and spatial manipulations, would replicate the effects previously described by others. Performance in the traditional line bisection task was examined as a function of the spatial position of the stimulus (to the left, right or centre of the subject's body midline), and as a function of attentional cueing to either or both ends of the line.

METHOD

Subjects. Twelve subjects (7 female, 5 male) ranging in age from 23 to 36 years (mean = 27), participated as unpaid volunteers in the experiment. All were strongly right-handed as assessed both by self-report and by administration of the 12-item Annett Handedness Inventory (Annett, 1967).

Materials. Twenty-four black *Letraset* lines of 20 cm length and 1.5 mm width were placed horizontally and centrally on two sheets of A4 paper, 12 lines on each sheet. Of these 24 lines, subsets of six had either a letter at the left end, a letter at the right end, a letter at both ends, or no letter at either end. The letters were separated from the end of a line by a 1 mm space. Cued and uncued lines were ordered pseudorandomly on the sheets, and different orderings were used in each spatial condition for a given subject. The letters used as cues were visually similar to each other (O, Q, C, or G) and thus required fixation for identification. Bilaterally cued lines always had different letters at the two ends, and in all conditions the letters occurred equally often at left and right.

Procedure. Subjects were seated at a table opposite the experimenter, who ensured that the subject's body position remained constant throughout the experiment. Subjects were instructed to name the letter(s), if any, and then to centrally bisect the line as accurately as possible using the right hand, proceeding line by line through each sheet. After each transection that line was covered with a card in order to prevent comparison of the present response with previous bisections. Head and eye movements were not restricted in any way. The set of 24 lines was presented once in each spatial location (left, right or central to the subject's body midline). The order of locations was counterbalanced between subjects according to a Latin square. In the central condition the viewing distance was approximately 45cm from the line that was to be bisected. In the left and right hemispace presentations the sheets were located such that the centre of each line lay at a distance of 30cm from the sagittal body midline.

Errors in line bisection for each subject and for each condition were measured in millimetres and averaged across the six instances. Errors to the right of the midpoint were given a positive value and those to the left a negative value.

Statistical Analyses. The mean error scores and their standard deviations were analysed. They were first subjected to three-way analyses of variance with sex as a between-subjects factor, and space (left, centre, right) and cueing (no letter, two letters, letter left, letter right) as within-subjects factors. This analysis revealed no main effect of nor any interactions with sex [$F(1,10) < 1$], so male and female data were combined in 2-way analyses. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

Analysis of the mean error scores showed significant main effects for both spatial location [$F(1.2,13.3) = 12.41$, $p< 0.005$] and cueing [$F(2.3,24.8) = 53.12$, $p< 0.001$]. There was however no significant interaction between the factors.

Post hoc analyses revealed significant differences between central and right spatial locations and between left and right, but not between central and left. Bisection errors tended to be rightward in right space, and leftward in both left and centre space (see Figure 2.1). The leftward bisection errors made in left and central space differed significantly from zero (left space: $t= 4.52$, $p< 0.001$, with 9 out of 12 subjects showing the effect; central space: $t= 2.26$, $p< 0.05$ with 10 out of 12 subjects showing the effect). However the trend for

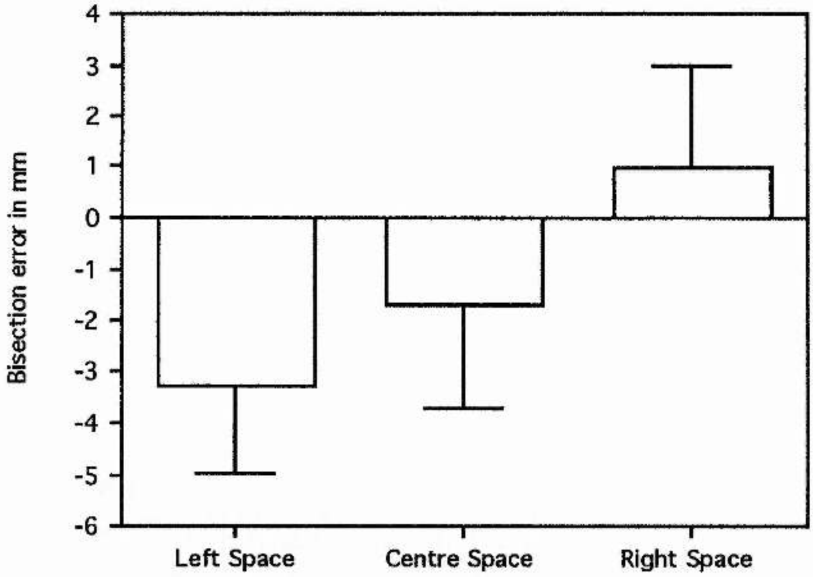

Figure 2.1: Mean Error in mm in the bisection of lines, performed by younger subjects, as a function of space (left, centre, right). Rightward errors are coded as positive, leftward as negative. Errors bars indicate the intersubject variability.

rightward errors in right hemispace (8 out of 12 subjects) did not reach significance. Over all, subjects averaged a small, statistically nonsignificant, leftward error (-1.35mm), with 8 out of 12 subjects showing this.

Post hoc analyses of the cueing effect showed that unilateral left and right cues, apart from being significantly different from each other were also each significantly different from the no-cue and and two-cue conditions, which did not differ. The unilateral left cue 'pulled' bisection responses towards the left end of the line whereas the right cue pulled responses towards the right end of the line (see Figure 2.2). Bisection under the no-cue and bilateral-cue conditions showed small leftward bisection errors, but neither were significantly different from zero.

Analysis of the variability (SDs) of the bisection resonses showed no significant effects ($F < 1$ for both main effects and for their interaction).

DISCUSSION

The results show clearly that space as well as cueing affected performance in the bisection task. Leftward bisection errors in left space and (nonsignificant) rightward errors in right space were found. This may be seen as a relative underestimation of the leftward extent of lines presented in right hemispace and of the rightward extent of stimuli in left hemispace. The result agrees with most previous work in other laboratories (Bradshaw *et al.*, 1985; 1987a; Schenkenberg *et al.*, 1980) and in our own (Dudgeon, 1988), but is directly opposite to the results reported by Nichelli *et al.* (1989). The reasons for this disagreement are unclear, although it is notable that Nichelli *et al.* positioned their laterally-placed lines at only a 70mm eccentricity, so that part of any line longer than 140 mm would have appeared on the 'wrong' side of the sagittal midline. Their data show that it was in fact only with the longest lines

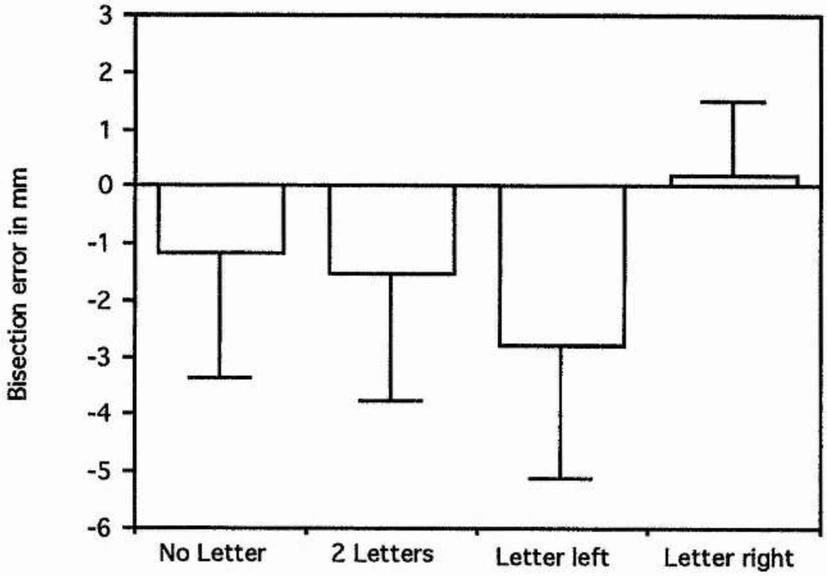

Figure 2.2: Mean error in mm in the bisection of lines, performed by the younger subjects, as a function of cueing (no letter, 2 letters, letter left, letter right). Interpretation of positive and negative values as in Figure 2.1. Errors bars indicate the intersubject variability.

used (200 or 240mm) that their paradoxical effect appeared. Nichelli *et al.*'s subjects were also older than the subjects of this experiment (mean 64 years) although it is unclear why that would cause the observed reversal; nonetheless it is interesting that other investigators using older subjects have failed to find the usual effect of spatial location (Fukatsu *et al.*, 1990). In any event, it is clearly not possible on the present data to endorse Nichelli *et al.*'s proposal that a tendency to attend centrally causes a perceptual overestimation of the inward parts of lines placed laterally.

Independently of spatial location, unilateral left or right cues caused bisection to err towards the side of cueing. This replicates the results of Dudgeon (1988) and Nichelli *et al.* (1989) and is clearly consistent with the idea that attention directed toward one end of a line causes a relative perceptual overestimation of that part of the line.

Bisection of centrally presented lines erred significantly leftwards, in agreement with the findings of Bradshaw *et al.* (1985; 1987a). Others have found no clear population bias among their subjects (e.g. Manning *et al.*, 1990; Halligan *et al.*, 1990). As indicated above, it could either be argued that this bias, when it is seen, is due to an orienting/motor asymmetry or to a perceptual/attentional asymmetry; either of these might plausibly follow from a right hemisphere dominance for spatial processing. In other words, a motor-based tendency due to a greater right hemisphere activation due to the visuospatial processing demands of the task, rather than a perceptual asymmetry, could cause the leftward bias.

In the same vein, it could be further argued that both the space and cueing effects might be attributable to a tendency for the subjects to respond in the direction contralateral to the more activated hemisphere (Kinsbourne, 1987; Reuter-Lorenz *et al.*, 1990). Thus the use of lateral presentation conditions might, through activating the contralateral hemisphere, cause an increased lateral orienting response which results in 'overshoot' bisection responses. Similarly, the effect of cueing, at least with a centrally-located line, could be to activate the contralateral hemisphere, with the result of causing an increased motor orienting tendency in the direction of the cue.

In other words, all of the three influences on bisection found in Experiment 1 could be the result of the operation of *either* a motor/orienting bias *or* a perceptual/attentional bias. The problem with the standard bisection task is that it requires a motor response and therefore inevitably confounds perceptual and motor factors. Therefore in the following experiment bisection judgements were studied using a 'landmark' task, to enable an examination of perceptual effects in isolation.

EXPERIMENT 2

In this experiment, the subjects were not asked to bisect a line, but instead were presented with lines that were already transected. The subjects had to make a forced-choice judgement as to whether each line was transected nearer to its right end or its left end. A motor (pointing) response was required as to the side the transection mark was perceived to be nearer. This should dissociate more directly the perceptual biases from possible orienting biases. It can be reasoned that when faced with a difficult or impossible psychophysical judgement, a subject's manual response may be swayed by any orienting biases that might be operating. Thus if such biases are strong enough to cause error in the standard bisection task, then they might cause the observer to veer toward pointing in that same direction in this manual landmark task.

Three influences were apparent in the bisection behaviour described in Experiment 1: (a) an overall leftward bias, (b) a bias towards the cued side, and (c) a sideward bias with laterally placed lines. As argued earlier, bias (a), the constant error whereby subjects tend to bisect a line to the left of its true centre, might be due to a leftward *motor* bias, in addition to a *perceptual* overestimation of the left part of the line. If the predominant bias was leftward-motor, then in the pointing version of the landmark task, subjects would be expected to point generally to the *left* when faced with a centrally transected line. The contrary effect would occur with a predominantly perceptual bias: if subjects perceived the left half of a line as being longer, *right*ward pointing would be predicted. If the two effects are both present, then they would presumably subtract from one another.

For each of the effects under examination, the use of the pointing version of the landmark task sets perceptual and motor factors in opposition: if a motor bias is operating, it should work against the perceptual bias. It should be emphazised that the task is objectively impossible, and is perceived as difficult by subjects. Thus it seems unlikely that a firm perceptual decision is made on each trial that determines the subject's response in a manner immune to putative output biases.

METHOD

Subjects. The same twelve subjects as in Experiment 1 participated as unpaid volunteers in the experiment. All were strongly right-handed as assessed both by self report and by administration of the 12-item Annett Handedness Inventory (Annett, 1967).

Materials. Eighty-four black *Letraset* lines of 20 cm length and 1.5 mm width were used, each line placed horizontally and centrally on a separate sheet of A4 paper. Sixty of these lines were asymmetrically pretransected, 6 lines each being marked at 1, 2, 3, 4 or 5mm to the right or the left of the true centre. These asymmetrical stimuli were added with the intention to estimate the psychophysical 'neutral' point at which a noncentral transection would appear subjectively central.

The remaining 24 lines were transected in the centre and cued as in Experiment 1, with 6 lines in each of the 4 cue conditions. The set of 84 lines was then divided into 2 subsets of 42 lines, each subset containing an equal number of asymmetrically and centrally transected, cued and uncued lines. Each subset was presented once in each spatial location (left, right or central with respect to the subject's body midline), the order of spatial presentations being counterbalanced between subjects. The viewing distance and spatial locations of the lines was the same as in Experiment 1 and head and eye movements were in no way restricted.

Procedure. Again subjects were seated at a table opposite the experimenter, who ensured that their body position remained constant throughout the experiment. They were falsely informed that none of the transections were placed at the exact centre of a line. They were asked to name the letter(s) if there were any, and then to point to the line that appeared closer to the transection, using their right hand. Subjects were forced to make a left/right choice even if it was necessary to guess: no other response was permitted.

Statistical Analyses. Subjects' performance on the stimuli pretransected 3 to 5mm from the true midpoint was perfect for 11 subjects (one subject judged all leftward transections as transected to the right when lines were presented in right space). Subjectively subjects found it as hard to judge transections that deviated 1 or 2mm from either side of the midpoint as lines that were actually centrally bisected. However, the distribution of the errors on the 1 and 2 mm deviating lines was equally distributed between left and right responses.

For the lines pretransected in the centre, the *number of rightward responses* (maximum six per cell) were first subjected to a three-way analysis of variance with sex. (Although the distribution of choices was approximately rectangular, ANOVA is sufficiently robust to cope with such data). Since again there were no effects of sex, male and female data were combined in the subsequent analysis which was a two-way ANOVA with space and cueing as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used for testing against chance performance in particular test conditions.

RESULTS

Unlike in Experiment 1, no main effect of spatial location was found [$F(1.4,15.9) < 1$]. Cueing, however, remained highly significant [$F(2.4,26.2) = 38.64$, $p < 0.001$)]. The two-cue and no-cue means did not differ significantly, but all other pairs of cueing conditions did differ from each other at the .05 level. With a unilateral left cue, subjects tended to judge the right end of the line as being closer to the transection mark, whereas a unilateral right cue had the opposite effect: subjects saw the left end of the line as being closer (see Figure 2.3). Both unilateral cue conditions differed highly reliably from chance performance ($t = 5.01$, $p < 0.001$ for left cues and $t = -4.96$, $p < 0.001$ for right cues). Responses under the no-cue and bilateral-cue conditions showed an approximately equal number of rightward and leftward responses, and did not differ significantly from chance. Similarly subjects divided their responses evenly within each of the 3 spatial locations, and when summed over

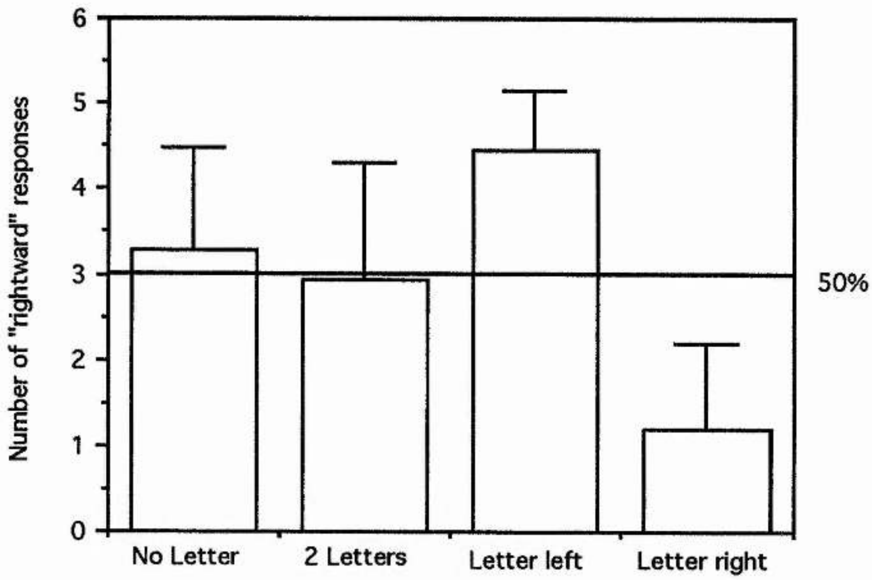

Figure 2.3: Manual landmark judgements of the younger subjects as a function of cueing (no letter, 2 letters, letter left, letter right): the mean number of forced-choice manual indications (out of 6) that an objectively central transection is placed right of centre. Errors bars indicate the intersubject variability.

all conditions. The space x cue interaction approached but did not reach significance [F(3.4,37.0= 2.35, p> 0.08].

DISCUSSION

As in Experiment 1, a strong effect of cueing was found. In this experiment, the half of a symmetrically transected line *opposite* a letter cue was regularly chosen as appearing shorter, indicating a relative perceptual overestimation of length on the cued side. This result supports the view that the effect of cueing in Experiment 1 was also due to a similar relative over-scaling of the cued side.

Unlike Experiment 1 spatial location did not affect performance. This result indicates that the findings of Experiment 1, with subjects bisecting lines presented in left and right space too far laterally cannot be wholly attributed to a perceptual bias. An overestimation of the lateral part of those lines should have produced rightward responses in left space and leftward responses in right space. This was however not the case. On the other hand a motor bias in terms of an 'overshoot' (see **Discussion** of Experiment 1) would have predicted the opposite response (righward judgements in right space, leftward judgements in left space) and again this was not found. Nevertheless both factors operating together and thus cancelling each other out would have resulted in a nonsignificant effect, as indeed reported here. Similarly both factors (motor and perceptual) operating together could also explain the lack of overall constant error as described here.

DISCUSSION OF EXPERIMENTS 1 AND 2

It is evident that cueing procedures provided clear and robust results throughout the two experiments. Use of a single letter consistently biased landmark judgements toward the other end of the line, i.e. caused a relative overscaling of the cued end of the line. This effect was not reduced by the use of a directional motor response (Experiment 2). This supports the idea that the influence of cueing upon active line bisection (found in Experiment 1 and by others) operates at the *perceptual* level, and little if at all at the level of any putative orienting response bias. (The latter in any case could only have explained cueing effects for lines placed in central space, without additional assumptions.) It seems likely that this perceptual bias can be attributed to a differential attentional salience of the two ends of a unilaterally cued line.

However, the overall leftward bias in line-bisection tasks in normal subjects as shown in Experiment 1 proved to be only partly the result of a perceptual bias, as demonstrated in Experiment 2. In order to substantiate this point it is interesting to mention an experiment similar to Experiment 2 which was carried out in our laboratory (Pagliarini, 1988; Milner *et al.*, 1992). The only distinction was that this experiment required a *verbal* judgement instead of a motor response. The surprising finding was that with a verbal rather than a motor response a perceptual effect was found: subjects showed an overall rightward choice bias when the data were summed over all conditions (Pagliarini, 1988), i.e. subjects subjectively underscaled the rightward extent of transected lines relative to the left. This finding clearly lends support to perceptual or attentional theories of the bisection bias. However this perceptual effect was no longer found when a motor response was required (Experiment 2). It seems therefore plausible that both factors (perceptual and motor) are indeed operating together, as this would produce the pattern of data observed here.

Thus the two factors may be about equally strong determinants of the constant error seen in active bisection. That is, the data presented here would be consistent with a dual role of the right hemisphere in both enhancing the perceptual salience of spatial stimuli in the left hemispace, and also in activating leftward orienting response tendencies.

Experiment 1 confirmed most previous reports (Bradshaw *et al.*, 1987a; Dudgeon, 1988; Schenkenberg *et al.*, 1980) that the leftward error in line bisection tends if anything to increase in the left half of egocentric space, but to reverse direction in the right half. Pagliarini (1988) extended this finding by demonstrating a parallel spatial effect on landmark judgements, in which subjects perceive midpoint-transected lines placed on either side as transected nearer to the spatial midline. (N.B. Superficially similar results have also been reported for judgements of tachistoscopically-presented stimuli (Reuter-Lorenz *et al.*, 1990); however those effects were demonstrated to be hemiretinally based, while the present data were obtained in free-gaze conditions, and are therefore most probably hemispatial in nature.) However Experiment 2 indicates that this perceptual bias can be nullified by a requirement to make a motor response to the end of the line subjectively nearer the landmark. A perceptually-determined preference for the medial end of a laterally placed line in Pagliarini's experiment may have been lost in Experiment 2 because the response was subject to a motor orienting bias tending to cause the subject to respond too far laterally. If so, then that same orienting factor probably also contributes to the hemispatial 'overshoot' effect in active bisection evident in Experiment 1.

Nonetheless it must be admitted that it could be argued that the hemispatial effect was just not strong enough to be replicated in Experiment 2. Certainly it was statistically weaker than the cueing effect in Experiment 1 (see also Fukatsu *et al.*, 1990).

LINE BISECTION PERFORMANCE OF ELDERLY NORMAL SUBJECTS

Although the findings of Experiment 1 agree with most previous reports (Bradshaw *et al.*, 1985; 1987a; Schenkenberg *et al.*, 1980; Dudgeon, 1988) the results on spatial location, with subjects bisecting towards the *right* in *right* hemispace and towards the *left* in *left* hemispace directly contradict the data of Nichelli *et al.* (1989). Their subjects marked lines presented in *right* hemispace towards the *left* of the true centre and lines displayed in *left* hemispace towards the *right* of the true centre. These discrepancies in the findings might be due to the fact that in Experiment 1 laterally presented lines were of considerably larger eccentricity than those used by Nichelli *et al.* (see also **Discussion** Experiment 1). However the data of Fukatsu *et al.* (1990) who found *no* effect of spatial location also differ from those of the first experiment. As both of those studies used subjects considerably older than the subjects studied in Experiment 1, another bisection experiment was carried out on elderly subjects in order to illuminate the effect of age. Performance of both hands was assessed as the data of Scarisbrick *et al.* (1987) suggest that use of the left hand may enlarge bisection errors due to increased right hemisphere activation.

EXPERIMENT 3

The third experiment was performed in order to ensure that the particular cueing and spatial location effects described in Experiment 1 would be replicated in elderly subjects. Additionally hand was included as an extra factor in order to assess possible differences in bisection performance and its interactions with spatial location and cueing.

METHOD

Subjects. Twelve elderly subjects (8 female, 4 male) ranging in age from 61 to 71 years (mean = 66), participated as unpaid volunteers in the experiment. All were strongly right-handed as assessed both by self-report and by administration of the 12-item Annett Handedness Inventory (Annett, 1967).

Materials. Materials were the same as in Experiment 1 except that only half the stimuli (12 lines instead of 24) were used in order to avoid fatigue in these elderly subjects.

Procedure. Again procedure was identical to Experiment 1 except that only a total of 72 lines was given with the 12 lines presented once in each spatial location (left, right or central to the subject's body midline), and that this was repeated using each hand separately. The order of locations and hand used was counterbalanced between subjects according to a Latin square.

Errors in line bisection for each subject and for each condition were measured in millimetres and averaged across the 3 instances. Errors to the right of the midpoint were given a positive value and those to the left a negative value.

Statistical Analyses. The mean error scores and their standard deviations were analysed. They were first subjected to a four-way analyses of variance with sex as a between-subjects factor, and hand (left vs right hand), space (left, centre, right) and cueing (no letter, two letters, letter left, letter right) as within-subjects factors. This analysis revealed no main effect of nor interactions with sex [$F(1,10) < 1$], so male and female data were combined in 3-way analyses. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5%

level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

Analysis of the mean error scores showed a significant main effect for cueing [$F(2.5,27.9) = 21.39$, $p < 0.001$].

Post hoc analyses revealed that unilateral left and right cues, apart from being significantly different from each other were also each significantly different from the no-cue and and two-cue conditions, which did not differ. The unilateral left cue 'pulled' bisection responses towards the left end of the line whereas the right cue, although bisection errors were still towards the left of the true centre, pulled responses towards the right end of the line (see Figure 2.4). Bisection under the no-cue and bilateral-cue conditions showed leftward bisection errors which were both significantly different from zero (no cue: $t= -2.83$, $p< 0.05$, with 9 out of 12 subjects showing the effect; bilateral cue: $t= -3.03$, p, 0.05, with 8 out of 12 subjects showing the effect).

Similarly over all, subjects averaged a significant leftward error (-2.16) with 8 out of 12 subjects demonstrating the effect ($t= -2.66$, $p< 0.05$).

However no main effect for spatial location was found, and subjects bisected towards the left of the true centre in all three conditions. Errors in all three locations differed significantly from zero (-2.53mm, $t= -2.25$, $p< 0.05$ for left space; -1.73mm, $t= -2.13$, $p< 0.05$ for the centre; -2.22, $t= -2.49$mm, $p< 0.05$ for right space).

There were no interactions between the three factors and neither was there an effect of hand.

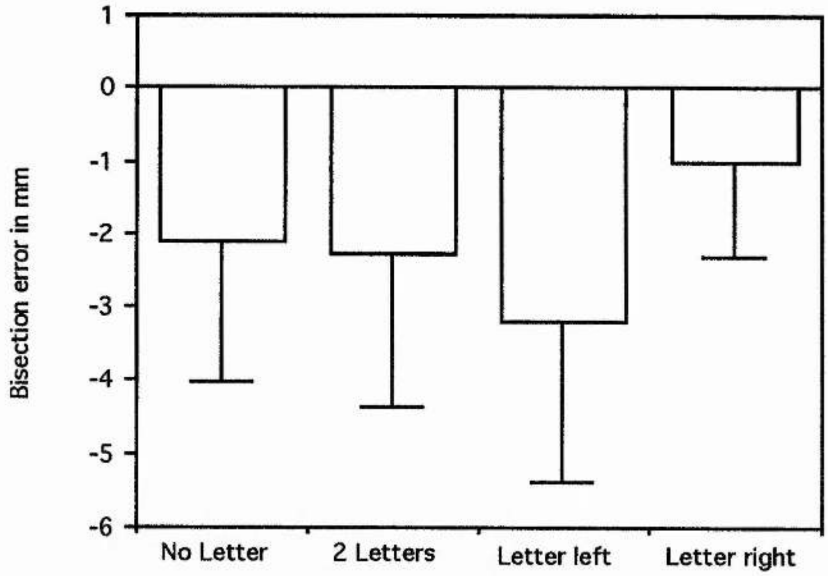

Figure 2.4: Mean error in mm in the bisection of lines, performed by the elderly subjects, as a function of cueing (no letter, 2 letters, letter left, letter right). Interpretation of positive and negative values as in Figure 2.1. Errors bars indicate the intersubject variability.

Analysis of the variability (SDs) of the bisection resonses also showed no significant effects (F < 1 for main effects and interactions).

DISCUSSION

Replicating the findings of Experiment 1 and various other investigations (Nichelli *et al.*, 1991; Reuter-Lorenz *et al.*, 1990) strong cueing effects were found in that unilateral left or right cues caused bisection to err towards the side of cueing. Like Experiment 1 this gives strong support to the idea that attention directed towards one end of a line causes a relative perceptual overestimation of that part of the line.

Nevertheless unlike Experiment 1 no effect of spatial location was found. This replicates the findings of Fukatsu *et al.* (1990) who also failed to find these effects in elderly subjects. However Nichelli *et al.*'s (1989) claim that 'subjects... overevaluate the linear length of those portions of space lying around the body line' could again not be confirmed: in this experiment elderly subjects demonstrated leftward displacement errors of similar magnitude over all three spatial conditions. The results are in line with the findings of Bradshaw *et al.* (1985; 1987a) who demonstrated leftward errors with centrally presented lines and strongly suggests a right hemisphere mechanism which is at work in all three spatial locations.

Unlike Scarisbrick *et al.*'s findings (1987) use of the left hand did not enlarge leftward bisection errors. On the other hand Bisiach *et al.* (1976) also reported no differential effect of hand on bisection performance of normal subjects.

If it is assumed that a right hemisphere mechanism is responsible for the leftward displacements found in this experiment it is again not clear whether this bias is due to an orienting/motor asymmetry or to a perceptual/attentional asymmetry; either of these might plausibly follow from a right hemisphere dominance for spatial processing (see also **Discussion** of Experiment 1). In the same vein, it could be argued that the effect of cueing results in 'overshoot' bisection responses (i.e., motor asymmetry) or perceptual overestimation of the cued end of the line. Again the problem with the standard bisection task is that it inevitably confounds perceptual and motor factors. Therefore in the following experiment the 'landmark' task was used once more to set perceptual/attentional and motor/orienting factors in mutual opposition.

EXPERIMENT 4

In this experiment (as in Experiment 2) the subjects were not asked to bisect a line, but instead were presented with lines that were already transected. They had to make a forced-choice judgement as to whether each line was transected nearer to its right end or its left end. A motor (pointing) response was again required as to the side the transection mark was perceived to be nearer. In the elderly subjects only two influences (as opposed to three in the younger subjects) were apparent in the bisection behaviour: (a) an overall leftward bias and (b) a bias towards the cued side. As argued earlier, bias (a), the constant error whereby subjects tend to bisect a line to the left of its true centre, might be due to a leftward *motor* bias, and/or to a *perceptual* overestimation of the left part of the line. If the predominant bias was leftward-motor, then in the pointing version of the landmark task, subjects would be expected to point generally to the *left* when faced with a centrally transected line. The contrary effect would occur with a predominantly perceptual bias: if subjects perceived the left half of a line as being longer, *right*ward pointing would be predicted. If the two effects are both present, then they would presumably subtract from one another.

The same principle applies for the cueing effect: if a motor bias is operating, judgements should be towards the cued line. If however a perceptual bias affects performance than judgements should be towards the end of the line opposite the cue.

No hand effects were found in Experiment 3. It seems thus unlikely that differences between hands should become relevant in this psychophysical judgement task, so hand was not included as a factor.

METHOD

Subjects. The same twelve elderly subjects as in Experiment 3 participated as unpaid volunteers in the experiment. All were strongly right-handed as assessed both by self-report and by administration of the 12-item Annett Handedness Inventory (Annett, 1967).

Materials. Materials were the same as in Experiment 2 except that only half of the centrally prebisected stimuli and only 10 asymmetrically pretransected lines were used. This set of 22 lines was presented once in each spatial location (left, right or central with respect to the subject's body midline), the order of spatial presentations being counterbalanced between subjects.

Procedure. Seating and instructions of the subjects were the same as in Experiment 2.

Statistical Analyses. Subjects' performance on the stimuli pretransected 5mm from the true midpoint was perfect for all 12 subjects. Subjectively however, subjects found it as hard to judge transections that deviated from either side of the midpoint as lines that were actually centrally bisected. The distribution of the errors on the 1 to 4 mm deviating lines was unequally distributed towards leftward responses in that all subjects more frequently judged the marks deviating to the right as being closer to the left end of the line than judging the left marks as closer to the right. This bias was highly significant ($t = 3.51$, $p < 0.01$).

For the lines pretransected in the centre, the *number of rightward responses* (maximum three per cell) were first subjected to a 3-way analysis of variance with sex. (Although the distribution of choices was approximately rectangular, ANOVA is sufficiently robust to cope with such data). Since again there were no effects of sex, male and female data were combined in the subsequent two-way analysis with space and cueing as whithin-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used for testing against chance performance in particular test conditions.

RESULTS

Although not significant in Experiment 3, spatial location proved to be a significant main effect in this experiment [$F(2.0,21.7 = 5.19$, $p < 0.015$]. Leftward judgements (presumably indicating a leftward *motor* bias) were significantly more frequent in left and central space than in right space (Figure 2.5), though responses were mainly leftward in right space as well. Only in left and central space did these judgements significantly differ from 50% chance performance ($t = -5.35$, $p < 0.001$ for left space; $t = -3.26$, $p < 0.001$ for central space).

As reported in the other experiments there was a highly significant effect of cueing [$F(1.8,19.5) = 7.18$, $p < 0.001$] with unilateral left and right cue conditions being significantly different from each other. However only the left

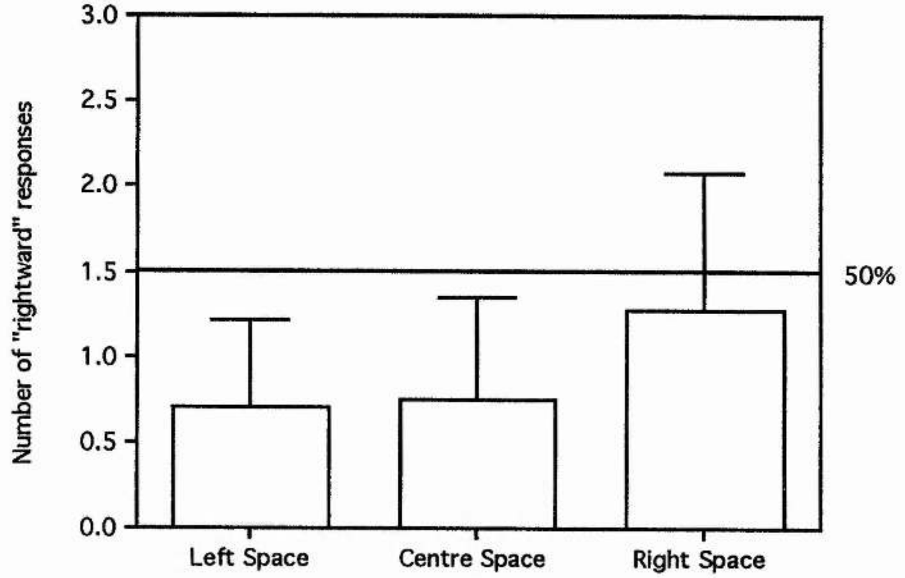

Figure 2.5: Manual landmark judgements of the elderly subjects as a function of space (left, centre, right): the mean number of forced-choice manual indications (out of 3) that an objectively central transection is placed right of centre. Errors bars indicate the intersubject variability.

cue condition differed significantly from the no-cue and bilateral cue conditions. Judgements made under the right cue conditions were not significantly different from those made under the no-cue and bilateral cue conditions which themselves did not differ from each other. So with a unilateral left cue subjects perceived the right end of the line as being closer to the transection mark, whereas a unilateral right cue had the opposite effect: subjects judged the left end of the line as being closer (Figure 2.6). Additional to this cueing effect there seemed to be a tendency to point leftwards, as these responses were not only more frequent than rightward judgements in the right cue condition but also in the no-cue and bilateral cue conditions; for all three conditions (including right cues) responses differed significantly from chance performance (no cues: $t = -2.36$, $p < 0.05$; bilateral cues: $t = -2.10$, $p < 0.05$; right cues: $t = -8.29$, $p < 0.001$).

Regarding overall performance subjects averaged a significant leftward pointing response ($t = -2.77$, $p < 0.05$) with 8 out of 12 subjects demonstrating this effect.

DISCUSSION

Comparable to Experiment 3, a strong effect of cueing was found. Subjects consistently chose the half of a symmetrically transected line *opposite* a letter cue as appearing shorter. Thus Experiment 4 strongly indicates that the effects of cueing on line bisection should be wholly or largely attributed to a perceptual overestimation of the cued half of the line. Biases to overestimate the cued end of the line remain strong even when a directional motor response is made (in the opposite direction).

The constant error found in this experiment demonstrates that the tendency to bisect to the left of the true centre (Experiment 3) cannot be

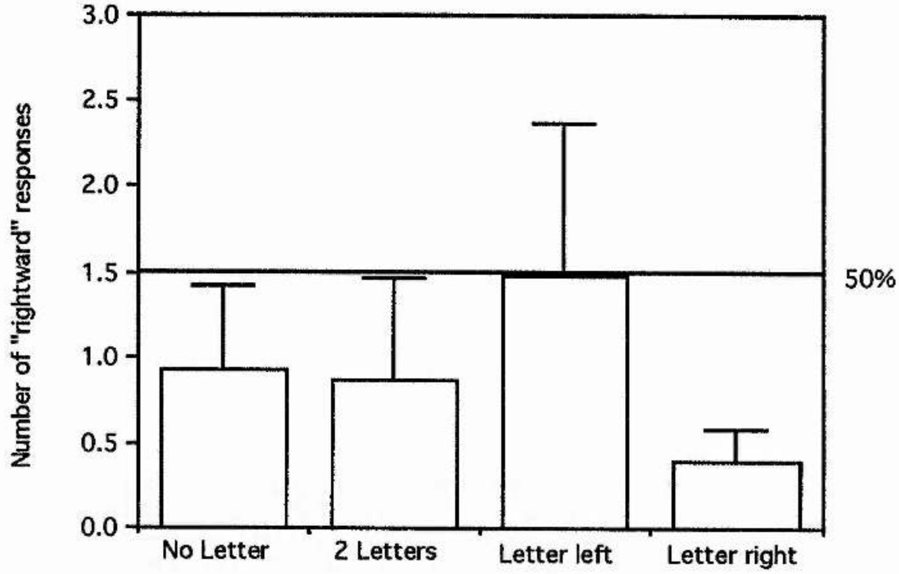

Figure 2.6: Manual landmark judgements of the elderly subjects as a function of cueing (no letter, 2 letters, letter left, letter right): the mean number of forced-choice manual indications (out of 3) that an objectively central transection is placed right of centre. Errors bars indicate the intersubject variability.

attributed mainly to a perceptual overestimation of the leftward half of the line. Pointing responses remained towards the left in the landmark task (Experiment 4), indicating a leftward *motor* bias which is strong enough to overcome any slight perceptual bias in favour of the left half-line.

Spatial location also affected the results. Presentation of the line stimuli in left and central space led to a significant preponderance of leftward responses. A similar tendency was nonsignificant in right spatial presentations. These findings could indicate that apart from demonstrating a leftward motor bias, subjects also overscaled the *medial* part of the line, comparable to the findings of Nichelli *et al.* (1989). The latter would tend to result in a centrifugal pattern of responses in the landmark task, i.e. rightward in right hemispace and leftward in left hemispace. Consequently both factors might operate together in the landmark task resulting in a greater leftward pointing tendency in left space but none in the right. For the bisection task however, an activation-determined motor bias (bisect laterally) would be cancelled out by the perceptual bias (bisect medially) thus resulting in a nonsignificant effect.

GENERAL DISCUSSION

It is puzzling that differences between the performance of elderly and younger subjects were found both in the traditional line bisection task and the 'landmark' test. Only cueing procedures provided consistently clear and robust results throughout the whole set of experiments. For both subject groups and both tests (bisection and 'landmark') use of a single letter biased judgements in a manner consistent with a relative overscaling of the cued end of the line. So for both subject populations it may be inferred that the influence of cueing upon active line bisection (found in Experiment 1 and 3, see also Nichelli *et al.*, 1989; Reuter-Lorenz and Posner, 1990) seems to operate at the perceptual level (overestimation of the cued half-line) and little if at all at the level of any putative orienting response bias. It seems likely that this perceptual bias can be attributed to a differential attentional salience of the two ends of a unilaterally cued line, perhaps due to visual areas within the contralateral hemisphere being especially activated.

Repeating the findings of Bradshaw *et al.* (1985; 1987a) significant leftward displacements of bisection responses in the central presentation condition were found for both subject groups. Both groups also showed an overall leftward bisection error but this proved significant for the elderly subjects only. It is commonly assumed that this bisection error is caused by a right hemisphere advantage for spatial processing. Tasks which involve the appreciation of visual space are assumed to selectively activate the right hemisphere (Bowers and Heilman, 1976; Kinsbourne and McMurray, 1975; Tartaglione *et al.*, 1983). However only a task such as the 'landmark' test could illuminate whether this activation is reflected in a relatively magnified percept of the leftward part of the line (Milner, 1987) or by a response bias in the form of a predominantly leftward orienting tendency (Heilman *et al.*, 1985a). The landmark data of the elderly subjects indicate that activation is reflected in leftward orienting responses, as judgements remain toward the left (Experiment 4). However no consistent bias on the landmark task was found in the younger subjects. There are two possible explanations for this: one is that both factors (perceptual and motor) were operating together in the younger subjects and thus cancelled each other out. This explanation would be consistent with a dual role of the right hemisphere in both enhancing the perceptual salience of spatial stimuli in the left hemispace, and also in activating leftward orienting response tendencies. On the other hand it could be argued that the overall effect (and the effect in central space) was simply not strong enough to be replicated in the landmark task (Experiment 2). It was certainly statistically weaker in the bisection experiment (Experiment 1) than the overall effect found in the elderly subjects (Experiment 3).

Regarding spatial location, the data of the younger subjects (Experiment 1) confirmed most previous reports (Bradshaw *et al.*, 1987a; Dudgeon, 1988; Reuter-Lorenz *et al.*, 1990) that the leftward error in bisection tends if anything to increase in the left half of egocentric space, but to reverse direction in the right half. However, the leftward errors found in central and left space in the younger subjects were significantly larger than the rightward errors in right space (Experiment 1). Right hemisphere involvement appeared even larger in the elderly subjects, as leftward bisection errors were found in all three spatial positions (Experiment 3). As use of lateral presentation conditions is assumed to activate the contralateral hemisphere it thus seems that, for these particular tasks, the contribution of the right hemisphere was greater than that of the left hemisphere.

In the landmark task younger subjects (Experiment 2) showed no consistent bias regarding spatial location. Again this could be due to a failure to replicate a weak effect. On the other hand Pagliarini (1988) demonstrated a perceptually- determined response bias toward the *midline* of laterally places lines. His subjects indicated the *midline* (the half of the line closer to the centre) of lines presented laterally in left and right hemispace, as being shorter than the lateral part. These data indiacte that the *lateral* part of laterally displayed lines appears relatively enlarged. However in Pagliarini's experiment, subjects made a verbal not a directional motor response. It is therefore possible that in Experiment 2, where a motor response was made, a perceptual bias toward the midline (indicating that part of the line as being shorter) may have been counteracted by a motor- orienting bias in terms of a lateral overshoot, independent of the actual perception.

This would be in direct opposition to the location effect reported in the elderly subjects (Experiment 4) who indicated the *lateral* part of laterally presented lines as being shorter. (This was only significant for left space which was probably due to the existence of a general leftward motor bias added on to the spatial biases; see also **Discussion** Experiment 4). So if a perceptual bias is at work in the elderly subjects it seems to enlarge the *medial* rather than the lateral part of laterally presented lines.

So regarding the effects of space in young and elderly subjects, it is not at all clear why elderly subjects should overscale the *medial* extent of a line while younger subjects if anything overscale the *lateral* extent. Consequently the results on spatial location presented here should, if possible, be replicated and the interpretations offered regarded as preliminary.

SUMMARY

Normal young and elderly subjects were tested in a series of 4 experiments to examine the influences of spatial location and cueing upon line bisection judgements. Judgements in all 4 experiments were strongly influenced by cueing with a letter at one or other end of the line. The spatial location of the line (in left, central or right body space) also had a minor effect in Experiments 1, 3 and 4, where also evidence was found for a small constant error when lines were presented centrally. It is argued from the results of Experiments 2 and 4, where no explicit bisection response was required, that perceptual/attentional factors, rather than a motor bias, play the major role in mediating the cueing effect. It is concluded that there is a substantial attentional effect upon judgements of extent, whereby paying greater attention increases perceived relative line length. However the constant error and the effect of spatial location, seem to be both perceptual and motor in nature and it seems

that the perceptual effect operates differently in younger than elderly subjects: whereas younger subjects seem to overestimate the lateral half-line of laterally presented lines, elderly subjects showed the opposite pattern, i.e. an overestimation of the medial part.

CHAPTER THREE

LINE BISECTION PERFORMANCE OF PATIENTS WITH UNILATERAL CEREBRAL STROKE

As aready mentioned in chapter one, Heilman and Valenstein (1979) proposed some years ago that the rightward bisection errors found in patients with hemispatial neglect might be due to constant errors in directing an action in egocentric space, rather than to defects in sensation (Denny-Brown *et al.*, 1952), attention (Kinsbourne, 1970) or internal space representation (Bisiach *et al.*, 1981). They attributed these errors in turn to an under-activation of right-hemisphere premotor systems which (in normal subjects) would initiate action in a leftward direction. In neglect patients however, intended acts are biased by a predominance of rightward vectors. In two later studies (1983; 1985b) Heilman and his colleagues demonstrated this phenomenon of 'directional hypokinesia' directly. In the earlier study (Heilman *et al.*, 1983) control subjects and patients with left- sided hemispatial neglect were asked to close their eyes, point their right index finger to their sternum, and then point to an imaginary point in space which was midline with respect to their chest. The patients with neglect pointed approximately 9cm to the right of the midline, whereas the controls pointed slightly to the left of the midline. It was argued, that because this task did not require visual or somesthetic input from left hemispace, the defective performance could not be attributed to hemispatial inattention or to a defect in hemispatial visual or somesthetic memory. Similarly, because the patient did not need to explore left hemispace, the deviation could not be due to an exploratory or gaze defect. Consequently the findings seemed most compatible with the directional hypokinesia hypothesis. In the later study, Heilman *et al.* (1985b) tested the ability of patients with left-sided hemispatial neglect to move a lever toward or away from the side of their lesion in response to a central visual stimulus. They demonstrated that the neglect patients needed more time to initiate movement toward the neglected left hemispace than the right hemispace, an asymmetry which was not found in brain damaged controls without neglect. The results of this study were again interpreted in favour of a directional hypokinesia operating in these patients.

Rather recently, a different model has been proposed that could also explain the nature of rightward bisection errors in neglect patients, although the underlying assumptions are rather different: Halligan and Marshall (1991) examined visuospatial localization in a patient with severe visual neglect. In the critical task condition, the subject was required to judge the spatial location of an arrow on a TV screen, the arrow being located either at the bottom or top of the screen, pointing inwards. The subject made her location judgements by indicating verbally which of an array of 15 numbers, on the opposite edge of the screen, the arrow was aligned with. It was found that the patient (PP) erred rightwards in these judgements, with an average error of about 1 cm. However the errors of judged location tended to be greater the nearer the arrow was presented to the left edge of the screen (up to an average of 1.75 cm), and less when it was near the right edge of the screen (ultimately declining to zero). The authors liken their results to the compression of a spring from left to right: it is as if the coordinates of PP's subjective space were pushed over to the right but uniformly 'shrunk' at the same time, thus maintaining Euclidean properties of equal spacing.

Generalization of this model could possibly account for the line bisection behaviour of neglect patients. If the horizontal dimension of space is visualized as a compression spring, a horizontal line might be equivalent to (say) 4 coils of the spring. If this subjective space is *uniformly* compressed in a neglect patient, a 20 cm horizontal line should appear to be (say) 17 cm long, irrespective of where it appears in objective space. However, if the compression is toward a fixed point on the right, as hypothesized by Halligan and Marshall (1991), then the horizontal line should appear to be shifted *as a whole* rightwards in space. This would predict a corresponding rightward error of the hand in moving to bisect the line, just as is assumed to occur in directional hypokinesia. Interestingly, this space-compression model would also predict a variation in line bisection error as a function of spatial location. Although all lines should appear subjectively shifted rightwards in location, a line placed on the patient's right should be shifted rather less, but one to the left shifted more, than a central line. Thus the arm should be misdirected more in respect of lines placed in left hemispace and less for lines in right hemispace. This has indeed been reported several times (Schenkenberg *et al.*, 1980; Nichelli *et al.*, 1989).

An alternative kind of spatial misperception that might be present in neglect patients was proposed by Milner (1987). It was suggested that there might be a distortion of the subjective space of a neglect patient that was *non*-Euclidean. That is, subjective space might be compressed, but progressively more so in more leftward parts of space. According to this view, the space occupied by the left half of a line would literally appear shorter to a neglect patient than the right half, therefore bisection would tend to be performed in a rightward direction. This idea would predict rightward bisection errors, but can only account for the increased errors in left space and the lesser ones in right space if it is assumed that the gradient of distortion is steeper in the leftward parts of ego-space than in the rightward parts.

All experiments presented in this chapter were designed to test this hypothesis, but the data of Halligan and Marshall (1991) may also be regarded as a direct test of this hypothesis in one patient: for each of 15 locations, 1 cm apart, their patient was asked to indicate the arrow's subjective position. According to Milner (1987), the subjective spacing between adjacent pairs of these 15 points should increase as one passes from left to right. The actual mean spacing of PP's judgements, however, show no trend for such an increase. Therefore the distortion of PP's subjective space appears to be more closely modelled by a uniform compression that maintains Euclidean geometry, rather than a distortion of space that is *non*-Euclidean.

On the other hand, there could be a problem with the task used by Halligan and Marshall in that it might underestimate abnormalities in subjective spatial relationships in neglect. Changes in the perception of the arrow's location might be matched by similar changes in the perceived locations of the numbers used to code the response. In addition, there is a necessary ceiling effect on judgements near the right edge of the screen, since large rightward errors would have hit or exceeded the edge. In any case, Milner's hypothesis might apply to the perceived *sizes* of objects rather than to the *distances between* them. Gainotti and Tiacci (1971) showed several years ago that in many right hemisphere damaged patients, visual shapes tended to be underestimated in size when compared with similar shapes shown on the right. They attributed this to the presence of patients with neglect in their group, and presented evidence to support this contention. Their data thus lend support at least to the more restricted version of Milner's hypothesis.

Interestingly neither the directional limb hypokinesia theory (Heilman and Valenstein, 1979) nor the uniform compression of space theory (Halligan and Marshall, 1991) would predict that a given line would appear of different length when located in different parts of visual space, nor that its true midpoint would appear to be shifted from centre. Instead, rightward bisection errors are explained on these theories as resulting from a spatial misdirection of the act of bisecting. One simple test of such accounts is therefore to present a *pre*-bisected line (Marshall and Halligan, 1989; Reuter-Lorenz *et al.*, 1990) in particular to use the 'landmark task' (see also chapter two). When the pre-transection is at the objective midpoint of a line, then on either the uniform-compression or the hypokinesia theory, a neglect patient should see the mark veridically as being at the midpoint. If, however, the patient literally sees the left half of the line as shorter than its right half, then a central transection should be judged as nearer to the left end of the line. On the additional assumption that the distortion of size scaling might change more steeply in left hemispace, the errors in landmark judgements should be more pronounced there than in central or right space.

In the following experiments six patients with clinically manifest neglect syndromes are described. They were first tested on the traditional line bisection test, where they demonstrated typical rightward bisection errors which varied in the usual way when the lines were presented in different parts of visual space. Subsequently the performance of these patients on the landmark task was assessed, containing an examination of the effects of spatial location, as Milner's hypothesis would predict that the gradient of distortion experienced by the neglect patients is steeper in the leftward parts of ego-space than in the rightward parts. Finally, cueing procedures were included. Although visual cues have been reported to reduce the amount of rightward displacement shown in the traditional bisection task (Riddoch and Humphreys, 1983; Halligan *et al.*, 1991) it is hardly ever abolished completely. It remains to be seen whether providing cues compensates for the (presumed) distortion of the patient's subjective space. Although it has been shown that normal control subjects overestimate whichever part of a line it explicitly cued (chapter two; Milner *et al.*, 1992) this might not necessarily be replicated for neglect patients.

EXPERIMENT 5A: LINE BISECTION PERFORMANCE OF RIGHT AND LEFT CVA PATIENTS AND CONTROLS

Experiment 3 (chapter two) revealed substantial leftward bisection errors when normal elderly subjects were asked to bisect lines. Bradshaw and colleagues (1985; 1987a) have argued that this behaviour pattern indicates the greater visuospatial processing power of the right hemisphere. Consequently right hemisphere *lesioned* patients should display rightward bisection errors. Evidence for this has been reported in the literature (Schenkenberg *et al.*, 1980; Bisiach *et al.*, 1976) although displacements are most commonly reported in patients who also show symptoms of hemispatial neglect (Heilman and Valenstein, 1979; Riddoch and Humphreys, 1983; Halligan and Marshall, 1988; 1989a;b; Halligan *et al.*, 1991 etc). In order to distinguish bisection errors of neglect patients from those of right hemisphere damaged patients in general, only RCVA patients without any evidence of neglect were included in Experiment 5A. In a subsequent experiment (5B) their performance was then directly compared to those of 6 RCVA patients with symptoms of neglect at the time of testing. The present experiment also investigated the line bisection behaviour of LCVA patients. Bisiach *et al.* (1976) reported leftward bisection errors for such patients, but Schenkenberg *et al.* (1980) pointed out that left hemisphere lesioned patients showed no larger errors than other groups using their left hand, suggesting that such damage produces no additional leftward error beyond that caused by use of the left hand (which presumably activates the right hemisphere).

As almost all of the brain lesioned subjects were strong right-handers, patients with left hemisphere damage found it difficult to handle a pencil with their left hand. The control group, who was also strongly right handed, was therefore asked to bisect all lines with their right *and* left hand (in separate blocks of trials). Comparisons were then made between the RCVA group and the control group, using their right hand, and the LCVA group and the control group, using their left hand.

METHOD

Subjects. Three groups of subjects were tested: 12 patients with unilateral right hemisphere infarct (mean age = 65.8, SD = 6.2; 6 male, 6 female), 12 patients with unilateral left hemisphere infarct (mean age = 58.4, SD = 12.3; 6 male, 6 female) and 12 normal control subjects (mean age = 66.2, SD = 3.8; 4 male, 8 female). All subjects in the two patient groups (LCVA and RCVA) had suffered cerebrovascular accidents within the previous 20 months of testing, and none betrayed any evidence of hemispatial neglect at the time of testing. CT scans were available on all of the patients, and none of these aroused any suspicion of bilateral damage. Two patients (J.M. and M.H., see Table 1) had shown signs of neglect acutely, but had recovered by the time of testing. All subjects were right-handed, with the exception of one LCVA patient (Patient J.R., Table 2) who was classified as mixed-handed according to a 12-item handedness inventory (Annett, 1967). The control group consisted of patients' spouses and friends, with no appreciable medical, neurological or psychiatric history.

No significant age differences were found between the control group and each of the two patient groups (one-way ANOVA), but the two patient groups differed in that the LCVA group was younger than the RCVA group. The three groups also did not differ with respect to education (one-way ANOVA), nor were there any significant differences between occupations held, when classified as skilled versus unskilled jobs (Chi-square test). Finally one way analyses of variance revealed that no group differences occurred with respect to smoking (number of cigarettes per day and years of smoking) or drinking (units of alcohol per week)

The two patient groups did not differ regarding prevalence of hemianopia or hemiplegia (Chi-square tests) or the time elapsed between onset of illness and testing (mean RCVA = 9.5 months, SD = 5.3; mean LCVA = 12.1 months, SD = 6.4, one way ANOVA). Clinical details of each patient and locations of lesions are summarized in Tables 3.1 and 3.2.

Neuropsychological Tests. All patients were assessed with a variety of neuropsychological tests. The *New Adult Reading Test* (NART) was used to provide a means of estimating the premorbid intelligence levels of adult patients, by presenting irregular words that can only be read correctly if the subject knows and recognizes them in their written form (Nelson and O'Connell, 1978). Powell's *Very Short Minnesota Aphasia Test* was used for a brief assessment of aphasia, and included subtests on language comprehension/production, reading and writing (Powell *et al.*, 1980). The *Benton Visual Form Discrimination Test (VFDT)* was used as an assessment of pattern perception (Benton *et al.*, 1978). Intellectual level was estimated by use of 3 verbal subtests (Information, Vocabulary and Digit Span) and 3 performance subtests (Picture Completion, Block Design and Object Assembly) of the *Revised Wechsler Adult Intelligence Scale* (Wechsler, 1981). Finally the *Behavioural Inattention Test (BIT)* was given as an assessment of hemispatial neglect: scores were derived from subtests of line-crossing, letter- and star-cancellation, figure copying, line-bisection and representational drawing (Wilson *et al.*, 1987).

Excluding the *WAIS-R*, no significant differences were found between the LCVA and RCVA patients (2-tailed t-tests for *NART*, *Minnesota*, *VFDT* and *BIT*). As the control subjects were also tested on the *WAIS-R*, two-way analyses of variance were carried out upon the three groups, using verbal vs performance subtests as a within-subjects factor. Two analyses were performed: one on the scaled scores and one on the age-adjusted scores (note that these means were based on only three subtests rather than the full six). Both analyses showed no main effects, but significant interactions of group by task ($F(2,33) = 4.41$, $p <$

Table 3.1: Clinical Data (R CVA Patients)

Patient	Age/Sex	Education	Post-CVA	Visual Field	Hemiparesis	Lesion (CT Scan)
J.B.	69/F	9 yr	15 mth	L hemianopia	yes	R fronto-temporo-parietal
G.B.	72/F	9 yr	6 mth	normal	yes	R subcortical
A.C.	70/F	9 yr	5 mth	normal	yes	R subcortical
S.C.	67/M	15 yr	3 mth	L hemianopia	yes	R parietal
R.D.	62/M	16 yr	20 mth	normal	no	R subcortical
J.M.	76/M	19 yr	17 mth	L hemianopia	yes	R parietal
M.H.	57/F	9 yr	12 mth	L hemianopia	yes	R fronto-parietal
H.G.	71/F	9 yr	8 mth	normal	no	R frontal
H.V.	58/M	9 yr	7 mth	normal	yes	R parietal
W.G.	60/M	16 yr	7 mth	normal	yes	R fronto-parietal
E.P.	60/F	9 yr	6 mth	normal	no	R subcortical
L.R.	67/M	9 yr	8 mth	normal	yes	R fronto-parietal
Mean	65.8	11.5 yr	9.5 mth			

Table 3.2: Clinical Data (L CVA Patients)

Patient	Age/Sex	Education	Post-CVA	Visual Field	Hemiparesis	Lesion (CT Scan)
J.B.	77/F	9 yr	4 mth	normal	yes	L subcortical
E.C.	67/F	9 yr	15 mth	normal	no	L subcortical
M.F.	42/F	9 yr	20 mth	normal	no	L fronto-parietal
J.C.	59/M	9 yr	11 mth	R hemianopia	yes	L temporo-occipito-parietal
J.K	50 F	9 yr	18 mth	R hemianopia	no	L parietal
G.M.	37/M	9 yr	5 mth	normal	no	L parietal
I.P.	66/F	9 yr	16 mth	normal	no	L parietal
E.P.	62/M	9 yr	2 mth	normal	no	L subcortical
J.P.	58/M	9 yr	14 mth	normal	yes	L temporal
J.R.	46/M	9 yr	19 mth	normal	yes	L subcortical
R.S.	67/M	9 yr	5 mth	normal	no	L parietal
M.S.	70 F	9 yr	16 mth	normal	yes	L subcortical
Mean	58.4	9.0 yr	12.1 mth			

0.02, scaled scores; $F(2,33) = 4.92$, $p < 0.002$, age-adjusted scores). The LCVA patients scored lower than the control group on the verbal but not on the performance subtests, while the RCVA patients scored lower than the control group on the performance but not on the verbal subtests (Newman-Keuls, $p < 0.05$). See Tables 3.3 and 3.4 for details of the patients on the neuropsychological tests.

Materials. Materials were the same as in Experiment 1 (chapter two) except that only half the stimuli (12 lines instead of 24) were presented in order to avoid fatigue.

Procedure. The procedure was also identical to Experiment 1 but only a total of 36 lines was given with 12 lines presented once in each spatial location (left, right or central to the subject's body midline). Both patient groups used their ipsilesional hand to bisect the lines, whereas the control group used each hand separately and thus bisected a total of 72 lines. The order of spatial locations was counterbalanced between subjects and order of hand used was also balanced across the control subjects. Whenever a subject failed to read out a letter, this letter was then subsequently pointed out by the experimenter and the patient encouraged to name it before bisecting the line.

Errors in line bisection for each subject and for each condition were measured in millimetres and averaged across the three instances. Errors to the right of the midpoint were given a positive value and those to the left a negative value.

Statistical Analyses. The mean error scores and their standard deviations were subjected to analyses of variance. The two sets of analyses (for both mean and SD) were three-way ANOVA's comparing the performance of one patient group to the control group using the *ipsilateral* hand. In each case the factors were: group (patients/controls) as a between-subjects factor, and space (left, centre, right) and cueing (no letter, two letters, letter left, letter right) as within-

Table 3.3: Neuropsychological Test Data (R CVA Patients)

Patient	NART (IQ)	Minnesota (errors)	Benton VFDT (correct /32)	WAIS (Verbal) Scaled Score	WAIS (Perf) (Age-adjd score)	BIT (correct /146)
J.B.	102	2	24	7.3 (8.3)	2 (4)	119
G.B.	116	1	25	8.3 (9.6)	5 (8.3)	136
A.C.	109	1	28	8.3 (9.6)	4.3 (6.6)	133
S.C.	121	0	23	12.3 (13.3)	7 (10)	133
R.D.	120	0	30	13 (14)	13.3 (16.3)	146
J.M.	124	0	29	14 (15)	8.6 (12.6)	134
M.H.	114	0	27	7.6 (8.3)	6.6 (8.3)	144
H.G.	95	2	31	6.3 (7.6)	7.3 (11)	139
H.V.	98	2	25	5.6 (6)	8.6 (11)	138
W.G.	121	0	32	13 (14.3)	8.3 (11)	143
E.P.	105	2	32	7.3 (8.3)	9 (11.6)	146
L.R.	98	1	28	7.5 (9)	9 (12.3)	144
Mean	110	0.91	27.8	9.2 (10.3)	7.4 (10.3)	137.9
SD	10.41	0.90	3.09	3.0 (3.0)	2.9 (3.2)	7.72

(see *Neuropsychological Tests* for description of tests)

Table 3.4: Neuropsychological Test Data (L CVA Patients)

Patient	NART (IQ)	Minnesota (errors)	Benton VFDT (correct /32)	WAIS (Verbal) Scaled Score		WAIS (Perf) (Age-adjd score)		BIT (correct /146)
J.B.	106	3	30	7	(8.6)	6.3	(10.3)	145
E.C.	110	1	23	7.6	(8.6)	8	(11)	146
M.F.	100	0	31	7.3	(8)	9	(10.6)	145
J.C.	97	30 (comprehension difficulties)	13	2.3	(2.6)	5.3	(6.3)	141
J.K.	105	0	22	6	(6.6)	7.3	(9)	145
G M.	107	0	32	10	(12.1)	13.3	(14)	146
I.P.	109	1	25	6	(7.6)	7.6	(11)	140
E.P.	110	1	26	10	(12.1)	8.3	(10.6)	145
J.P.	106	0	26	7.6	(8.3)	10.3	(11.3)	145
J.R.	100	2	28	6	(6)	7	(8)	139
R.S.	100	1	32	7	(8)	7	(9.3)	144
M.S.	112	1	28	9	(10)	7	(9.3)	145
Mean	105.2	3.3	26.3	7.2	(8.1)	8	(10.1)	143.8
SD	4.85	8.4	5.3	2.0	(2.4)	2.1	(1.9)	2.4

(see *Neuropsychological Tests* for description of tests)

subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

12 RCVA patients vs 12 controls (right hand only)

Surprisingly, analysis of the mean error scores revealed no significant differences between the two groups. Both groups however, showed a significant main effect of cueing [$F(2.6,57.7) = 9.24$, $p < 0.001$], and it transpired that unilateral left and right cues, apart from being significantly different from each other were also each significantly different from the no-cue and two-cue conditions, which did not differ. The unilateral left cue 'pulled' bisection responses towards the left end of the line whereas the right cue, although bisection errors were still towards the left of the true centre, pulled responses towards the right end of the line (see Figure 3.1). Bisection under the no-cue and bilateral-cue conditions showed leftward bisection errors, but only errors under the bilateral cue condition proved significantly different from zero (bilateral cue: $t= -2.46$, $p< 0.05$, with 17 out of 24 subjects showing the effect).

Similarly over all, subjects averaged a mean leftward error (-1.77mm) with 16 out of 24 subjects demonstrating the effect. Nonetheless a two-tailed t-test revealed that this constant error was not significantly different from zero.

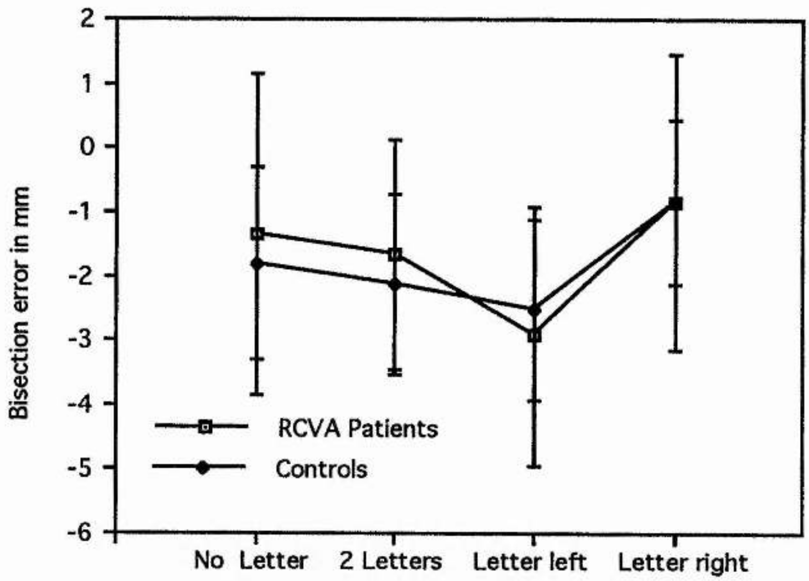

Figure 3.1: Mean Error in mm in the bisection of lines, performed by the RCVA patients and the control group, as a function of cueing (no letter, 2 letters, letter left, letter right). Rightward errors are coded as positive, leftward as negative. Errors bars indicate intersubject variability.

No main effect for spatial location was found, and subjects bisected towards the left of the true centre in all three conditions, although again none of these errors proved significantly different from zero (-1.62mm for left space; -1.37mm for the centre; -2.32mm for right space). No interactions between any of the three factors were found.

Analysis of the variability (SD's) of the bisection responses showed that it was larger for transections in left than right and central spatial positions for both groups ($F(1.9, 42.3) = 4.55$, $p < 0.02$; main effect of spatial location). No other effects were found.

12 LCVA patients vs 12 controls (left hand only)

Comparison of the LCVA group with the control group gave very similar results to the data reported above for the RCVA patients. Again analysis of the mean error scores revealed no significant differences between the two groups but both groups showed a highly significant main effect of cueing [$F(2.4,52.2) = 13.61$, $p < 0.001$].

Post hoc analyses revealed the same patterns as for the RCVA patients compared to the control group, in that unilateral left and right cues, apart from being significantly different from each other were also each significantly different from the no-cue and two-cue conditions, which did not differ. The unilateral left cue 'pulled' bisection responses towards the left end of the line whereas the right cue, although bisection errors were still towards the left of the true centre, pulled responses towards the right end of the line (see Figure 3.2). Bisection under the no-cue and bilateral-cue conditions showed leftward bisection errors which were both significantly different from zero (no cue: $t = -2.40$, $p < 0.05$ with 14 out of 24 subjects showing the effect; bilateral cue: $t = -2.20$, $p < 0.05$ with 18 out of 24 subjects showing the effect).

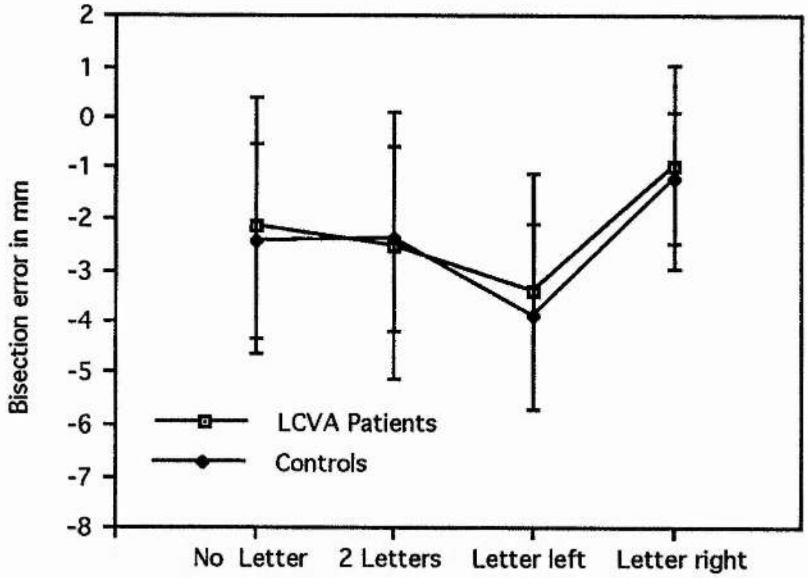

Figure 3.2: Mean Error in mm in the bisection of lines, performed by the LCVA patients and the control group, as a function of cueing (no letter, 2 letters, letter left, letter right). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

Similarly over all, subjects averaged a significant mean leftward error (-2.38mm) with 15 out of 24 subjects demonstrating the effect ($t= -2.24$, $p< 0.05$).

Again no main effect of spatial location was found, and subjects bisected towards the left of the true centre in all three conditions. However only errors in left and right spatial locations differed significantly from zero (-2.46mm, $t= -2.01$, $p< 0.05$ for left space; -2.72mm, $t= -2.55$, $p < 0.05$ for right space). No interactions between any of the three factors were found.

A group effect was found with regard to the variability of the bisection response ($F(1,22)= 4.92$, $p< 0.05$): over all conditions LCVA patients proved more variable than the control group.

EXPERIMENT 5B: LINE BISECTION PERFORMANCE OF NEGLECT PATIENTS COMPARED TO RCVA PATIENTS WITHOUT NEGLECT

Experiment 5B used the same paradigm as experiment 5A, but six further RCVA patients who demonstrated strong hemispatial neglect at the time of testing were included and their performance compared to those of the 12 RCVA subjects described above. With this comparison it might be possible to elucidate effects that are specific to neglect patients rather than to right hemisphere lesioned subjects *per se*. Furthermore an attempt was made to replicate cueing effects that have by now been repeatedly reported for patients with neglect syndrome (Riddoch and Humphreys, 1983; Halligan *et al.*, 1991). All subjects bisected the lines with their right hand.

METHOD

Subjects. Two groups of subjects were compared: 12 patients with unilateral right hemisphere infarct (see *Subjects* Experiment 5A) and 6 further patients with unilateral right hemisphere infarct who displayed hemispatial neglect at the time of testing (mean age= 69.5, SD= 8.4; 6 females).

All subjects in the neglect group had suffered from cerebrovascular accidents in the right hemisphere within the previous 12 months of testing and all performed outside normal limits on the administered subtests of the *BIT*. CT-scans which were available on five of the patients did not arouse any suspicion of bilateral damage. Details of each patient are given:

M.J. is a 61-year-old woman who had sustained a right hemisphere stroke 8 months prior to testing. A CT-scan performed ten days post-onset showed a patchy low attenuation in the right mid/anterior white matter. The patient had a left hemiplegia and also a left homonymous hemianopia. Her BIT score was 30/146 with 100% omissions in contralesional and central space for all cancellation tasks; in fact only stimuli on the extreme right of the page were attended to.

I.H. was a 67-year-old woman who had sustained right hemisphere damage 6 months prior to testing. CT-scan evidence at 7 months post-onset indicated an extensive right parieto-occipital infarct. The patient had a left hemiplegia but no reported visual field deficit. Her BIT score was 125/146 with all omissions occurring in contralesional space.

L.H. was a 76-year-old woman who sustained a right hemisphere stroke 6 months prior to testing. She showed a left hemiplegia and a left homonymous hemianopia and was also dysarthric. CT-scan evidence was not available, but the history and all clinical signs were consistent with right-sided stroke. Her BIT score was 48/146 with 100% omissions in contralesional and central space; only stimuli on the extreme right of the page were attended to.

A.O. was a 83-year-old woman who had sustained right hemisphere damage 2 months prior to testing. CT-scan evidence at 14 days post-onset indicated a right parietal infarct. She had a left hemiplegia and also a left homonymous hemianopia. Her BIT score was 41/146 with 100% omissions in contralesional and central space for all cancellation tasks; again only stimuli on the extreme right of the page were attended to.

M.F. was a 67-year-old woman who sustained a right hemisphere stroke 3 months prior to testing. She also showed a left hemiplegia and a left homonymous hemianopia. CT-scan evidence at 21 days post-onset showed a right parietal infarct. Although her BIT score was fairly high with 133/146 and did in fact exceed the cut-off score of the *BIT*, her scanning, bisection and cancellation behaviour proved consistent with left visual neglect and she was therefore included in the neglect group.

E.L. was a 63-year-old woman who sustained a right hemisphere stroke 3 months prior to testing. She showed a left hemiplegia but no reported hemianopia. CT-scan evidence at 10 days post-onset revealed an extensive right fronto-parietal infarct. Her BIT score was very low with only 21/146 with 100% omissions in contralesional and central space; only stimuli on the extreme right of the page were attended to.

All neglect patients proved to be right-handed and no significant age differences were found between the RCVA and the neglect group (one-way ANOVA) and the two groups also did not differ with respect to education (one-way ANOVA). There were however significant differences between occupations held, categorized as skilled versus unskilled jobs (Chi-square test), in that there was a higher frequency of unskilled employment in the neglect group (6 out of 6 unskilled) compared to the RCVA group (4 out of 12 unskilled). Finally one-way analyses of variance revealed that no group differences occured with respect to smoking (number of cigarettes per day and years of smoking) or drinking (units of alcohol per week). Additionally, the two patient groups did not differ regarding prevalence of hemianopia or hemiplegia (Chi-square tests) or the time elapsed between onset of illness and testing (mean RCVA = 9.5 months, SD = 5.3; mean neglect group = 5.8 months, SD = 3.86, one way ANOVA).

Neuropsychological Tests. The neglect patients were assessed with the same neuropsychological test battery as the other patients (see *Neuropsychological Tests*, Experiment 5A). One way ANOVAs revealed that there were no significant differences between RCVA and neglect group when tested for aphasia (*Minnesota*) or premorbid intelligence levels (*NART*). There were however highly significant differences with respect to visual form discrimination (*VFDT*) and assesssment of hemispatial neglect (*BIT*), in that the neglect group performed considerably worse than the RCVA group ($F(1,16) = 49.3$, $p < 0.001$ and $F(1,16) = 34.8$, $p < 0.001$ respectively). Regarding the *VFDT* it should be noted that four of the six neglect patients (I.H. and M.F. excluded) attended to the designs on the right of the page only (100% rightward responses in all four subjects), although the test was presented in right hemispace. This bias probably contributed to the bad performance of the neglect group in this test (though it is possible that it was secondary to a perceptual deficit). The same four patients who displayed this strong rightward bias in the *VFDT* also scored very low on the *BIT* (see Table 5), showing 100% omissions in contralesional and central space and only attending to stimuli on the extreme right of the page. Patients I.H. and M.F. displayed omissions in contralesional space only. Regarding the WAIS-R two way analyses of variance were carried out upon the two groups, using verbal and performance subtests as a within-subject factor. Again two analyses were performed: one on the scaled scores and one on the age-adjusted scores. Both analyses showed main effects for group and task, but significant interactions of group by task ($F(1,16) = 4.35$, $P < 0.05$, scaled scores; $F(1,16) = 6.1$, $P < 0.02$, age-adjusted scores) modified these findings, in that for the scaled scores neglect patients scored lower than RCVA patients in the performance subtests only, and on the age adjusted scales, although they scored lower on both parts, the difference on the verbal subtests was marginal ($p = 0.042$, Newman-Keuls). See Table 3.5 for details of the neglect patients on the neuropsychological tests.

Materials and *Procedure.* Materials, procedure and scoring were the same as in Experiment 5A. Both patient groups used their ipsilesional (right) hand to bisect the lines. The order of spatial locations was counterbalanced between subjects.

Statistical Analyses. Again the mean error scores (scored as rightward = positive) and their standard deviations were subjected to analyses of variance comparing the performance of the RCVA and the neglect patients using the factor of group (RCVA/neglect) as a between-subjects factor, and space (left, centre, right) and cueing (no letter, two letters, letter left, letter right) as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

The mean rightward error scores proved substantially larger in the neglect group than the RCVA control group ($F(1,16) = 24.87$, $p < 0.001$) and whereas the RCVA patients displayed small insignificant leftward deviations (-1.7mm), significant rightward errors (18.3mm) were found in the neglect group (t-test against zero: $t(5) = 6.97$, $p < 0.01$).

Table 3.5: Neuropsychological Test Data (Patients with visuo-spatial neglect)

Patient	NART (IQ)	Minnesota (errors)	Benton VFDT (correct /32)	WAIS (Verbal) Scaled Score	WAIS (Perf) (Age-adjd score)	BIT (correct /146)
I.H.	112	1	19	8.0 (9.0)	2.3 (4.3)	125
L.H.	100	3	12	7.3 (8.6)	2.3 (4.3)	48
M.J.	98	1	15	6.0 (6.6)	3.0 (4.3)	30
A.O.	101	3	15	8.0 (9.3)	1.6 (3.0)	41
M.F.	110	2	22	9.0 (10.3)	5.0 (7.3)	133
E.L.	96	2	12	6.3 (7.3)	1.6 (2.3)	21
Mean	103	2	15.8	7.4 (8.5)	2.6 (4.3)	66.3
SD	6.6	0.9	4.0	1.1 (3.0)	1.3 (1.7)	49.5

(see *Neuropsychological Tests* for description of tests)

There was also a highly significant group x cue interaction ($F(1.9, 29.6) = 8.64$, $p < 0.001$) with the neglect group demonstrating largest deviations for the no-cue and right cue conditions and smallest displacements for the left cue and two cue conditions (Figure 3.3). *Post hoc* analyses revealed significant differences between left and right cues and between the left and no cue condition but not between left and bilateral cue condition. Similarly the right cue condition differed from the left and two cue, but not the no-cue condition (Figure 3.3). None of these *post hoc* comparisons proved significant for the RCVA group. However, this was probably due to the large mean square error which must have concealed the effect. Cueing effects were clearly demonstrated in Experiment 5A.

There was no effect of spatial location although the neglect group showed a trend [interaction group x location, ($F(2.0, 31.7) = 3.12$, $p = 0.058$)] for larger rightward errors in left and central spatial locations than right locations (22.6mm, 19.5mm vs 13.1mm respectively). No other effects were reported.

Analysis of the standard deviations also revealed an interaction of group x cueing ($F(2.1, 34.1) = 7.69$, $p < 0.001$) indicating an overall greater variability for the neglect patients as opposed to the RCVA controls. Also, within the neglect group, bisection responses under the no-cue condition proved of greater variance than all other conditions.

DISCUSSION OF EXPERIMENTS 5A AND 5B

Strong cueing effects were found for the left and right CVA patients and the control group. As in Experiments 1 and 3 (chapter two), unilateral left or right cues caused bisection to err towards the side of cueing. Again this finding is consistent with the idea that attention directed toward one end of the line causes a relative perceptual overestimation of that part of the line. As

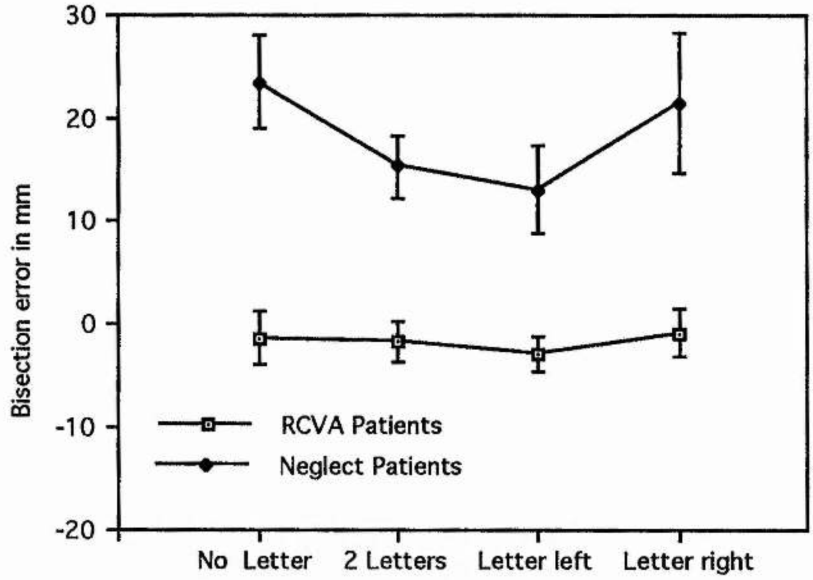

Figure 3.3: Mean Error in mm in the bisection of lines, performed by the RCVA patients and the neglect patients, as a function of cueing (no letter, 2 letters, letter left, letter right). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

predicted, cueing effects were the same for the two patient groups (LCVA, RCVA) and the control group. This suggests that most patients with unilateral brain damage have no deficit in consciously attending to targets.

There were also highly significant cueing effects for the neglect patients in that unilateral left cues decreased the amount of rightward displacements shown, whereas unilateral right cues increased the amount of error. It is interesting though, that bilateral cues where as effective in reducing rightward deviations as single left cues and on the other hand, single right cues produced no larger displacements than the no-cue condition. These data are in full agreement with the findings of Riddoch and Humphreys (1983) who in their first experiment, reported a reduction in neglect with the single left cue and (in their second experiment) a similar reduction in the bilateral cue condition when the patient was asked to report the left letter only. Although the patients presented here were required to read both letters, almost all neglect patients reported the right letter only, with the consequence that the left letter was then pointed out to them before bisecting the line. This resulted in a comparable experimental condition to that created by Riddoch and Humphreys in their second experiment. Nonetheless contrary to Riddoch and Humphreys' findings, single right cues produced no larger rightward displacements than the no-cue condition. According to the covert orientation argument (Posner *et al.*, 1982) neglect should increase with a right side cue as the patient has difficulty in shifting attention (disengaging) once it has been oriented to the right. On the other hand, it is possible that in the absence of any cues, the patient's attention is already prebiased to the right thus producing displacements equivalent to those made in the presence of a right side cue: certainly Kinsbourne (1987) argues that ...'the patient with neglect turns ever to the lesioned side when negotiating his environment'.

Nonetheless the findings still differ from those of Heilman and Valenstein (1979) who showed that in their neglect patients, cueing had no significant effect on performance: the amount of neglect was equivalent whether patients had to report the letter on the left or right end of the line. However, various investigators have now been able to show that left cues, or forcing the patient to scan towards the left end of the line significantly reduces the amount of rightward displacement shown in these patients (Halligan and Marshall, 1989a; Halligan *et al.*, 1991, Reuter-Lorenz and Posner, 1990). On the other hand it should be noted that the rightward displacement is hardly ever abolished completely.

The rightward error was certainly still present for the six neglect patients presented here: even when a cue was provided at the left end of the line (the condition with produced smallest rightward displacement) a considerable mean error of 13mm remained. Surprisingly though, no significant displacements were found for the RCVA group who did not show any evidence of neglect at the time of testing. Indeed the overall error score of this group proved not significantly different from perfect performance. This is contrary to the findings of Schenkenberg *et al.* (1980) who found significant rightward displacements in their right hemisphere damaged patient group. Bisiach *et al.* (1976) also reported rightward bisection errors in their right hemisphere damaged group but the data of both these studies might be biased, as no attempt was made to analyse patients with hemispatial neglect separately. The more recent literature gives little information regarding the bisection behaviour of right or left hemisphere damaged subjects as most studies compare the performance of neglect patients with that of normal controls (Halligan and Marshall, 1991; Halligan *et al.*, 1990; Reuter-Lorenz and Posner, 1990). However in very recent work, Halligan and Marshall (1992) point out that, although some people in the field seem to think that right hemisphere lesions will invariably provoke an abnormal shift to the right on line bisection, this is not always the case (even when the patients show neglect on other tests). They quote the performance of two patients as evidence against this assumption. Indeed Tegner and Levander (1991b), who tested 25 neglect patients on lines of varying length and used right and left hemisphere lesioned patients and normal subjects as controls, found very similar displacements to those presented here: on lines of 20cm length, both right hemisphere lesioned patients and controls showed small leftward displacements (-0.22mm and -1.mm respectively). The left hemisphere lesioned group also made leftward errors (-3.3mm) but these were slightly larger. This was also the case for the LCVA group presented here: they averaged an overall error of -2.26mm which proved significantly different from zero. Nonetheless these deviations were no greater than those shown by the control group when using their left hand. Although these findings might indicate that use of the left hand increases leftward bisection errors (Scarisbrick *et al.*, 1987) no significant hand differences were reported for the control subjects when assessed for differences between right and left hand (see Experiment 3, chapter two).

As in Experiment 3, no effect of spatial location was found but bisection errors of the LCVA and the control group (using their left hand) revealed significant leftward displacements in both left and right spatial positions. This finding together with the reported constant error might suggest a leftward bias operating in both LCVA and control group (through use of left hand), but not in the RCVA or control group (with use of right hand). As in Experiment 3 this could indicate a right hemisphere mechanism responsible for the bias (Bradshaw *et al.*, 1985; 1987a) but if present, this seems to be a weak effect as the LCVA patients do not differ significantly from the controls.

It is not clear whether this bias (assuming it is a consistent effect) is due to an orienting/motor asymmetry or to a perceptual/attentional bias; either of these might plausibly follow from a right hemisphere dominance for spatial processing. The same problem applies for the findings on the neglect patients: does the overall rightward error or the slightly larger displacement in left and central as opposed to right space, reflect a directional hypokinesia (Heilman *et al.*, 1987) or a perceptual underestimation of the left part of the line (Milner, 1987)?

EXPERIMENT 6A: LANDMARK PERFORMANCE OF LCVA, RCVA AND CONTROL SUBJECTS

To attempt to resolve this question, in the next experiment the landmark task (see Experiments 2 and 4, chapter two) was presented to the RCVA, LCVA and control patients. Two influences were apparent in the bisection behaviour described in Experiment 5A: (a) a bias toward the cued side, and (b) an overall leftward bias for the LCVA patients and the control group when using their left hand. This constant error might be due to a leftward *motor* bias, with or without a *perceptual* overestimation of the left part of the line. If the predominant bias was leftward-motor, then in the landmark task, subjects would be expected to point generally to the *left* when faced with a centrally transected line. The contrary effect would occur with a predominantly perceptual bias: if subjects perceived the left half of a line as being longer, *right*ward pointing would be predicted. If the two effects are both present, then they would presumably subtract from one another.

The same principle applies for the cueing effect: if a motor bias is operating (through an activation of the contralateral hemisphere), pointing judgements should be towards the cued end of the line. If however a perceptual bias affects performance than judgements should be made towards the end of the line opposite the cue.

No hand effects were found for the control group in Experiment 3 (chapter two). Furthermore as this task required pointing only, no difficulties were experienced by the LCVA group when asked to do this with their left hand. It also seems unlikely that differences between hands would become relevant in this psychophysical judgement task when they were not apparent in the bisection task, so hand was not included as a factor and the data of all three groups (RCVA, LCVA and controls) analysed together. An objection could be raised against direct comparison of right and left CVA patients as the LCVA group proved younger than the RCVA group. On the other hand both groups had little difficulty in performing the bisection task and produced virtually the same results as the controls, suggesting that age was not a relevant factor. However an additional analysis excluding the three youngest patients of the LCVA group, was performed in order to ensure that age differences did not affect the results.

METHOD

Subjects. Subjects were the same as in Experiment 5A with 12 patients with unilateral right hemisphere infarct, 12 patients with unilateral left hemisphere infarct and 12 normal control subjects.

Materials. Materials were the same as in Experiment 2 except that only half of the centrally prebisected stimuli and only 10 asymmetrically pretransected lines were used. This set of 22 lines was presented once in each spatial location (left, right or central with respect to the subject's body midline), the order of spatial presentations being counterbalanced between subjects.

Procedure. Seating and instructions for the subjects were the same as in Experiment 2. However, in order to ensure that all subjects understood the instructions correctly, randomly cued lines which were transected noticeably to the right or left of the true centre (2 to 4 cm from the middle) were first presented to the subjects. Each subject had to give five continously correct responses before the landmark experiment was started.

Statistical Analyses. For the lines pretransected in the centre, the *number of rightward responses* (maximum three per cell) were subjected to two separate three-way analysis of variance: in the first analysis all subjects were included and group (LCVA patients, RCVA patients and controls) was a between-subjects factor, and space and cueing were within-subjects factors. The second analysis was the same apart from excluding the three youngest LCVA patients. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used for testing against chance performance in particular test conditions.

RESULTS

Confirming the expectations, no significant differences between LCVA and RCVA group or interactions with group were found for the second analysis, which excluded the three youngest subjects of the LCVA group. Consequently only the results of the first analysis shall be reported in detail.

As in Experiment 5A, no main effects of group or interactions with group were found. There was however a highly significant effect of cueing for all three groups [$F(2.3,76.6) = 8.88$, $p < 0.001$], with unilateral left and right cue conditions being significantly different from each other. However only the left cue condition differed significantly from the no-cue and bilateral cue conditions. Judgements made under the right cue conditions, although significantly different from those made under the no-cue condition, did not differ from the bilateral cue condition. Nonetheless no-cue and bilateral cue condition did not differ from each other. With a unilateral left cue subjects perceived the right end of the line as being closer to the transection mark, whereas a unilateral right cue had the opposite effect: subjects judged the left end of the line as being closer (Figure 3.4). However, only the unilateral right cue condition differed reliably from chance performance ($t(35) = 4.60$, $p < 0.01$). Responses under the no-cue, bilateral-cue and left cue conditions showed approximately equal numbers of rightward and leftward responses, and did not differ significantly from chance performance.

Similarly all subjects in the three groups divided their responses evenly between left and right at each of the three spatial locations, and when summed over all conditions.

All subjects performed perfectly for the stimuli pretransected 5mm from the true midpoint. Subjectively however, they found it as hard to judge transections that deviated from either side of the midpoint as lines that were actually centrally bisected. As already mentioned in Experiment 4, errors of the control subjects on the 1 to 4 mm deviating lines were unequally distributed towards leftward responses, in that all subjects more frequently judged the marks deviating to the right as being closer to the left end of the line than judging the left marks as closer to the right. This bias was highly significant ($t=(11) = 3.51$, $p < 0.01$). The same bias was found for LCVA patients ($t(11) = -3.08$, $p < 0.01$). The RCVA group, on the other hand, showed no significant difference between the numbers of errors made with rightwardly versus leftwardly transected lines ($t(11) = 1.48$).

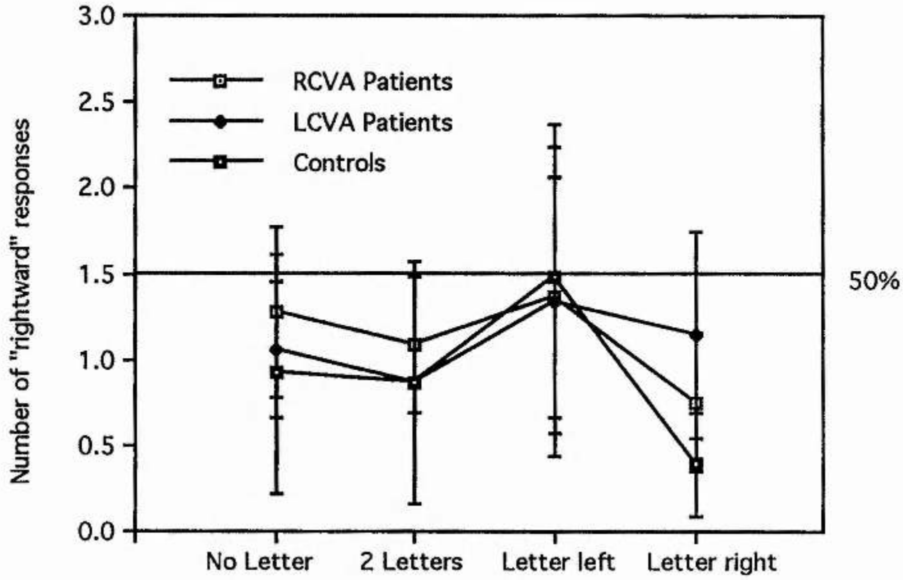

Figure 3.4: Manual landmark judgements of the RCVA and LCVA patients and the control group, as a function of cueing (no letter, 2 letters, letter left, letter right): the mean number of forced-choice manual indications (out of 3) that an objectively central transection is placed right of centre. Errors bars indicate intersubject variability.

EXPERIMENT 6B: LANDMARK PERFORMANCE OF NEGLECT PATIENTS COMPARED TO RCVA PATIENTS WITHOUT NEGLECT

Neglect patients also revealed a bias toward the cued side in the bisection task, but their generalized rightward error was superimposed on this effect. If this rightward deviation is due to a rightward *motor* bias (i.e., directional hypokinesia) subjects would be expected to point generally to the *right* (if anything) when faced with a centrally transected line. The contrary effect would occur with a predominantly perceptual bias: if subjects actually perceived the left half of a line as being shorter, *left*ward pointing would be predicted. If the two effects are both present, then again they would presumably subtract from one another. The cueing effect should be the same as for the other subjects in that, if a motor bias is operating, pointing judgements should be towards the cued end of the line. With a perceptual bias judgements should be towards the end of the line opposite the cue. However, the rightward bias observed in bisection would be expected to skew this effect either towards leftward or rightward judgements depending whether an overall perceptual or motor bias proved dominant.

METHOD

Subjects. Subjects were the same as in Experiment 5B with 12 patients with unilateral right hemisphere infarct without neglect and 6 further patients with unilateral right hemisphere infarct who displayed hemispatial neglect at the time of testing.

Materials and *Procedure.* Materials and procedure were the same as in Experiment 6A.

Statistical Analyses. For the lines pretransected in the centre, the *number of rightward responses* (maximum three per cell) were subjected to a three-way analysis of variance with group as a between-subjects factor, and space and cueing as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used for testing against chance performance in particular test conditions.

RESULTS

The only significant effect resulting from the analysis of the number of rightward responses was an interaction of group x cueing [$F(2.1,33.3) = 5.6$, $p < 0.001$]. Whereas the RCVA group showed cueing effects with the half-line opposite the cue being indicated as shorter (see also Experiment 6A), the neglect group showed the contrary response in that they pointed to the cued end of the line, thus indicating a possible motor bias toward the cued side. Comparisons of the no cue and bilateral cue conditions revealed that the neglect group made more leftward judgements than the RCVA group in these presentations (see also Figure 3.5). No other comparisons proved significant.

No overall group effect was found but this was due to the fact that one of the neglect patients (E.L.) pointed mainly to the right end of the lines (left space: 9 out of 12 judgements to the right, centre: 8 out of 12, and right space 8 out of 12 judgements to the right). A Chi-square test revealed that she demonstrated significantly more right than leftward judgements overall: $chi^2 = 5.4$, $p < 0.05$., thus supporting an interpretation of her neglect symptoms in terms of directional hypokinesia. Indeed when she was excluded from the analysis of variance a group effect was found ($F(1,15) = 4.56$, $p < 0.05$), with

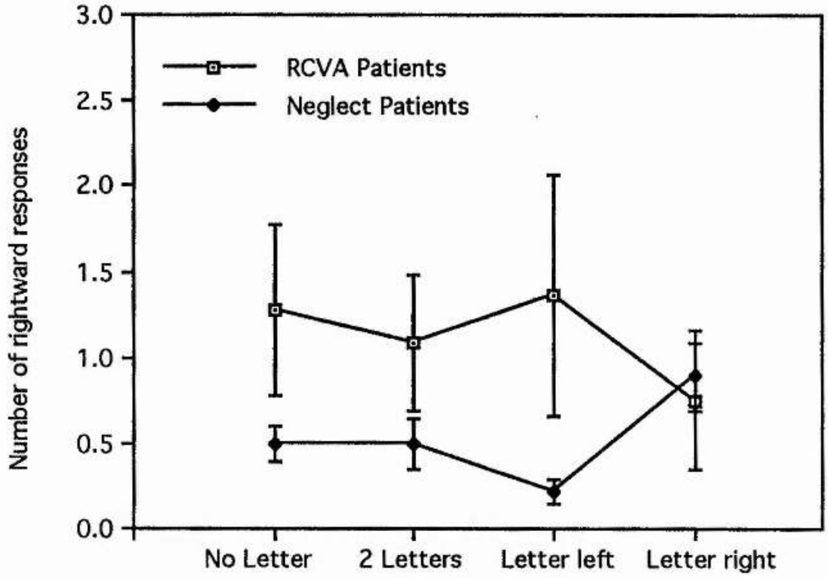

Figure 3.5: Manual landmark judgements of the RCVA patients and the neglect group, as a function of cueing (no letter, 2 letters, letter left, letter right): the mean number of forced-choice manual indications (out of 3) that an objectively central transection is placed right of centre. Errors bars indicate intersubject variability.

neglect patients displaying a larger proportion of leftward judgements than the RCVA group. Furthermore performance of the neglect group revealed a significant leftward bias that differed from chance performance ($t(4) = -8.00$, $p < 0.01$) whereas overall judgements of the RCVA group were randomly distributed.

Regarding the asymmetrically pretransected lines, E.L. again showed indications of directional hypokinesia in that she judged all marks to the right of the true centre correctly (5 out of 5 for all three spatial conditions) whereas lines marked to the left were responded to as if the mark was closer to the right (5 out of 5 for left and central spatial positions, 2 out of 5 for right space; again a Chi-square test uncovered significantly more overall rightward than leftward judgements: $chi^2 = 5.4$, $p < 0.05$). On the other hand all other neglect patients showed the opposite tendency in that lines pre-transected to the left of centre, were indicated correctly (to the left) at levels averaging from 93% (I.H.) to 100% (all other patients). However, with lines pre-transected to the right, errors (responses to the left) ranged from 73% (I.H.) over 86% (M.F.) to 100% errors (M.J., A.O. and L.H.): i.e. they still tended to point to the left end of lines. Evidently even a line marked 5 mm to the right of centre appeared to these 5 patients as marked to the *left* of centre. In both M.F. and I.H., these errors with non-centrally transected lines were significantly more frequent in left hemispace than in right.

DISCUSSION OF EXPERIMENTS 6A AND 6B

As in Experiment 5A (bisection) strong cueing effects were also found for the LCVA, RCVA and control group in the landmark task. Subjects consistently chose the half of a symmetrically transected line *opposite* a letter cue as appearing shorter. Thus the experiment strongly indicates that the effects of cueing on line bisection should be wholly or largely attributed to a perceptual overestimation of the cued half of the line. Biases to overestimate the cued end of the line remain strong even when a directional motor response is made (in the opposite direction). This seems to be the case for brain lesioned subjects (without neglect) as well as for normal controls.

The constant leftward error found in Experiment 5A for the LCVA and the control group when using their left hand, was not replicated for centrally pre-transected lines in the landmark task, in which both groups showed an overall equal distribution of left and rightward judgements. Surprisingly though, both these groups showed a leftward bias on the asymmetrically pre-bisected lines, in that transections to the right of the true centre were more frequently judged as if closer to the left than leftward transections were indicated as if closer to the right. This trend was not apparent for the RCVA group. If anything, this would indicate a leftward *motor* bias in the LCVA and control group, which is strong enough to overcome any slight perceptual bias in favour of the left half-line as being perceived longer. It is, however, difficult to explain why this motor bias was not found for landmark judgements of centrally pre-bisected lines. If one assumes that it was cancelled out by a *perceptual* bias to indicate the right end of the line as being shorter, this perceptual bias should, if anything, have been even more obvious with rightwardly transected lines, as in this condition the transections were actually closer to the right end of the line. It seems therefore likely that the leftward bias is at best a weak effect which might not be replicated in another experiment.

The findings on most of the neglect patients, on the other hand, demonstrated clearly that the rightward bisection errors found in Experiment 5B were due to a spatial misperception. Over all conditions, five out of six neglect patients predominantly indicated the left part of a line as being shorter than the right half. Even lines transected as far as 5mm to the right of centre were predominantly judged in this way. This response pattern is clearly consistent with the idea that the subjective space of neglect patients is distorted in so far as it is leftwardly compressed (Milner, 1987; Milner et *al.*, 1993). The space occupied by the left half of a line literally appears shorter to a neglect patient than the right half. This is presumably why the active bisections were performed in a rightward direction in these five patients. Milner's hypothesis also predicts that the gradient of distortion is steeper in the leftward parts of ego-space than in the rightward parts. Although no effect of spatial location or interaction with space was found in Experiment 6B, the results tended to be in the expected direction, with fewer rightward judgements in left and central spatial positions than right space (15% left space, 16% centre, 19% right space, excluding E.L.'s data as they were mainly to the right anyway). Similarly, when lines pre-transected to the right of the true centre were indicated correctly (patients I.H. and M.F.) this occurred in right hemispace only.

Nonetheless one of the neglect patients (E.L.) did show mainly *rightward* responses and this behaviour extended to asymmetrically bisected lines as well. Consequently her rightward bisection errors seem to have been due to a directional hypokinesia, i.e. a spatially misdirected action possibly due to an underactivation of the right hemisphere premotor system which would normally initiate action in a leftward direction (Heilman *et al.*, 1987). As already pointed out by other investigators (Bisiach et al., 1983; De Renzi, 1982) this adds further evidence for the notion that hemispatial neglect is qualitatively less homogeneous than might be expected. The majority of the patients presented here demonstrated a perceptual distortion of their subjective space; nonetheless one of them showed no such effect, but instead a directional hypokinesia. Similar findings have been reported by Bisiach *et al.* (1990) who demonstrated that some patients would move a manipulandum leftwards from the spatial midline in order to set a transection pointer rightwards from the midpoint of a line that they were asked to bisect. Other patients however, gave evidence for a spatially misdirected movement such as would be expected with a directional hypokinesia.

Experiment 5B revealed significant cueing effects for bisection responses in the neglect group. This supports the notion that patients with neglect are capable of consciously orienting to stimuli (Riddoch and Humphreys, 1983; Milner, 1987). Consequently cueing in the landmark experiment should have produced similar effects to those reported for the right CVA patients, i.e. judging the half-line *without* the cue as *shorter* than the cued half. Surprisingly though, all patients (including E.L.) pointed towards the *cued* half of the line. It should be noted that this effect was embedded in an overall tendency to indicate the left half of a line as being shorter: judgements varied significantly from chance performance in all four conditions (no-cue, bilateral cue, single left and right cue). Nonetheless it seems that in these neglect patients cueing produces motor rather than perceptual effects. This bias is different from a directional hypokinesia as it operates towards the cued side rather than producing a general rightward bias independent of cueing conditions (Heilman and Valenstein, 1979). It seems likely that the cueing effects reported for the bisection task (Experiment 5B) were also due to increased motor response amplitudes, which shifted marks closer towards the cued sides, thus reducing errors with a left cue but increasing rightward deviations with a right cue. The only proposal which can be made at present to explain these increased motor responses, is to assume that the lateralized cues produced an activation imbalance in favour of the directly stimulated hemisphere (see also Reuter-Lorenz *et al.*, 1990) which in turn facilitated turning towards the cued side. Presumably the attentional structures damaged by the neglect-causing lesions were not able to mediate a normal effect of cueing on size perception (Milner *et al.*, 1992).

EXPERIMENT 7A: BISECTION OF LINES OF VARYING LENGTH (COMPARISON OF LCVA, RCVA AND CONTROL GROUP)

As already mentioned in chapter one, line length has been found to affect the bisection performance of patients with neglect syndrome. Bisiach *et al.* (1983) point out that although earlier studies (Bisiach *et al.*, 1976; Schenkenberg *et al.*, 1980) failed to find an effect of line length on the relative degree of rightward displacement shown by the patients, there was a clear increase of the rightward deviation of the bisection response with line length in their study. It seemed however, that some patients showed displacements that were independent of line length, whereas others produced far larger rightward displacements the longer the lines presented were. Halligan and Marshall (1988) concluded from the data associated with this second finding that, if one extrapolated the performance to even smaller lines, the subject's subjective midpoint should cross over from a rightward to a leftward displacement. They did indeed demonstrate this on a patient who showed linear increase of the rightward displacement with line length and also a consistent leftward displacement with lines of 2.5 cm length. Halligan and Marshall interpreted these findings in terms of an attentional boundary placed slightly to the left of the objective midline. In order to explain the 'crossover' to the left they suggested a perceptual completion to the hypothesized attentional boundary, i.e. the patient incorporates the space to the attentional boundary into his representation of the line. Nonetheless in a later study (Halligan and Marshall, 1989c) they fail to confirm their theory of an attentional boundary operating in neglect patients and in yet another single case study explain bisection errors through the Weber fraction (Marshall and Halligan, 1990). They argue that in psychophysical terms, a bisection task requires one to place a mark such that one line is divided into two lines whose respective lengths differ within one 'just noticeable difference'. Moreover the larger the original magnitude of the stimulus, the greater the range of transections that cut the initial stimulus length in two equal segments (Wolfe, 1923 cited by Marshall and Halligan, 1990). The authors then argue that if standard deviations are regarded as a metric for the 'indifference zone' of bisections it seems that this value of the Weber fraction has greatly increased in their patient. Control subjects were not discussed in this study (a control group was mentioned in Experiment 1 only) and an investigation performed by the same group on normal subjects (Manning *et al.*, 1990) suggested that healthy subjects show the same behaviour pattern, i.e. the variability and the mean displacement of the transections both correlate positively with line length. So it seems that an increase in magnitude and variability for transections of longer lines, occurs in normal subjects as well as neglect patients. It could therefore be argued that this theory on its own does little to explain why neglect patients show an *overall* greater magnitude of errors. Indeed Marshall and Halligan (1990) seem to realize this as they then, in the same article, explain the differences between neglect patients and normal controls with the argument that, with longer lines, patients with neglect approach the line from the right, and make rightward errors, whereas with smaller lines, they approach from the left and accordingly produce leftward errors. This line of argument is quite different from their earlier work (Halligan and Marshall, 1988) in which, through linear extrapolation of Bisiach *et al.'s* data (1983), they predict that line bisection errors become smaller with shorter lines and eventually cross over into leftward errors for sufficiently small lines.

A different line of argument could be that the leftward errors produced by neglect patients on very short lines simply resemble 'normal' bisection behaviour: Marshall and Halligan report this pattern for their control subjects on lines varying in length from 1 inch to 11 inches (Experiment 1). Similarly, the results reported in this and the previous chapter also reveal consistent leftward displacements for most subject groups. In other words it may be that the 'reversed' bisection errors found in neglect patients with short lines, are not a symptom of disordered behaviour at all, and therefore not in need of special explanation. To further substantiate this point it remains to be seen whether these leftward displacements are also found for very short lines, so in the next experiment subjects were tested on lines with varying lengths.

Again patients with left hemisphere damage found it difficult to handle a pencil with their left hand, so the control group was asked to bisect all lines with their right *and* left hand. Comparisons where then made between the RCVA group and the control group, using their right hand, and the LCVA group and the control group, using their left hand.

METHOD

Subjects. Subjects were the same as in Experiments 5A and 6A with 12 patients with unilateral right hemisphere infarct, 12 patients with unilateral left hemisphere infarct and 12 normal control subjects.

Materials. Twenty-four black *Letraset* lines of variable length and 1.5 mm width were placed horizontally and centrally on two sheets of A4 paper, 12 lines on each sheet. Of these 24 lines, subsets of six were of either 2.5cm, 5 cm, 10 cm or 20cm length. None of the lines were cued and all lines were ordered pseudorandomly on the sheets, and different orderings were used in each spatial location for a given subject.

Procedure. Subjects were seated at a table opposite the experimenter, who ensured that the subject's body position remained constant throughout the experiment. Subjects were instructed to centrally bisect the line as accurately as possible proceeding line by line through each sheet. After each transection that line was covered with a card in order to prevent comparison of the present response with previous bisections. Both patient groups used their ipsilesional hand to bisect the lines, whereas the control group used each hand separately and thus bisected a total of 144 lines. Head and eye movements were not restricted in any way. The set of 24 lines was presented once in each spatial location (left, right or central to the subject's body midline). The order of spatial locations was counterbalanced between subjects and order of hand used was also balanced across the control subjects. In the central condition the viewing distance was approximately 45cm from the line that was to be bisected. In the left and right hemispace presentations the sheets were located such that the centre of each line lay at a distance of 30cm from the sagittal body midline.

Errors in line bisection for each subject and for each condition were measured in millimetres and averaged across the six instances. Errors to the right of the midpoint were given a positive value and those to the left a negative value.

Statistical Analyses. The mean error scores and their standard deviations were analysed separately. The two sets of analyses were three-way ANOVA's comparing the performance of one patient group to the control group using the ipsilateral hand. In each case the factors were: group (patients/controls) as a between-subjects factor, and space (left, centre, right) and line length (2.5cm, 5cm, 10cm and 20cm) as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

12 RCVA patients vs 12 controls (right hand only)

Analysis of the mean error scores did not show any significant effects, i.e. there were no differences between the groups, no effects of space or interactions with space. Surprisingly, there was not even an effect of line length with longer lines producing larger errors than shorter lines (Figure 3.6). Both groups produced small insignificant leftward displacements for all lines.

Nonetheless bisection responses proved more variable for longer lines i.e., the variance increased significantly with every increase in length for both groups ($F(1.9, 41.5) = 92.63$, $p < 0.001$, main effect). There was also an overall effect of group with RCVA patients showing more variance than the control group ($F(1,22) = 5.62$, $p < 0.027$), see also Figure 3.7.

12 LCVA patients vs 12 controls (left hand only)

Again both groups produced leftward displacements for all lines (although not significantly different from zero). Only line length produced a significant finding in that the 20cm line produced larger leftward displacements than the 2.5 and 5cm lines but did not differ from the 10cm line (Figure 3.8). No other effects were found.

Again analysis of the variability showed a main effect of line ($F(1.6, 34.9) = 95.9$, $p < 0.001$) with a significant increase for every increase in line length, for both groups (Figure 3.8). The LCVA group proved also more variable than the control group ($F(1,22) = 5.79$, $p < 0.025$), see Figure 3.9.

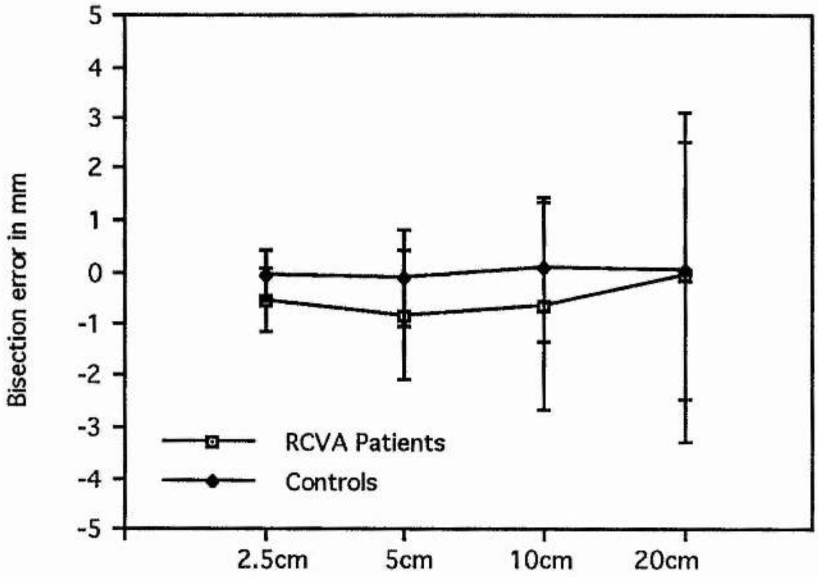

Figure 3.6: Mean Error in mm in the bisection of lines, performed by the RCVA patients and the control group as a function of line length (2.5cm, 5cm, 10cm, 20cm). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

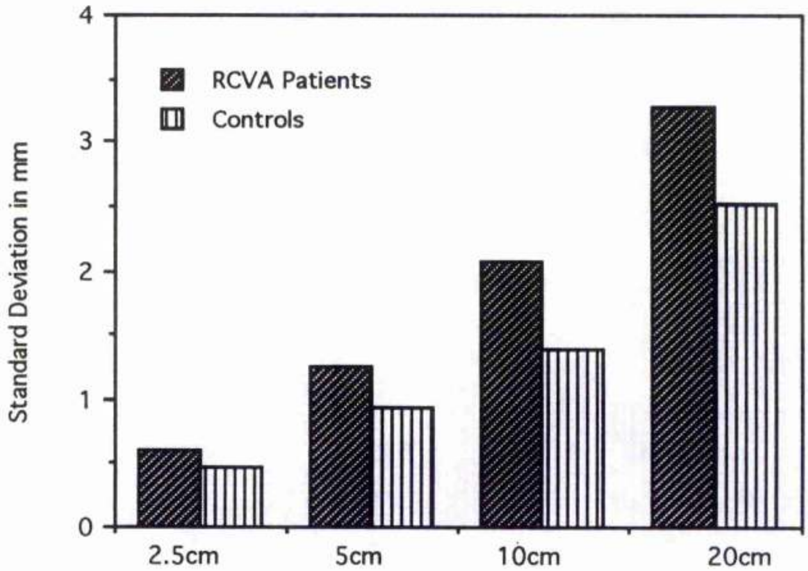

Figure 3.7: Intersubject variability of the bisection response for the RCVA patients and the control group as a function of line length (2.5cm, 5cm, 10cm, 20cm).

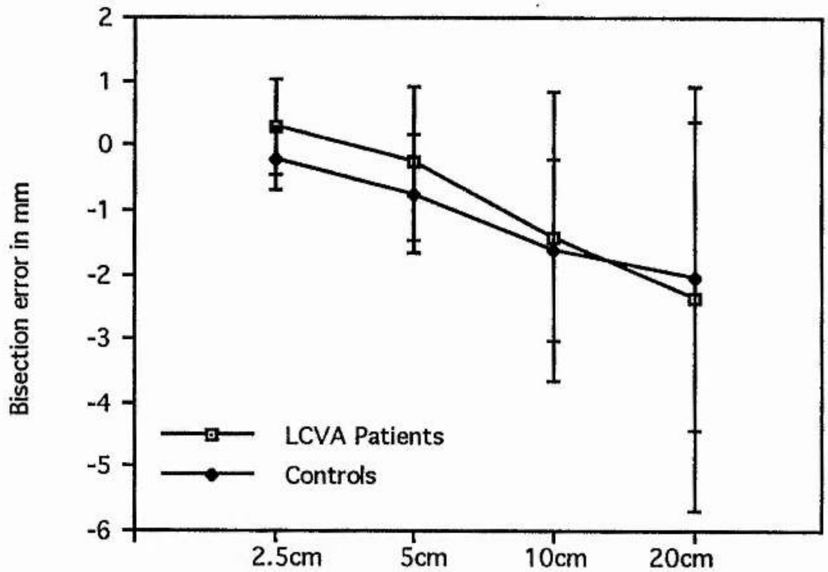

Figure 3.8: Mean Error in mm in the bisection of lines, performed by the LCVA patients and the control group as a function of line length (2.5cm, 5cm, 10cm, 20cm). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

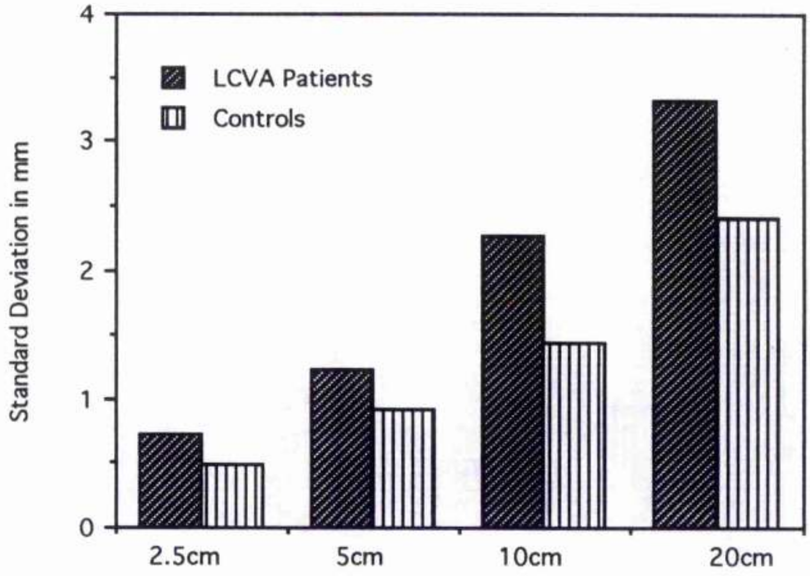

Figure 3.9: Intersubject variability of the bisection response for the LCVA patients and the control group as a function of line length (2.5cm, 5cm, 10cm, 20cm).

EXPERIMENT 7B: BISECTION OF LINES OF VARYING LENGTH (COMPARISON OF NEGLECT AND RCVA PATIENTS)

As already mentioned in Experiment 7A Halligan and Marshall (1988) were the first to demonstrate that patients with neglect syndrome show leftward displacements when asked to bisect very short lines. This behaviour pattern has been demonstrated repeatedly since then (Marshall and Halligan, 1990; Tegner and Levander, 1991b) and although all authors point out that the displacements shown for lines of 2.5cm length are significantly different from those shown by normal control groups, it will be argued here that these errors are indeed comparable to those made by the control group. It is obvious (and this can be confirmed by self reports of subjects executing the task) that bisecting shorter lines is easier than bisecting long (say 20cm) lines. Consequently problems experienced by neglect patients should be diminished when the task becomes less difficult. It is feasible that reducing lines to a very short length (say 2.5cm) makes it as easy for neglect patients as other subjects to produce small insignificant errors. Bisecting short lines in right hemispace should produce the best performance, although it should be pointed out that no significant effect of hemispace was found for neglect patients in Experiment 5B, only a trend for largest displacements in left and smallest in right space.

METHOD

Subjects. Subjects were the same as in Experiments 5B and 6B with 12 patients with unilateral right hemisphere infarct and 6 further patients with unilateral right hemisphere infarct who displayed hemispatial neglect at the time of testing.

Materials and *Procedure.* Materials, procedure and scoring were the same as in Experiment 7A.

Statistical Analyses. The mean error scores and their standard deviations were subjected to analyses of variance comparing the performance of the RCVA and the neglect patients using the factor group (RCVA/neglect) as a between-subjects factor, and space (left, centre, right) and line length (2.5cm, 5cm, 10cm and 20cm) as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

As in Experiment 5A, mean error scores proved substantially larger in the neglect group than the RCVA control group ($F(1,16) = 44.76$, $p < 0.001$) and whereas the RCVA patients displayed small insignificant leftward deviations (a mean of -0.5mm), significant rightward errors (mean 8.8mm, $t(4) = 2.9$, $p < 0.05$) were found in the neglect group. Interpretation of the group x space x line interaction ($F(2.6,41.2) = 7.46$, $p < 0.001$) revealed that whereas the RCVA patients showed no difference in the amount of error with regard to spatial location, the neglect group produced largest errors in left space and smallest in right space, although this was not significant for lines of 2.5cm length. Moreover, in contrast to the RCVA group who showed no increase in error with line length, there was a strong effect of line in the neglect patients in that errors became larger with every increase in line length. *Post hoc* comparisons revealed further that no differences were found between the neglect group and the RCVA control group on very short lines (2.5cm), whereas the neglect group produced significantly larger errors on all other lines (see also Figures 3.10 and 3.11).

Four out of the six neglect patients demonstrated a 'crossover' with the shortest lines (2.5cm) being bisected to the left of the true centre in all three spatial positions. However this was not apparent as an overall effect, as one neglect patient (E.L.) made such large rightward errors on these lines (mean: 10.3mm) that her responses often missed the line altogether. This behaviour was more pronounced in left space. Excluding E.L. from the analyses did in fact reveal insignificant ($t < 1$) leftward bisection errors on the shortest lines (-2.8mm). Nonetheless interpretation of the group x line interaction ($F(1.5,22) = 52.59$, $p < 0.001$) still showed again that neglect patients did not differ from the RCVA group on these very short lines (Figure 3.12). Furthermore whereas the neglect group produced larger displacements in left and central than right space, post hoc comparisons proved that this was only the case for longer lines: for lines of 2.5cm length errors did not vary with regard to spatial position (interaction group x space x line ($F(2.2,32.7) = 11.63$, $p < 0.001$)

To further substantiate the argument that neglect patients do indeed not differ from normal subjects on the bisection of very short lines, an additional three way ANOVA was performed including the right hand data of the normal control subjects along with the RCVA and neglect patients (excluding E.L.) in the analyses. Again there was a significant group x space x line interaction, and on the very short lines (2.5cm), neglect patients did not differ either from the RCVA or the control group (Figures 3.13, 3.14 and 3.15). And again although the neglect group produced larger displacements overall in left and central than right space, post hoc comparisons proved that this was only the case for longer lines: for lines of 2.5cm length errors did not vary with regard to spatial position (Figure 3.15).

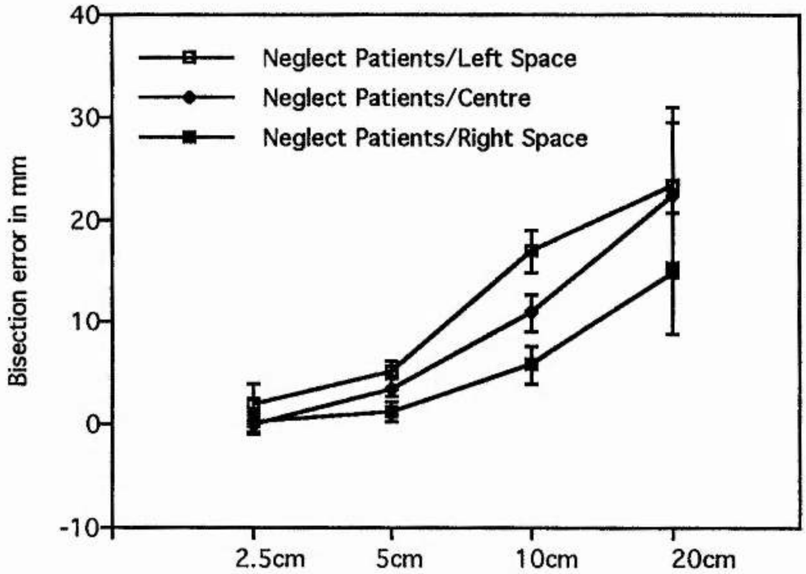

Figure 3.10: Mean Error in mm in the bisection of lines, performed by the neglect group as a function of line length (2.5cm, 5cm, 10cm, 20cm) and space (left, centre, right). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

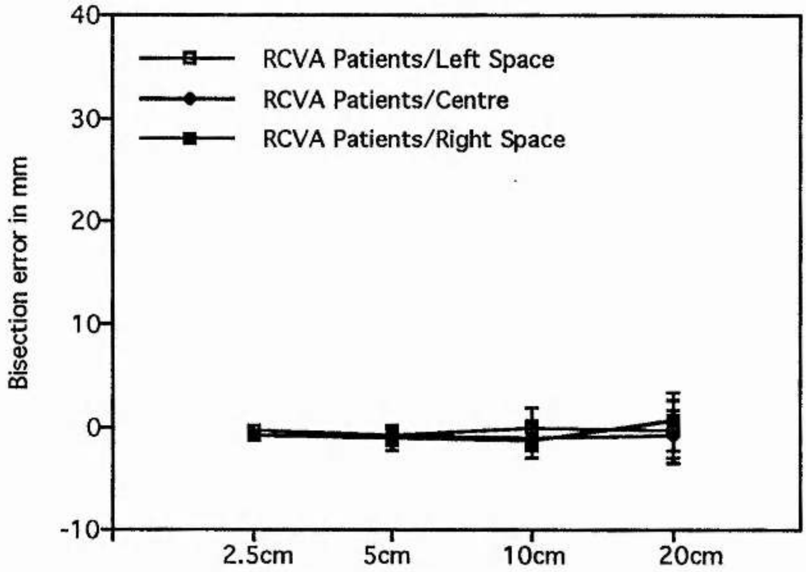

Figure 3.11: Mean Error in mm in the bisection of lines, performed by the RCVA patients as a function of line length (2.5cm, 5cm, 10cm, 20cm) and space (left, centre, right). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

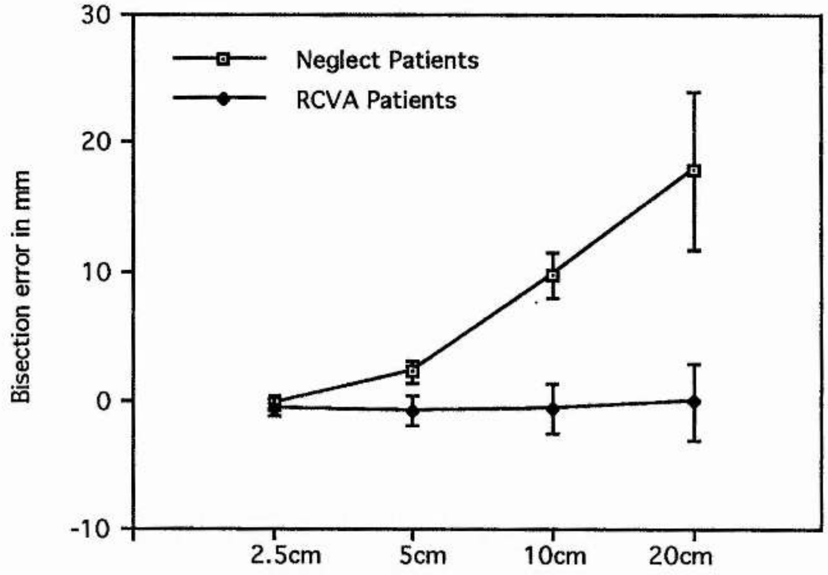

Figure 3.12: Mean Error in mm in the bisection of lines, performed by the neglect group (excluding patient E.L.) and the RCVA patients as a function of line length (2.5cm, 5cm, 10cm, 20cm). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

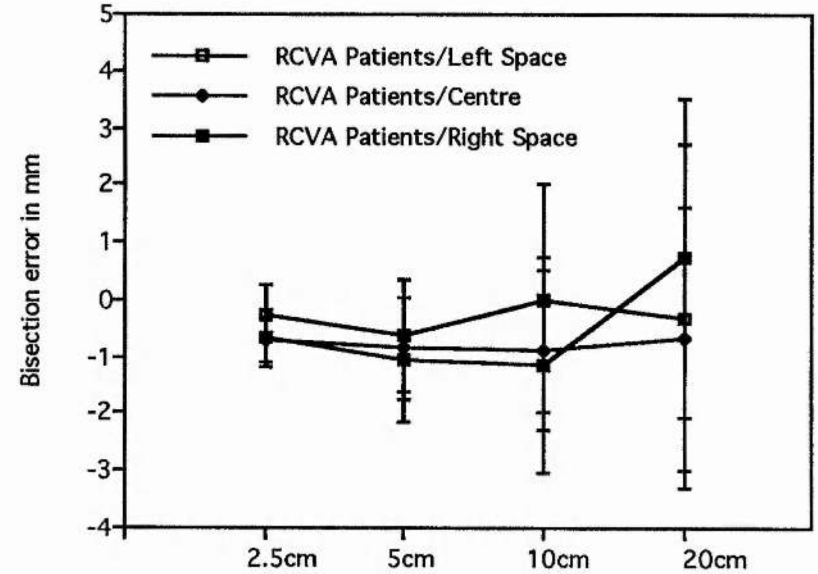

Figure 3.13: Mean Error in mm in the bisection of lines, performed by the RCVA patients as a function of line length (2.5cm, 5cm, 10cm, 20cm). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

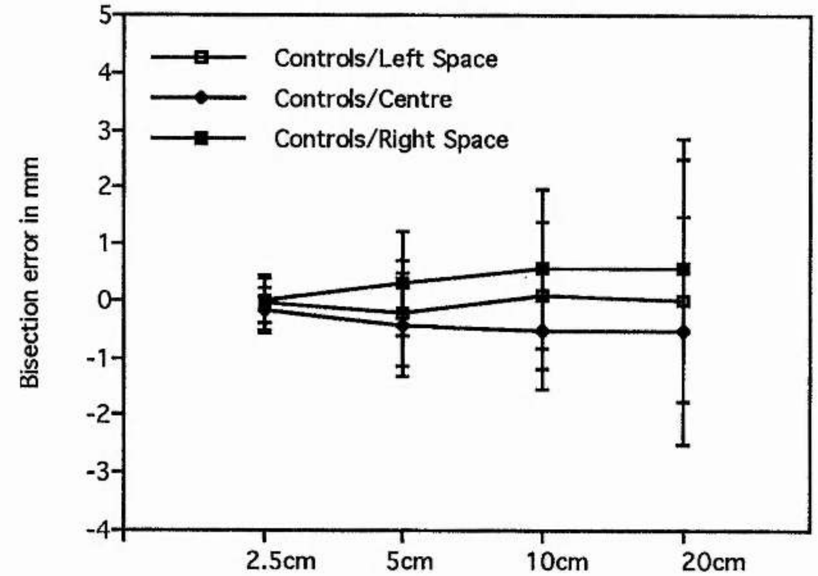

Figure 3.14: Mean Error in mm in the bisection of lines, performed by the control subjects as a function of line length (2.5cm, 5cm, 10cm, 20cm). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

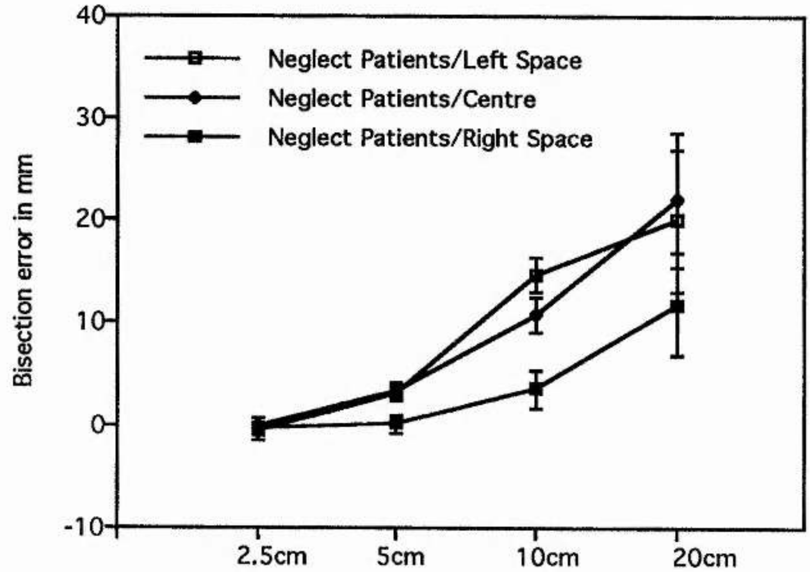

Figure 3.15: Mean Error in mm in the bisection of lines, performed by the neglect patients (excluding patient E.L.) as a function of line length (2.5cm, 5cm, 10cm, 20cm) and space (left, centre, right). Rightward and leftward errors are coded as in Figure 3.1. Errors bars indicate intersubject variability.

Analysis of the standard deviations demonstrated larger within-cell variation for the neglect group compared to both the RCVA and the control group ($F(2,27) = 35.59$, $p < 0.001$). Again there was a main effect of line with longer lines producing more variable responses than shorter lines for all three groups ($F(1.8, 47.6) = 52.70$, $p < 0.001$, main effect). However this last finding was modified by the significant group x line interaction which demonstrated that none of the groups differed in their variability regarding the shortest lines. For all other line lengths however, the neglect group showed larger variability than both the RCVA and control group who themselves did not differ from each other with respect to variability of line length ($F(3.5, 47.6) = 4.76$, $p < 0.01$).

Furthermore it could be shown that the neglect patients did not differ more from each other than the subjects of the RCVA and control group as the variance ratio did not exceed the required F-value: $F(11,5) = 1.8$ for neglect group and RCVA patients; $F(11,5) = 3.1$ for neglect patients and control group.

DISCUSSION OF EXPERIMENTS 7A AND 7B

The bisection results of the right and left CVA groups in Experiment 7A confirmed the findings of Experiment 5A in that neither group differed significantly from the control group. In fact findings on the longest lines (20cm) were almost identical to those reported in Experiment 5A (which used 20cm lines throughout) with significant leftward displacements for the LCVA and control group (-2.2mm, $t = -2.1$, $p < 0.05$) but insignificant errors for the RCVA and control patients (-0.35mm, $t < 1$). For all groups leftward bisection errors were found for very short lines as well as longer lines. As expected, four out of the six neglect patients tested in Experiment 7B also showed leftward bisection errors on the shortest lines, but more importantly the magnitude of these errors did not differ from those of the RCVA and the control group. It can thus be argued that, for very short lines, most neglect patients experience no greater difficulty than other subjects. That is, there is no evidence for a disorder which requires special explanation. With longer lines, on the other hand, the operation of attentional biases may become more prominent because of the need to make successive ocular fixations.

Although only noticeable as a trend in Experiment 5B, spatial location effects were reported for the neglect patients in Experiment 7B: in agreement with Heilman and Valenstein (1979) larger errors were found in left and central as opposed to right spatial positions. It should be noted, however, that spatial position did not affect bisection performance for very short lines (Experiment 7B). Again this could indicate that neglect patients found the task too easy to be influenced by spatial position. As all lines were arranged centrally on the sheet, shorter lines actually extended less into left (and right) space than longer lines. This could have contributed further to the lack of a spatial effect. Nonetheless the fact that leftward displacements were found in left hemispace disagrees with the idea of an attentional boundary. If as argued by Halligan and Marshall (1988), neglect patients have an attentional boundary placed slightly to the left of the objective midline, lines in left hemispace should either be missed or if anything, bisected to the right of the true centre. The explanation given in a later paper (Marshall and Halligan, 1990) that neglect patients approach longer lines from the right, and make rightward errors and shorter lines from the left thus producing leftward errors seems unlikely to hold for lines presented in left space. To account for the leftward errors found in left hemispace in this experiment, this explanation would not only assume that neglect patients scan from the left, but that within the left space they start scanning from the left. This seems highly unlikely and is in fact contrary to eye-movement studies of visual search, line bisection and picture inspection (Ishiai *et al.*, 1987; Huber *et al.*, 1988; DeRenzi *et al.*, 1989b; Gainotti *et al.*, 1989) which have shown that fixations tend to be crowded to the right of the stimulus. Indeed a recent experiment by Hornak (1992) revealed further that even in the dark, fixations of neglect patients are confined almost entirely to the right hemispace.

Unlike the other neglect patients, E.L. produced considerable rightward bisection errors for very short as well as long lines. These errors were largest in left hemispace. It has already been pointed out **(Discussion of Experiments 6A and 6B)** that the displacements shown by this patient seem to be due to a directional hypokinesia. It could thus be argued that the line-length effect is only present in patients whose neglect is largely perceptual in nature. Heilman and Valenstein (1979) also reported larger bisection errors in left space but did not analyse their data with respect to line length. More patients with symptoms of directional hypokinesia need to be tested before any claim can be made between the relationship of rightward displacement and line length in any such patients.

EXPERIMENT 8A: LANDMARK PERFORMANCE OF LCVA, RCVA AND CONTROL SUBJECTS ON LINES OF VARYING LENGTH

All four groups studied in this series of Experiments were also tested with the landmark version, i.e. lines with varying length, each with a transection mark in the centre were presented to the subjects. The use of the landmark task should help resolve whether the line-length effect in neglect is related to perceptual or motor factors. First the results with the LCVA, RCVA and controls will be reported. As hardly any significant results were reported for the the bisection of lines with varying length, little would be expected from this landmark test when administered to these groups.

METHOD

Subjects. Subjects were the same as in Experiments 5A, 6A and 7A with 12 patients with unilateral right hemisphere infarct, 12 patients with unilateral left hemisphere infarct and 12 normal control subjects.

Materials. Twenty-four black *Letraset* lines of variable length and 1.5 mm width were placed horizontally and centrally on two sheets of A4 paper, 12 lines on each sheet. All of these were transected in the centre and subsets of six were of either 2.5cm, 5cm, 10cm or 20cm length. None of the lines were cued and all lines were ordered pseudorandomly on the sheets, and different orderings were used in each spatial location for a given subject. They were presented once in each spatial location (left, right or central with respect to the subject's body midline), the order of spatial presentations being counterbalanced between subjects. The viewing distance and spatial locations of the lines was the same as in Experiments 7A and 7B and head and eye movements were not restricted.

Procedure. Again subjects were seated at a table opposite the experimenter, who ensured that their body position remained constant throughout the experiment. They were falsely informed that none of the transections were placed at the exact centre of a line. They were asked to point to the line that appeared closer to the transection. Subjects were forced to make a left/right choice even if it was necessary to guess: no other response was permitted. After each judgement that line was covered with a card in order to prevent comparison of the presented transection with previous transections. In order to ensure that all subjects understood the instructions correctly, lines that were noticeably asymmetrically transected (2 to 4 cm from the true centre with lines of 20cm length) were first presented to the subjects. They had to give five continously correct responses before they were tested on the centrally bisected lines.

Statistical Analyses. The *number of rightward responses* (maximum six per cell) were subjected to a three-way analysis of variance with group (LCVA patients, RCVA patients and controls) as a between-subjects factor, and space and line length as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used for testing against chance performance in particular test conditions.

RESULTS

Again no effects of group or interactions with group were found. Nonetheless, although this was not found for bisection (in Experiment 7A) all groups showed an effect of spatial location ($F(1.7,56.6) = 6.81$, $p < 0.004$). Rightward judgements proved significantly more frequent in left than central and right space, indicating a perceptual relative overestimation of the lateral part of the lines. (I.e. in left hemispace the right half-line was judged shorter than the left, and in right hemispace the converse). No other effects were found to be significant.

EXPERIMENT 8B: LANDMARK PERFORMANCE OF NEGLECT PATIENTS COMPARED TO RCVA PATIENTS ON LINES OF VARYING LENGTH

Application of the landmark test in Experiment 6B demonstrated that the space occupied by the left half of a line literally appeared shorter to the neglect patients than the right half (patient E.L. excluded). Similarly although no effect of spatial location or interaction with space was reported, results showed fewer rightward judgements in left and central spatial positions than in right space (15% left space, 16% centre, 19% right space; E.L. excluded). It could be argued that, as the shorter lines (5cm and 10cm) produced relatively smaller rightward bisection errors than the longer lines (Experiment 7B), the gradient of spatial distortion experienced by neglect patients should also be less with shorter lines. As this gradient is also assumed to be steeper in left than right space, presenting small lines in right spatial locations should produce the smallest perceptual bias. Indeed as the neglect patients demonstrated leftward displacements for the smallest lines (2.5cm), a perceptual bias would predict rightward (i.e. normal) pointing tendencies for small lines which are pre-transected in the centre.

METHOD

Subjects. Subjects were the same as in Experiments 5B, 6B and 7B with 12 patients with unilateral right hemisphere infarct and 6 further patients with unilateral right hemisphere infarct who displayed hemispatial neglect at the time of testing.

Materials and *Procedure.* Materials, procedure and scoring were the same as in Experiment 8A.

Statistical Analyses. Again the *number of rightward responses* were subjected to analysis of variance comparing the performance of the RCVA and the neglect patients using the factor group (RCVA/neglect) as a between-subjects factor, and space and line length as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using a Geisser-Greenhouse adjustment to the degrees of freedom where appropriate. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance throughout. In addition, one-sample t-tests were used to test for constant error (departures from a mean of zero) in particular test conditions.

RESULTS

Analysis of the numbers of rightward responses showed significantly fewer such judgements for the neglect group than the RCVA patients ($F(1,26) = 4.21$, $p < 0.05$). The neglect patients tended indeed to indicate the left half of a line as being shorter than the right, a tendency which differed highly significantly from chance performance ($t = 4.6$, $p < 0.01$). The significant group x space interaction ($F(1.7,27.2)$) revealed further that, whereas the neglect group showed significantly more such leftward judgements in left as opposed to central and right space, there was an opposite trend in the RCVA group with more rightward judgements in left and central than right space (Figure 3.16). There was, however, no change in landmark behaviour as a function of line length in the neglect group, i.e. judgements were still mainly to the left even for the shortest lines.

Again patient E.L. showed a rightward response bias and although her rightward judgements were more frequent in left (75%) and central (70%) than

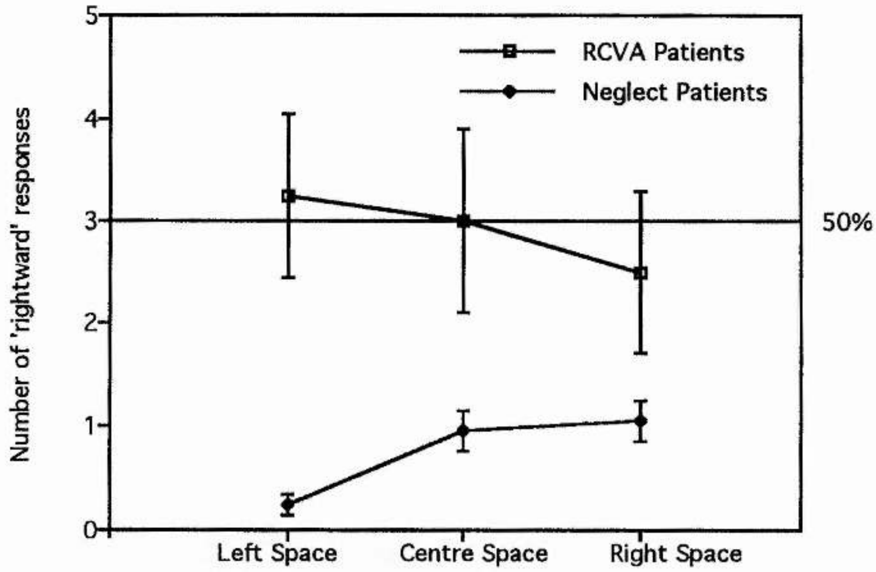

Figure 3.16: Manual landmark judgements of the RCVA patients and the neglect group, as a function of spatial location (left, centre, right): the mean number of forced-choice manual indications (out of 6) that an objectively central transection is placed right of centre. Errors bars indicate intersubject variability.

right spatial positions (54%) they did not differ with respect to line length. Again these results strongly indicate that this patient showed symptoms of directional hypokinesia rather than perceptual distortion.

DISCUSSION OF EXPERIMENTS 8A AND 8B

As before, it can be argued that the rightward bisection errors found in Experiment 7B for the neglect patients were due to a spatial misperception. Over all conditions five out of six neglect patients indicated the left half of the lines as being shorter than the right half. So there is now repeated evidence that the subjective space of neglect patients is distorted in so far as it is subjectively compressed in many neglect patients (Milner, 1987; Milner et *al.*, 1993). The space occupied by the left half of a line literally appears shorter to a neglect patient than the right half. The hypothesis also predicts that the gradient of distortion is steeper in the leftward parts of ego-space than in the rightward parts and although no effect of spatial location or interaction with space proved significant in the previous landmark experiment (6B), Experiment 8B did reveal significantly more leftward judgements in left spatial locations than central and right positions in neglect patients.

Nonetheless although it might further be supposed that the gradient of spatial distortion experienced by neglect patients might be less with intermediate - length lines, especially in right space, no such effect was reported in Experiment 8B using the landmark test. On the other hand, although the magnitude of the rightward bisection error (even in relative terms) was reduced with such lines in Experiment 7B, it was still quite considerable (mean error for 5 cm lines: 3.3mm; mean for 10 cm lines: 11.2mm). It is thus feasible that even for these intermediate lines, the amount of spatial distortion experienced is still sufficient to produce leftward judgements (i.e., perception of the left part of the line as shorter). This still seems to apply to the shortest lines (2.5cm):

neglect patients demonstrated leftward bisection errors for these lines (Experiment 7B), which might have been expected to produce rightward pointing in the psychophysical landmark judgement task. However, the leftward errors found in Experiment 7B proved to be very small and insignificantly different from zero. It is possible that the 2.5cm lines always fall fully within the focus of attention and that therefore perceptual biases in neglect cannot operate as they do with longer lines.

Throughout all four experiments (5B - 8B) patient E.L. can be seen to have demonstrated rightward response biases that proved larger in left space than central and right spatial positions. These data strongly agree with the idea of a directional hypokinesia operating in this patient (see also **Discussion of Experiments 6A and 6B**). So although the majority of the patients presented here demonstrated a perceptual distortion of their subjective space, one showed no such effect, but instead a directional hypokinesia. It is theoretically possible that both these factors (spatial misperception and hypokinesia) operate to an appreciable extent in a single patient. Had this been the case, although bisection errors would still have been to the right, responses should have been near random in the landmark task. None of the patients presented here revealed such a pattern and there seems to be no comparable finding in the literature. That is patients seem to fall into either one of two predominant symptom categories.

It has to be mentioned that a spatial effect was found for the LCVA, RCVA and control subjects on the landmark version of the line length task (Experiment 8A), with significantly more rightward judgements in left than central and right space. This response pattern indicates that the subjects relatively overestimate the lateral part of laterally placed lines. Although this finding agrees with the results reported for the younger subjects in Experiment 2 (these subjects also relatively overestimated the lateral part of laterally presented lines), it is contrary to the findings of Experiment 4 (same population as the control subjects presented here). In Experiment 4 subjects seemed to overestimate the medial part of laterally presented lines, as leftward judgements were more frequent in left and central than right space. This effect was no longer apparent when the subjects were analysed together with LCVA and RCVA patients, suggesting that it might not have been a very strong effect, otherwise it would have resulted in a group x space interaction. These findings suggest that another (as yet unknown) factor might be responsible for these diverging results. As pointed out in the method sections, eye movements were neither restricted nor recorded so little is known about the scanning patterns adopted by the subjects. Nonetheless it has been consistently shown (Experiments 4, 6A) that focusing a subjects attention to a particular side (by cueing) produces a perceptual overestimation of that part of the stimulus (see also Milner *et al.*, 1992). Consequently it seems possible that whatever part of a line is scanned longest is perceived as largest. Indeed Manning *et al.* (1990) also argue that normal subjects who adopt a predominantly left-to-right scan strategy should produce leftward errors, whereas a predominant right-to-left scan should result in rightward errors. It is possible that the subjects presented here adopted different scanning strategies for long and short lines or depending on whether lines did or did not vary in length from trial to trial. In Experiment 4 in which all lines were of 20 cm length they might have scanned the medial part of laterally presented lines more than the lateral part, this causing them to indicate that the lateral end was closer to the central mark. In Experiment 8A in which lines differed in length they might have scanned the lateral end more (as part of a strategy for line length estimation) thus indicating the medial part as being shorter.

The results of the neglect patients proved rather consistent across all four experiments. As it is assumed that neglect patients, unless prompted, scan mainly rightwards (Johnston and Diller, 1986, Ishiai *et al.*, 1987) this might have contributed to the reported consistency. However data on eye movements need to be available before any such claims can be made.

GENERAL DISCUSSION

The main question that this chapter addresses is whether neglect patients perceive the midpoint of a horizontal line to be subjectively shifted to one side. Neither the space-compression hypothesis (Halligan and Marshall, 1991), nor the directional limb hypokinesia hypothesis (Heilman *et al.*, 1985b), would predict this, since neither account predicts any nonlinear distortion of perception. The former account predicts only that the whole line should be subjectively shifted rightwards in space, along with a uniform shrinkage in its size. Thus both of these previous accounts explain bisection errors as due to a misdirection of response. Neither would predict that the two halves of a line should appear different in length to a neglect patient.

Yet it has been demonstrated in five patients with manifest hemispatial neglect, each showing large rightward bisection errors, that they consistently indicate the left end of a centrally pre-bisected line as appearing closer to the objective midpoint. This misperception occurred for long as well as short lines. Indeed, even 20cm lines transected as far as 5 mm to the right of centre were predominantly judged in this way. So it can be concluded that in these hemispatial neglect patients there was indeed a bias to perceive the left half of a line as shorter than the right half. Marshall and Halligan (1989) reported a patient (PP) who, when shown centrally pre-bisected lines, indicated on 94% of trials that they were 'wrongly' bisected, and generally then 'corrected' them toward the right. It is possible that this patient also experienced a distortion of her subjective space and that a centrally bisected line appeared to be offset to the left. Indeed it would be expected that the neglect patients of Bisiach *et al.*

(1990); Coslett *et al.* (1990) and Tegner and Levander (1991a) who did not demonstrate directional hypokinesia but some kind of 'perceptual' deficit all show this effect in that they would have perceived the left half-line of a centrally pre-bisected line as shorter than its right half.

The experiments carried out also addressed the frequently noted trend in neglect patients to show greater line bisection errors in contralateral space than in ipsilateral visual space. Again Halligan and Marshall's model (1991) could explain this, since it predicts that the subjective location of a line should be shifted rightwards to a greater extent within left hemispace than within right hemispace (see introduction to this chapter). This hypothesis alone, however, predicts no variation in the perceived appearance of a transected line placed in different parts of visual space. In contrast, Milner (1987) suggested that patients with left hemineglect might perceive leftwardly-located spatial extents as shrunken relative to more rightward ones, and that the gradient of this distortion might be greater within left than in right hemispace. If this is correct, then the tendency to judge the left halves of lines as shorter than the right, which was reported here for the two landmark tasks, should become particularly pronounced in left hemispace. This was indeed found for the second landmark task in which neglect patients showed significantly more leftward judgements in left than right hemispace. The same trend occurred in the first landmark study (Experiment 6B) but this failed to prove significant, possibly due to the fact that there were fewer trials (three as opposed to six repetitions). The landmark results are thus consistent with the hypothesis that neglect patients tend to judge the left half of a centrally bisected line as shorter, and that the gradient of distortion may be particularly pronounced in left hemispace. Neither of the other two theories can explain these landmark data.

It should be noted that one neglect patient (M.J.) was also directly tested on her ability to match the relative size of pairs of computer-generated patterns

(Milner *et al.*, 1993) which were presented in order to explore the point of subjective equality between patterns placed in left and right and upper and lower visual hemispace. The stimuli displayed (horizontal or vertical lines) were either identical or differed in length along a scale ranging from just-noticeable to large and obvious differences. Similarly random shapes differing in area were used. The patient was forced to make a left-right or up-down choice (indicating which of the two stimuli was longer/larger or, in a separate session, shorter/smaller). Again neither a *uniform* spatial compression nor a directional hypokinesia should in itself lead to any constant errror in such tasks. Yet similar to the findings of Gainotti and Tiacci (1971), gross errors in matching the sizes of stimuli presented to the left and right (but not upper and lower) visual hemispace were found. However, these errors of relative underscaling in left hemispace were not indiscriminate; they were present in comparing horizontal extents, but not in comparing vertical extents. It could be argued that the task of matching vertical lines between left and right was simply geometrically easier than matching horizontal lines. However this interpretation was not supported by an analysis of the unsigned errors made by the RCVA control patients. Their mean error score for the left/right matching of vertical lines (0.91; SD = 1.08) was identical to that for matching horizontal lines (0.91, SD = 1.31).

So it can be argued that in at least some patients suffering from hemispatial neglect, there is a perceptual factor operating which renders left-side stimuli subjectively smaller than rightwardly located ones. This phenomenon seems to be particularly pronounced in the perception of horizontal extent. Consequently this distortion of size perception must play an important role in the causation of line bisection errors in such patients. With regard to Halligan and Marshall's hypothesis however, it should be emphasized that there could be two different changes in perceptual experience: one affecting the subjective spatial location of an item, the other its subjective size. Thus would not be mutually incompatible. The two factors could be present in combination, each to a different extent in different patients.

As mentioned before, it is relevant to note that other investigators have recently argued for a perceptual factor in determining line bisection errors in neglect, to varying extents in different patients (Bisiach *et al.*, 1990; Coslett *et al.*, 1990). For example, Bisiach *et al.* (1990) showed that some patients would move a manipulandum *leftwards* from the spatial midline in order to set a transection pointer *rightwards* from the midpoint of a line that they were asked to bisect. Like the present data, this behaviour could not be explained by a leftward directional hypokinesia, or by a spatially misdirected aiming movement. Other patients, however, did give evidence for the operation of such a factor. In a similar experiment Tegner and Levander (1991a) tested 18 neglect patients on a line cancellation task which was presented either in normal view or through a 90 degree angle mirror, preventing a direct view. They found that in the mirror condition, 4 out of the 18 patients cancelled lines in right hemispace only, thus indicating symptoms of directional hypokinesia, whereas 10 patients cancelled lines in left hemispace only i.e., showing perceptual deficits. The remaining patients cancelled only central lines, a finding which the authors believe to be due to a combination of motor and perceptual deficits. It is interesting that in line with the patients of Tegner and Levander, the majority of the patients in the studies presented in this thesis, also showed perceptual deficits and only one of them (E.L.) gave an indication of a misdirected action in line with Heilman and colleagues' definition of directional hypokinesia.

So by now there seem to be four independent studies (Coslett *et al.*, 1990; Bisiach *et al.*, 1990; Tegner and Levander, 1991a and the experiments presented in this chapter) which suggest that a useful classification can be made between neglect patients showing mainly symptoms of directional hypokinesia and others experiencing perceptual difficulties. It also seems that the landmark test is by far the simplest means for classifying patients in either one of these groups, or even identifying patients who show a combination of motor and perceptual deficits. No complicated manipulandum devices or mirror images are necessary. This should be particularly relevant in a clinical context: the landmark task could be used as easily as the line bisection test and provide a classification, which could be used as a therapeutic guideline, at the same time. Some years ago Mesulam (1981) proposed that anterior lesions may be associated with 'intentional' neglect while posterior lesions cause attentional/representational deficits. Subsequently Bisiach *et al.* (1990) found an association between directional hypokinesia and anterior lesions and the data of Tegner and Levander (1991a) also seem to support this hypothesis: of the four patients with directional hypokinesia, three had a frontal and one a central lesion. On the other hand, all patients with isolated posterior lesions showed a perceptual pattern. However, the authors also point out that their results must be regarded with caution as patients with directional hypokinesia tended to have larger lesions and no patients with isolated anterior lesions were examined. Lesion analysis of the six neglect patients presented here is also ambiguous: E.L. who showed symptoms of directional hypokinesia had a large fronto-parietal lesion. Four out of the five 'perceptual' patients did indeed have posterior (parietal) lesions but one of them (M.J.) had a lesion in the mid/anterior white matter, a finding which appears to contradict Mesulam's theory (1981). The data also suggest that maybe only the 'perceptual' neglect patients show leftward bisection of short lines: four out of the five 'perceptual' neglect patients demonstrated a *'crossover'* to the left of the true centre in all three spatial positions. On the other hand patient E.L. showed significant rightward errors for short as well as intermediate and long lines in all three spatial positions. However more patients with symptoms of directional hypokinesia and 'perceptual neglect' need to be studied in order to make such a claim.

It was also shown that cueing can strongly influence both line bisection and landmark judgements in that visual cues produce a perceptual overestimation of that side. It seems that unilateral cueing directs selective attention unevenly to one or other end of the line, and that the perception of relative size is subject to systematic distortion as a function of this selective attention within the visual field. It is notable that this phenomenon was found in brain lesioned subjects (left and right CVA patients) just as strongly as in normal controls. On the other hand placing lines in different spatial locations resulted in inconsistent findings: if anything, presentation of long lines (20cm) of uniform length produced a perceptual overestimation of the medial part of laterally placed lines. On the other hand, the interspersion of short, intermediate and long lines led to an overestimation of the lateral part of all these lines, when presenting them laterallly. It is possible that these diverging findings could be explained through direction of selective attention in that the *medial* half of *long lines of uniform length* and the *lateral* half of *lines of varying length* are selectively attended to thus producing systematic distortion (overestimation) of that part of the line. As all lines were arranged centrally on the sheet, lines of uniform length did not vary in their lateral extent which perhaps led subjects to examine that part less closely. For the lines of varying length however, the amount of lateral extension changed constantly and might therefore have been more closely examined. As mentioned before, data on eye movements need to be available before any such claims can be substantiated. Nonetheless the findings on the five neglect patients can be interpreted as documenting an abnormal example of this attentionally-induced distortion. In patients with this 'perceptual' neglect syndrome, the distribution of attentional resources may be assumed to be abnormally biased towards the right hemispace

(Kinsbourne, 1970; 1987). Although this bias is partially reversible under voluntary control (Posner *et al.*, 1984; 1987; Riddoch and Humphreys, 1983), the result of this imbalance could be to cause, among other things, a gross abnormality of size perception, which in turn is manifest in disordered bisection behaviour as reported here.

SUMMARY

Heilman and colleagues (1979; 1985b) explain the rightward line bisection errors made by patients with visuo-spatial neglect as due to a 'directional hypokinesia'. An alternative view, which is put forward in this chapter, is that such patients actually misperceive the left half of a horizontal line as being shorter than the right half. This possibility was tested directly in 6 neglect patients, by giving them prebisected lines: 5 out of 6 patients were found to judge a central transection mark as lying nearer to the left end of the lines. This behaviour was apparent for long as well as short lines and more pronounced in left than right hemispace. It was suggested that an attentional deficit in left hemispace may result in the underestimation of horizontal extent which would in turn determine the magnitude of line bisection errors.

Nonetheless one of the patients showed rightward biases throughout all experiments thus producing a behaviour pattern in agreement with what Heilman and colleagues describe as 'directional hypokinesia'.

Control groups (RCVA, LCVA and normal subjects) produced little effects in both bisection and landmark tasks but for all subjects single cues led to a relative perceptual overestimation of that half of the line. These findings indicate that the perception of relative size is subject to systematic distortion as a function of selective attention within the visual field.

CHAPTER FOUR

VISUOMOTOR ANALYSIS OF POINTING AND BISECTION IN NORMAL SUBJECTS

In most previous research the right hand of right-handed subjects has been reported as superior to the left in visually guided stylus-aiming and finger-pointing tasks (Goodale, 1989). For example, Fisk and Goodale (1985) reported a smaller mean final error for right hand pointing, as well as a lower latency to initiate the hand movement. Some studies of repetitive aiming tasks have interpreted the preferred hand's superiority as a left hemisphere advantage in the processing of visual feedback information, allowing more efficient execution of error corrections (Flowers, 1975; Roy, 1983). Consistent with this is the finding of shorter execution times for right hand aiming, the locus of which seems to lie mainly in the final, deceleration, phase of the movement (Todor and Cisneros, 1985). Similar results have also been found in a free finger pointing task (Goodale *et al.*, cited by Goodale, 1989). Furthermore patients with left hemisphere damage show an exceptionally prolonged deceleration phase in this discrete finger-pointing task (Fisk and Goodale, 1988). It is possible that the right hand in normal subjects may benefit primarily from the superiority of the left hemisphere in controlling the fine temporal tuning needed during precision movements, especially in the final stage as the hand 'homes in' on the target (Goodale, 1988).

But under certain circumstances the left hand may become paradoxically superior. Guiard *et al.* (1983) reported a higher accuracy of aiming in the left hand under circumstances where vision of the responding limb was not available ('open loop' conditions). They accounted for their data by arguing for a predominant role of the right hemisphere in '... calculating limb displacement in visual space in the absence of visual information'. Thus their experiment may support a right hemisphere role for localizing stimuli in space at the outset of a reach, without excluding a left hemisphere role in the later utilization of visual feedback when available (Carson, 1989). However in a recent detailed study of different visual illumination conditions, Carson *et al.* (1990) failed to find a significant effect of hand, or an interaction of hand with visual condition, on the magnitude of aiming errors. Thus their data did not support any hypothesized differences between the hands in the utilization of visual feedback information.

EXPERIMENT 9

In this experiment the search for possible visuospatial influences on hand asymmetries during reaching was widened, by using a spatial 'bisection' task. In a recent visuomotor analysis of bisection, the present variant of the classical test was used, in which a pair of discrete points rather than a whole line was used. It was found that patients with damage to the right hemisphere made bigger rightward directional errors than matched controls at the outset of the reach (Milner and Goodale, 1988; Goodale *et al.*, 1990). These initial errors were observed not only in bisection but also in simple pointing; however they were poorly corrected in bisection, such that the *final* rightward errors remained much larger than for pointing. This finding argues for a role of the right hemisphere in programming initial heading direction in visual reaching in general, but it also suggests a more specific role in feedback correction which becomes more obvious in the spatially demanding bisection task.

The bisection task presumably increases the complexity of visual feedback processing, with the finger's position having to be compared on-line to two as opposed to a single stimulus as the finger approaches its target. According to the 'feedback' theory therefore one might expect an exaggerated right hand accuracy advantage in closed loop performance by normal subjects on this task. However the lesion evidence suggests that this may be outweighed by increased visuospatial demands that would tend to favour right hemisphere participation. This should be particularly apparent under open loop conditions, where no visual information on hand/target discrepancy is available, according to Guiard *et al.* (1983). Therefore a comparison between closed and open loop testing conditions (i.e. with vs without vision of the arm and hand) was incorporated. It was predicted that while bisection might maximize left hemisphere participation in closed loop reaching (right hand better), it should exaggerate right hemisphere participation in open loop reaching (left hand better).

In a further attempt to maximize the possibility of detecting right hemisphere influences on reaching, targets were also positioned in left or right hemispace, as well as directly ahead of the subject (Heilman and Valenstein, 1979). Differential engagement of the two hemispheres would be predicted as a function of hemispatial location, and this factor might therefore interact with the other variables. There is also evidence for greater accuracy of dot localization in the left hemifield (Kimura, 1969) suggesting more precise spatial coding there. Finally, similar to Experiments 1 and 3 (chapter two), Bradshaw *et al.* (1985) found a leftward bias in the bisection of centrally-located lines in normal subjects; it was hoped to replicate those findings within this paradigm, and if so gain information on how it would be reflected in reaching paths relative to those in simple pointing.

A relatively low sampling rate of 25 Hz was judged to be adequate for the purposes of this experiment, since the movements were expected to be relatively slow, with typical durations of 400-500 ms, and since the accuracy rather than the detailed kinematics of the movements was the primary object of interest.

METHOD

Subjects. Twelve subjects (6 male, 6 female) ranging in age from 21 to 36 years (mean = 26), participated as unpaid volunteers in the experiment. All were fully right-handed as assessed both by self report and by administration of the Annett Handedness Inventory (Annett, 1967).

Apparatus and tasks. The subject was seated at a table facing a vertical panel on which the stimulus lights (green 4mm-diameter LED's) appeared. The panel was fixed onto the table at a distance of approximately 60cm from the subject's eyes. LEDs were mounted on the panel behind black speaker cloth in a horizontal array at a height of 20cm above the table, and were invisible to the subject except when illuminated. A horizontal start platform (5x5cm), which contained a microswitch, was situated centrally in front of the subject at a distance of 25cm from the panel. All reaches were initiated from this platform.. A small (2mm) red LED was attached to the tip of the subject's index finger under all test conditions for recording purposes (see also Figure 4.1 for diagram of apparatus).

In the *pointing task*, a single target light was presented either centrally, directly in front of the subject, or at 15cm (approximately 14 degrees of visual angle) to the left or right of the centre. In the *bisection task*, two lights were presented simultaneously, either centrally or in the left or right hemispace. In central presentations the lights were located 5cm (approximately 5 degrees of visual angle) to either side of centre. In lateral presentations the two LEDs were located 10cm and 20cm (approximately 9.5 degrees and 18 degrees of visual angle) on the same side. Thus in each of the 3 spatial conditions the true midpoints in the bisection task were identical to the 3 locations of the LED targets used in the pointing task.

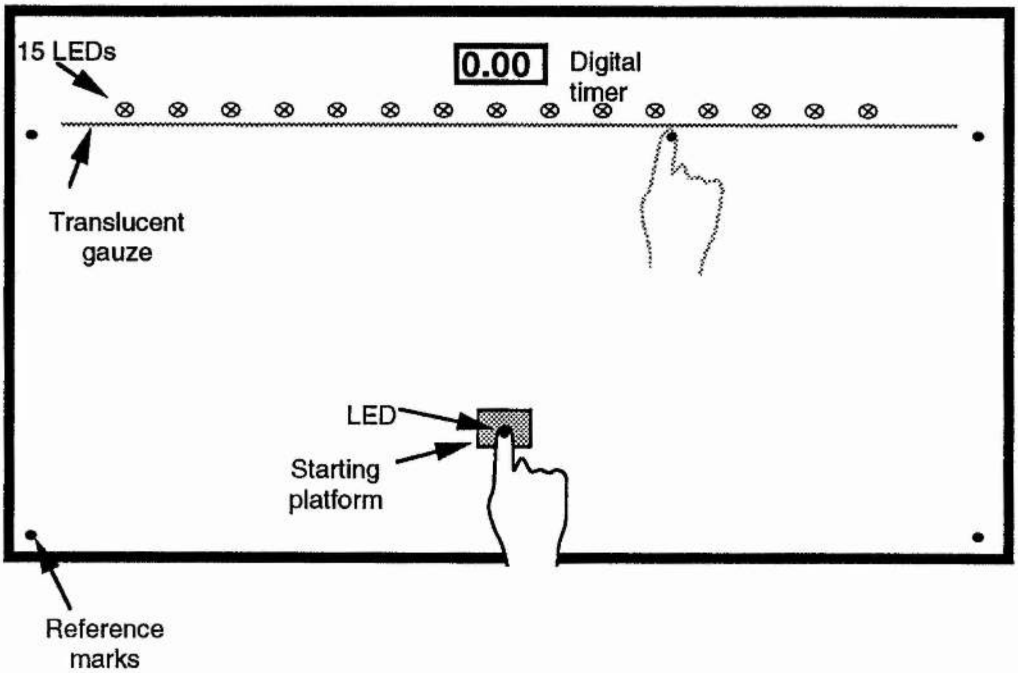

Figure 4.1: Schematic diagram of the reaching apparatus used in the Experiments 9-12.

Reaches were recorded on Super VHS videotape using a rotary shutter camera (JVC BY10E) which provided clear images at 25 frames/s. The camera was attached to the ceiling at a distance of 105cm above the LED's, providing a top view of the target lights and the subject's hand and arm.

Procedure. All subjects performed both the direct reaching task and the bisection task, under both visually open and closed loop conditions. In the closed loop condition, which was always carried out first, subjects had full vision of their arm and hand while carrying out the movement. However, in the open loop condition no visual information of the arm or hand position was available: the room was completely dark apart from two strip-lights covered in dense red filter, attached 45cm above each side of the table and shielded from the subject's view. Subjects wore ski goggles with green filters which enabled them to see the green LEDs on the panel but prevented vision of the hand or of the small LED attached to the finger. The viewing angle of the subject was such that the finger did not obscure the lights as it approached them. Head and eye movements were not restricted.

A total of 240 trials was given with subjects being tested under each feedback condition (open and closed loop) for 30 trials on direct pointing and 30 trials on bisection, and this was repeated using each hand separately. In each of these 30 trial blocks 10 reaches were directed towards left hemispace, 10 towards right hemispace and the remaining 10 to the centre, in pseudorandom sequence. The order of the pointing and bisection blocks, as well as of the hand used, was counterbalanced as completely as possible. Six practice trials were given before each block and there were short rest intervals in the light between the blocks. At the start of each trial subjects rested their index finger on the starting platform and at a variable time intervall following a 'ready' command the LED or LEDs were illuminated for 1 second. They were told to point as accurately and quickly as possible either directly to the light (pointing task) or midway between the two lights (bisection task). They were also asked not to correct the position once the finger had touched the panel.

Data analysis. Successive single frames of the video image were digitized for analysis using a 'Pluto' 12.0 graphics system (IO-Research) interfaced with a Dell AT computer. The time of release of the microswitch defined the initiation of a reach, and response latency after stimulus onset was measured using a millisecond timer. The position of the LED on the tip of the index finger was stored as X,Y Cartesian coordinates by the computer for each video frame. This process was continued from the initiation of the reach until the subject touched the panel.

The X-Y coordinates from successive frames during the forward/ lateral displacements of the limb allowed point estimates of velocity to be computed. Thus it was possible to estimate the *maximum velocity* achieved during each reach, the *time to peak*, i.e. from movement initiation to the point at which maximum velocity was achieved, and the *deceleration time,* i.e. from the point of maximum velocity to the end of the movement. In addition the total time of the movement was used to compute the *mean velocity* of the reach.

To permit spatial analysis of the trajectories, a linear interpolation of the X-Y coordinates of points derived from successive video frames was computed, forming a connected series of straight-line segments. This reconstruction of the route was then recoded by drawing ten axially equidistant lines ('slices') across it, so as to yield 10 standardized data points. (This procedure allowed each subset of similar trajectories to be averaged together and thus to be compared across conditions; examples of the recoded data are illustrated in Figure 4.4). The next step was to compute the lateral discrepancy of each of the 10 standardized points relative to the corresponding points on an imaginary direct path between the starting position of each movement and the actual target position. The following mean accuracy measures could then be computed: the *final error*, defined as the signed distance (in mm) from the final finger position to the actual (or virtual) target position; the *maximum deviation*, defined as the greatest medial-lateral deviation (in mm) of the actual route from the ideal direct path; and the *total deviation*, i.e. the summed areal discrepancy between the route taken and the direct line, measured in squarecm. To permit the last measure to be estimated, a mean axial distance was computed and used. It should be noted that in all cases the measures refer only to medial/lateral deviations; neither vertical displacements nor proximal/distal errors were measured.

Statistical Analyses. The mean of the 10 X,Y trajectories taken to a given target location within each block of trials was calculated for each subject following the 'slice' standardization. For each dependent variable these 10-trial means and also, where appropriate their standard deviations, were then subjected to five-way analyses of variance with sex (male/female) as a between-subjects factor, and conditions (open/closed loop), hands, task (pointing/bisection) and location (left/right/centre) as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using the Geisser-Greenhouse adjustment to the degrees of freedom. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance.

RESULTS

Since a large number of analyses were carried out, the presentation of the results is restricted to those findings that were consistent across related measures of performance. It should also be noted that the numerical values of the kinematic measurements of this and the following experiments are listed in the appendix.

For full description of the significant ANOVA terms see Tables 4.1 and 4.3.

Spatial trajectory of the limb movement.

(i) Final Error.

The mean signed final errors of finger position showed a strong main effect of location (Table 4.1). Over all conditions subjects showed mainly leftward errors in left space (negative values) and rightward errors in right space (positive values), i.e. on both sides they overshot the target (Table 4.2). The mean deviation from the central target was very small (-2.0 mm) and not significantly different from zero under any of the experimental conditions or with either hand. Comparison of the average errors in left and right hemispace (-14.9 mm on left and +12.4 mm on the right), showed no significant difference from one another in absolute magnitude ($t < 1$). Averaging all errors algebraically (including central space) revealed a nonsignificant mean leftward error of -1.5 mm.

Because final error was measured as a signed quantity and occurred in opposite directions in the two halves of space, greater errors in open loop would cancel out if tested for in a main effect of loop which indeed was not significant. Instead a difference between the feedback conditions had to be sought as a loop x location interaction. As is illustrated in Figure 4.2, open loop reaching did result in more overshooting than closed, the interaction being significant (see also Table 4.1).

The 'variable error', defined as the standard deviation of the signed error scores, was computed as a measure of the variability of the subjects' accuracy under each of the experimental subconditions. This variability was also greater

Table 4.1: ANOVA Results I: 12 normal subjects

ANOVA TERMS	Fin.Err.	Var.Err.	Max.Dev.	Tot.Dev.	Early Dev.	Late Dev.
Sex (Male, Female)					*	
Loop (Open, Closed)		***		***	**	***
Hand (Left, Right)						
Task (Point, Bisect)		**		***	**	*
Space (Lt., Ct., Rt)	***		***	***	***	***
Sex x Loop		**				
Sex x Hand						
Sex x Task						*
Sex x Space						
Loop x Hand						
Loop x Task						*
Loop x Space	***		***			
Hand x Task						
Hand x Space			*	**	***	***
Task x Space	*		***	**	**	
Sex x Loop x Hand						
Sex x Loop x Task						
Sex x Loop x Space						
Sex x Hand x Task						
Sex x Hand x Space						
Sex x Task x Space						
Loop x Hand x Task						
Loop x Hand x Space					**	
Loop x Task x Space						
Hand x Task x Space					**	
Sx x Lp x Hd x Tsk						
Sx x Lp x Hd x Spc			*		*	
Sx x Lp x Tsk x Spc						
Sx x Hd x Tsk x Spc						
Lp x Hd x Tsk x Spc						
Sx x Lp x Hd x Tsk x Spc						

Significance Level after Greenhouse-Geisser adjustments; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$
Abbreviations: Fin.Err.= Final Error, Var.Err.= "Variable Error", Max.Dev.= Maximum Deviation
Tot.Dev.= Total Deviation, Early Dev.= "Early Deviation", Late Dev.= "Late Deviation"

Table 4.2: Final Error (Deviation in mm) for the 12 subjects for left (LH) and right hand (RH) in left, centre and right spatial locations, averaged across both presentations and both feedback conditions.

Subject	Left Space		Centre		Right Space	
	LH	RH	LH	RH	LH	RH
1	-29.5	-12.6	-12.1	0.7	2.0	16.8
2	-11.6	-20.5	13.0	- 0.9	26.5	15.3
3	-18.8	-11.0	- 6.9	- 3.2	8.5	7.7
4	-10.3	5.4	1.9	17.8	7.3	29.2
5	-15.7	-15.3	- 2.1	1.3	10.3	16.6
6	- 9.6	-21.6	5.4	- 8.1	11.8	6.7
7	-21.0	- 9.4	-11.5	-11.0	- 0.6	2.3
8	-33.4	-10.0	-19.1	4.0	- 6.1	26.5
9	-11.3	- 6.0	- 2.7	- 1.1	9.8	11.8
10	-11.9	-15.9	- 1.1	1.3	14.6	20.8
11	-29.6	-33.2	-19.3	-28.1	- 3.7	-12.7
12	- 2.4	- 7.0	-17.3	15.6	43.1	34.7
Mean	-17.1	-13.1	- 6.0	- 1.0	10.3	14.6
SD	9.6	9.5	10.21	11.8	13.6	12.9

Negative scores indicate errors made to the left of the virtual target, positive scores indicate errors made to the right of the virtual target.

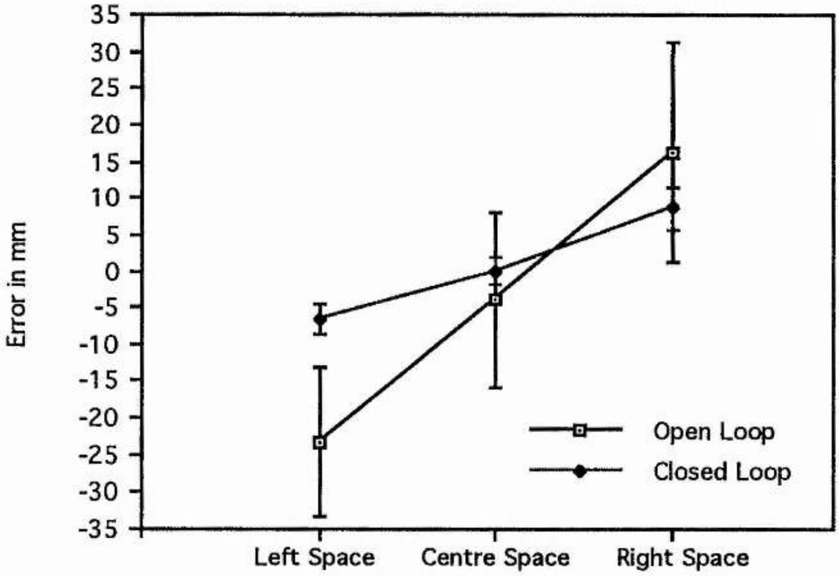

Figure 4.2: Mean final error for open and closed loop reaching toward each spatial location (left, centre, right). Negative values indicate displacements made to the left of the (virtual) target, positive values indicate displacements made to the right of the target. Errors bars indicate the intersubject variability.

in the open loop as compared to the closed loop condition, present as a highly significant main effect (Table 4.1).

Similarly there was a significant task x location interaction (Table 4.1), reflecting larger overshoot errors for bisection as opposed to pointing (Figure 4.3). However, the *post hoc* analysis (Newman-Keuls) revealed that this was only significant for targets in left hemispace.

The variability in final error ('variable error') was also significantly greater for bisection as opposed to direct pointing (see Table 4.1). There was no significant interaction of task x loop on either mean overshoot or SD.

No significant effects of hand (nor interactions with hand) on final error were found. The interaction of loop x hand x location was almost significant ($F(1.7,16.6)= 3.57$, $p< 0.06$), the left hand showing slightly larger average overshoots than the right hand in open loop (20.5 versus 19.1mm), but smaller overshoots in the closed loop condition (6.5mm versus 8.6mm). The direction of these differences (though nonsignificant) is directly contrary to the theoretical expectations (see beginning of this chapter). However, the hand x task x location interaction, while not significant ($p> 0.16$) did go in the expected direction, with overshoots of the left hand being larger in the pointing task (12.4mm vs 11.1mm) and smaller in the bisection task (14.5mm vs 16.6mm). Terminal variability gave no hint of any hand differences, in that neither the main effect of hand nor the interactions of hand x task nor hand x loop were significant.

(ii) Maximum Deviation.

The maximum lateral deviation of the mean route from the theoretical direct path similarly showed a strong main effect of location (Table 4.1), reflecting a significant leftward deviation in left space and a significant

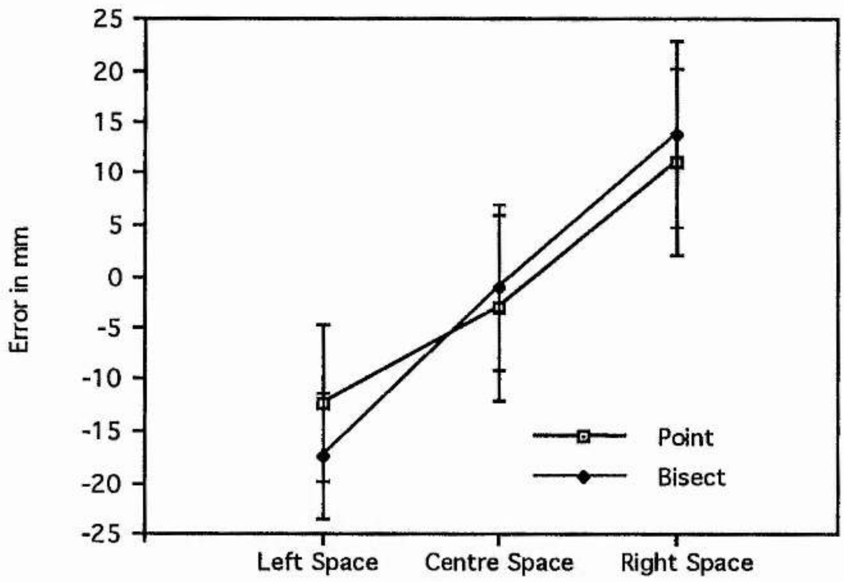

Figure 4.3: Mean final error for pointing and bisection toward each spatial location (left, centre, right). Interpretation of positive and negative values as in Figure 4.1. Errors bars indicate the intersubject variability.

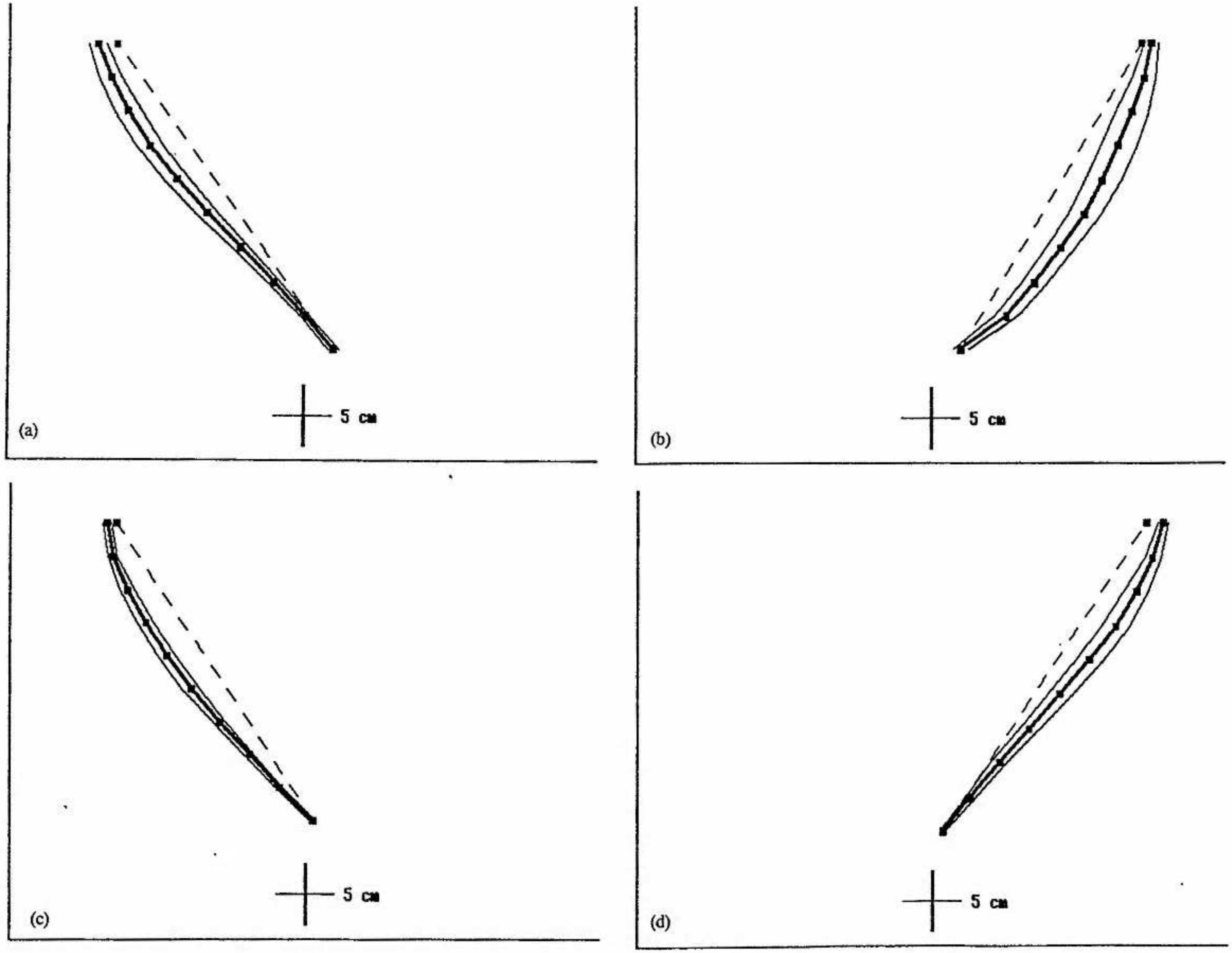

Figure 4.4: Averaged trajectories of a single subject performing the bisection task under closed loop reaching. Data are shown separately for a subject reaching with the left hand in left space (a), the left hand in right space (b), the right hand in left space (c) and the right hand in right space (d). For each mean trajectory 10 standardized data points (visible in each figure as black squares) were arrived at through interpolation, to allow averaging across 10 similar reaches. The thin lines at either side of the mean indicate the standard deviations across these 10 trials. The scale for both horizontal and vertical axes is indicated by the cross placed below each plotted trajectory.

rightward deviation in right space. The effect occurred in both left and right hand reaching, as illustrated in Figure 4.4.

The extent of this deviation was significantly increased in the open loop condition with routes erring further laterally than in the closed loop condition. Since maximum deviation is another signed quantity, this result was evident as a significant loop x location interaction (see Table 4.1).

The task x location interaction (Table 4.1) showed significantly larger maximum deviations for bisection as opposed to direct pointing. *Post hoc* analysis revealed that this difference was significant in both left and right hemispace.

There was also an interaction of hand x location (Table 4.1) with ipsilateral reaches (e.g. left hand towards left space) showing smaller sideward deviations than contralateral reaches. Individual comparisons showed significantly greater deviations for the left hand than the right in right and centre space; the reverse trend for the right hand to show greater deviations in left space was not significant.

(iii) Total Deviation.

The total summed deviations of each route (away from a hypothetical direct line) showed a significant main effect for location (Table 4.1) but as Figure 4.5 shows, this merely reflected a superiority for central targets as opposed to the lateral targets. Subjects tended to deviate much more from the hypothetical direct line in the open loop condition as opposed to the closed loop condition (Table 4.1)

Likewise the total deviations of the routes were greater in the bisection as compared to the pointing task, as shown by a significant task x location interaction (Table 4.1) the difference being significant in both left and right hemispace.

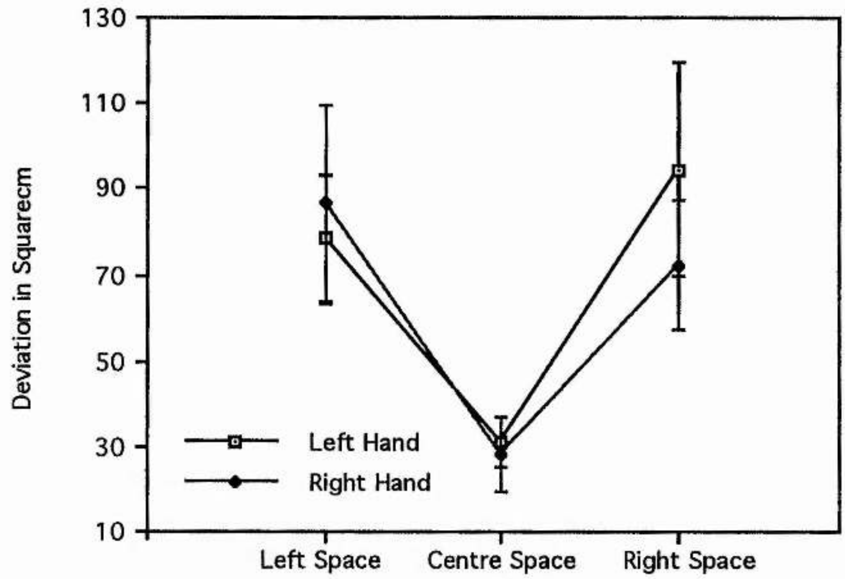

Figure 4.5: Total Deviation (areal departure of reaching trajectory from ideal straight line) of left and right hand reaches toward each spatial location (left, centre, right). Errors bars indicate the intersubject variability.

Ipsilateral reaches showed smaller total deviations than contralateral reaches, as indicated by the significant hand x location interaction (Table 4.1). Comparisons between the hands showed, however, that the apparent advantage of ipsilateral over contralateral reaches was only significant in right space.

(iv) Subdivision of the Total Deviation.

Since visual feedback should tend to influence routes mainly during their final stage, the total area was subdivided into an 'early deviation', defined as the area between the route taken and the direct line *up to the point of maximum velocity*, and a 'late deviation', defined as the summed deviation from the point of maximum velocity until the end of the movement. Analyses of variance were then performed separately for these two measures.

Subjects deviated more from the direct line in the open loop condition than in the closed loop condition at both stages of the movement. However, the conditions differed considerably more on late deviation (46% difference, Table 4.1) than on early deviation (26% difference, Table 4.1). The task variable also significantly affected both measures, with smaller deviations for the pointing task than the bisection task in both phases. However, on late deviation this task difference was only just significant (Table 4.1), and in fact was only apparent during closed loop reaching, with the loop x task interaction reaching significance, (see Figure 4.6).

Early deviation showed a highly significant task effect (Table 4.1), but this may simply reflect the shorter acceleration phase (Time to Peak) in the pointing than the bisection task (see findings on Time to Peak below).

Latency and kinematic measures of the limb movement.

(i) Latency.

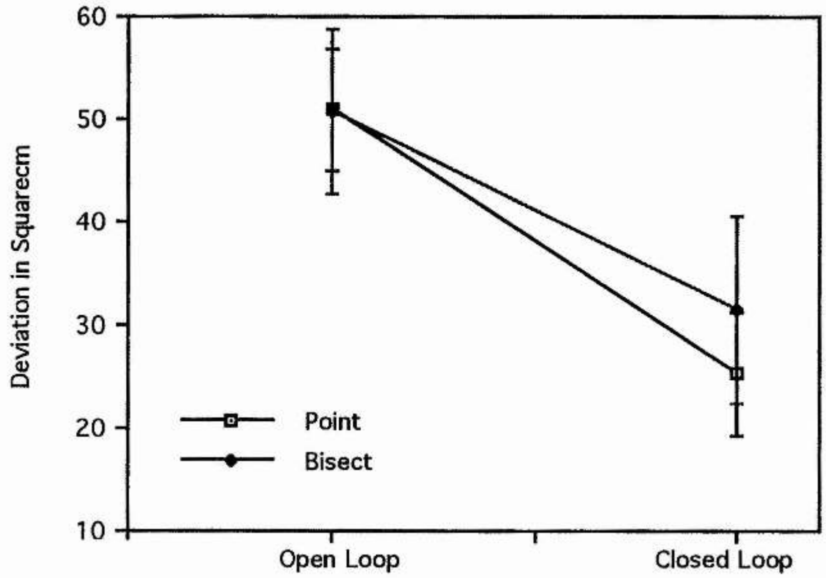

Figure 4.6: 'Late Deviations' (for definition see text) of open and closed loop reaching for pointing and bisection. Errors bars indicate the intersubject variability.

Table 4.3: ANOVA Results II: 12 normal subjects

ANOVA TERMS	Latency	Max. Vel.	Mean Vel.	Time to P.	Deceleration Time
Sex (Male, Female)		**	**		**
Loop (Open, Closed)	***				
Hand (Left, Right)					
Task (Point, Bisect)				**	
Space (Lt., Ct., Rt)	***	***	***	*	***
Sex x Loop					
Sex x Hand		*			
Sex x Task		*			*
Sex x Space			**		
Loop x Hand					
Loop x Task	***				
Loop x Space	***				
Hand x Task					
Hand x Space	**	***	***	***	*
Task x Space	***				
Sex x Loop x Hand					
Sex x Loop x Task					
Sex x Loop x Space			**		
Sex x Hand x Task					
Sex x Hand x Space			**		
Sex x Task x Space					
Loop x Hand x Task					
Loop x Hand x Space					
Loop x Task x Space	***				
Hand x Task x Space					
Sx x Lp x Hd x Tsk		**			
Sx x Lp x Hd x Spc					
Sx x Lp x Tsk x Spc					
Sx x Hd x Tsk x Spc					
Lp x Hd x Tsk x Spc					
Sx x Lp x Hd x Tsk x Spc					

Significance Level after Greenhouse-Geisser adjustments; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$
Abbreviations: Max. Vel.= Maximum Velocity, Mean Vel.= Mean Velocity, Time to P.= Time to Peak

Latency (to the onset of movement) showed a highly significant loop effect (Table 4.3), with a much greater mean reaction time (391 vs 305 ms) in the open loop condition. However, this difference is inflated by the effectively lower intensity of the stimulus LEDs in the open loop condition, due to the use of a green filter in viewing.

There was also a significant loop x location interaction with reaction time (RT) significantly lower for reaches towards left hemispace as compared to centre and right space, in the open loop condition only (see Table 4.3).

There was no main effect of hands ($p > 0.50$), but there was a significant hand x location interaction (Table 4.3). Individual comparisons revealed a shorter RT for the left hand as compared to the right, which reached significance in both left and centre space.

There was also a task x location interaction (Table 4.3), with a shorter RT for the bisection than the pointing task in left space and vice-versa in right hemispace. However, only the difference in left space reached statistical significance.

(ii) Maximum Velocity.

The peak velocity measure showed a significant hand x location interaction (Table 4.3), with ipsilateral reaches attaining a higher peak velocity than contralateral reaches; this difference held for both hands and on both sides of space (see Figures 4.7 and 4.8).

No effects of loop or task were found. Surprisingly there was a main effect for sex (Table 4.3), with male subjects showing on average a higher peak velocity than females.

(iii) Mean Velocity.

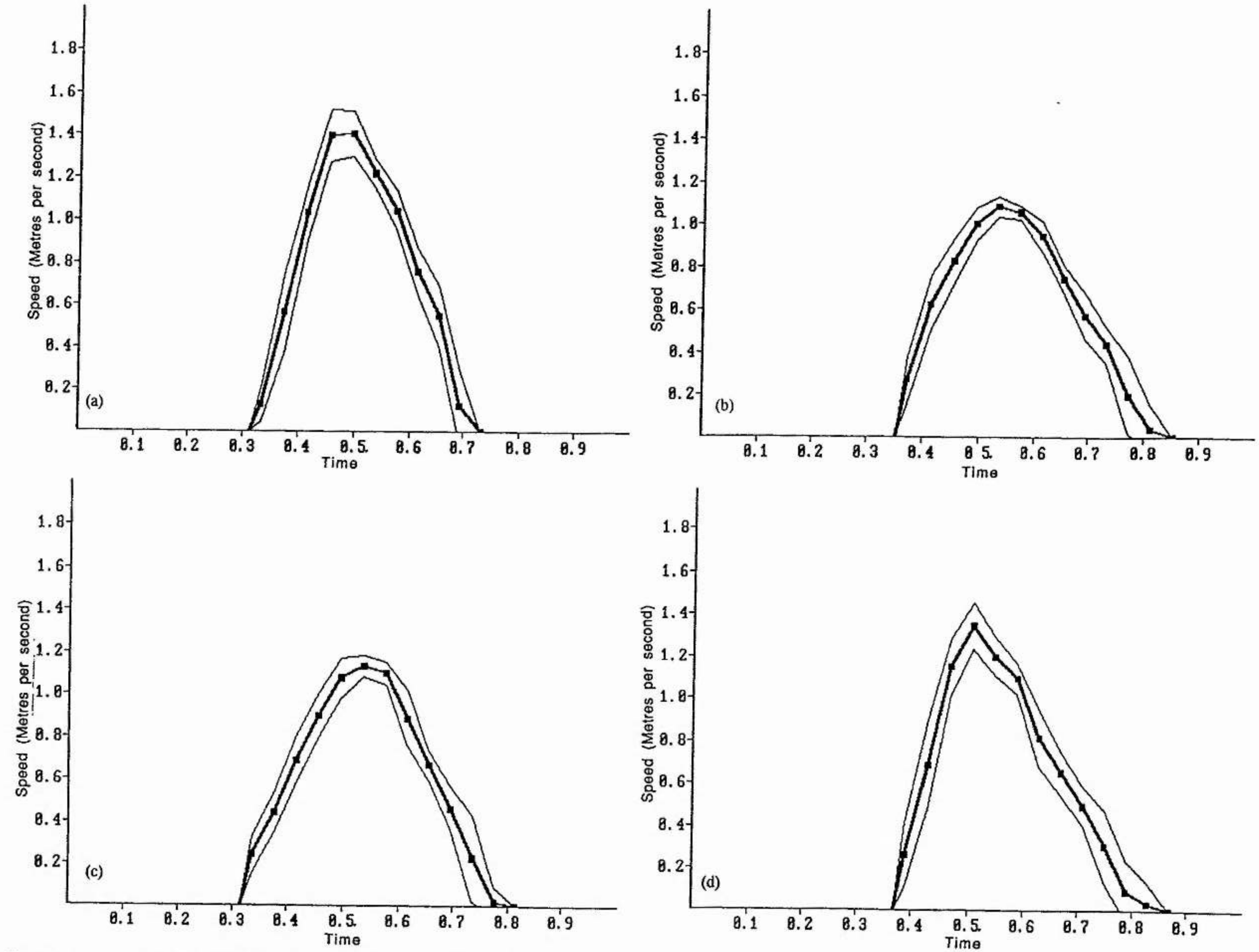

Figure 4.7: Average velocity profiles of a single subject performing the bisection task under closed loop reaching. Profiles were averaged across 10 trials for the left hand each in left (a) and right (b) hemispace and the right hand in left (c) and right hemispace (d). The markings around the profiles indicate the standard deviation across the 10 trials.

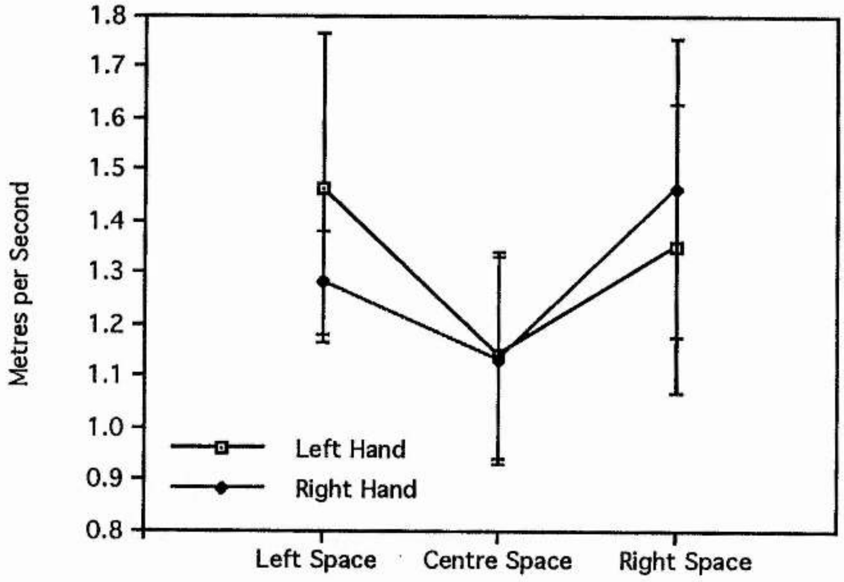

Figure 4.8: Maximum velocity of left and right hand toward each spatial location. Errors bars indicate the intersubject variability.

The mean velocity similarly proved higher for ipsilateral than contralateral reaches, as reflected in a highly significant hand by location interaction (Table 4.3). Again this difference was significant for both hands and for both left and right sides of space.

No effects of loop or task were found though there was a tendency for pointing to be faster than bisection, $F(1,10) = 4.49$, $p < 0.06$. Again there was a main effect for sex (Table 4.3) with male subjects showing overall faster reaches than females.

(iv) Time to Peak.

Ipsilateral reaches showed a shorter initial acceleration phase than contralateral reaches, as reflected in the hand x location interaction (Table 4.3); this difference held for both hands and on both left and right sides.

The main effect for task (Table 4.3) indicated a shorter acceleration phase for the pointing task as opposed to the bisection task. No effects of loop were found.

(v) Deceleration Time.

The time from the velocity peak to the endpoint of the reach also showed a significant hand x location interaction (Table 4.3), but in this case ipsilateral reaches showed longer durations than contralateral reaches. However, the hemispace difference was significant for the right hand only, and the hands differed only within right space (see Figure 4.9).

There was no overall significant hand effect. No significant effects of loop or task were found either, though there was a tendency for the direct pointing task to show a shorter deceleration time than the bisection task, $F(1,10) = 3.49$, $p < 0.10$. Male subjects showed an overall shorter deceleration time than female subjects (Table 4.3).

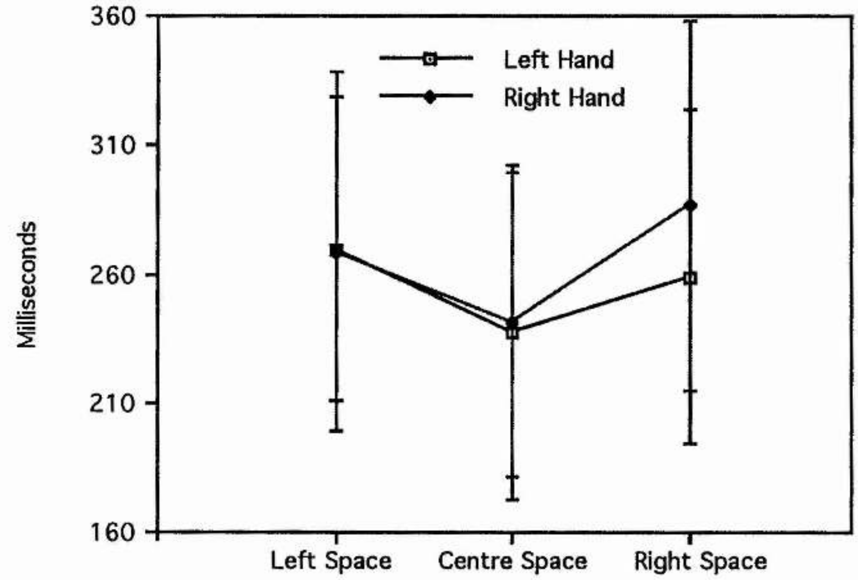

Figure 4.9: Deceleration time for left and right hand for each spatial location. Errors bars indicate the intersubject variability.

Summary of the data.

Subjects tended to overshoot the targets sidewards in all experimental conditions except direct pointing under closed loop feedback, which was highly accurate. These final errors were greater (and more variable) in the bisection than in the pointing task, and all these effects were greatly exacerbated under open loop conditions. These overshooting effects were closely associated with outwardly-curved reaching trajectories. Closer examination indicated that the increased path deviations caused by the removal of visual feedback tended to occur late in the movement, while those associated with the task of bisection occurred mainly early in the reach.

There was no significant overall asymmetry on any accuracy measure in relation to hemispace or hand used. The only hint was a finding of greater route variability in left hand reaches; this must have occurred mainly early in the movements, since there was no difference in endpoint variability. There was also no overall hand asymmetry on any chronometric measures, although a tendency for left hand responses to be made with a lower reaction time than right attained significance for central and left space reaches. The left hand also responded more quickly than the right hand in the deceleration phase of its reaches, this time in the right hemispace only.

There was a significant latency advantage for bisection over pointing in the left hemispace, though this seems attributable to a trend for the RTs in the pointing task to be significantly slower in the left than the right hemispace. RTs were faster overall in the left than right hemispace in open loop responding.

In general, reaches tended to be more efficiently executed by each hand when operating in its ipsilateral hemispace. This was shown clearly for the kinematic measures of latency, peak velocity, mean velocity, and the time taken to reach peak velocity; however deceleration time showed the opposite effect.

The outward curvature of reach paths was also more marked in contralateral reaches as compared with ipsilateral.

Finally, it was found that male subjects showed faster reaches on both velocity measures than females; this was associated with no difference in accuracy, despite a shorter deceleration phase in the male velocity profiles.

DISCUSSION

There was a general finding that subjects tended to 'overshoot' with respect to stimuli located laterally in space. Although this occurred to some degree across all experimental conditions, it can not be discounted as an artefact of measurement, since it almost disappeared in direct pointing under closed loop feedback. In this condition final overshoot errors averaged only 4.6mm, as compared for example to an average of 19.8mm in open loop performance. That small residual error may be partly due to an outward rotation of the top of the finger as it moved over toward one side, which would take the LED further out than the midpoint of the finger. But it should be noted that this effect would be constant throughout the experiment and therefore could not account for the large effects of task and condition. It seems most plausible to interpret the greater part of the overshoot errors in terms of a range effect (Brown *et al.*, 1948; Slack, 1953; Poulton, 1980): subjects tend to overshoot proximal targets and to undershoot distal ones. At a target distance of 15 cm from the midline of the display, overshoots would be expected, and the fact that these overshoots are exacerbated under open loop conditions is in accordance with previous findings (Prablanc *et al.*, 1979). Evidently making the task more visually difficult in other ways, such as requiring bisection, has a similar exacerbating effect. Both manipulations also increased the variability of response endpoint.

However range effects provide a redescription rather than an explanation; a true explanation of the observed curvilinear trajectories may ultimately be found in a consideration of the mechanics of the arm movement and/or in the optimization of late visual feedback that the curvature may provide. Alternatively the 'overshoot' responses may be attributable to a tendency for the subjects to respond in the direction contralateral to the more activated hemisphere. Lateralized visual input should produce an activation imbalance in favour of the hemisphere that is stimulated directly (Reuter-Lorenz *et al.*, 1990). Therefore presenting a stimulus in right (or left) space should produce a *greater* activation of the contralateral hemisphere and a concomitant orienting shift to the stimulated side of space. In this experiment this could have resulted in an increased lateral response ('overshoot'). In the same vein it could be argued that the larger overshoot errors in open loop might have been due to a greater salience of the stimulus in that condition, thus resulting in an even greater lateral response due to a more activated hemisphere. Finally as biggest overshoot errors were found for the bisection task in open loop, it seems likely that presentation of two stimuli as opposed to one (pointing) enhanced this effect even more.

Surprisingly, no hand differences in terminal accuracy were found, nor were there any significant interactions of hand with visual feedback or task (pointing vs bisection). This outcome was rather unexpected, and supports neither a right hand superiority when visual feedback is available (Flowers, 1975) nor a left hand advantage in the absence of visual feedback (Guiard *et al.*, 1983). (If anything there was a trend in the opposite direction: a slight right hand advantage in open loop and a slight left hand advantage in closed). However the results are in line with more recent experiments which have failed to find hand differences in terminal accuracy in either open or closed loop pointing tasks (Haarland and Harrington, 1989; Carson *et al.*, 1990). The use of the bisection task had been expected to enhance the right hemisphere's involvement as compared to pointing. Yet even here, although the exclusion of visual feedback decreased terminal accuracy, no differential effect of hand or hemispace was found. In part the failure to find clear asymmetries in final error might be due to the fact that the stimuli were visible throughout the movement, thus allowing unrestricted target feedback that could counterbalance any initial facilitatory effect the right hemisphere might have had.

Consistent with the findings of Carson *et al.* (1990), left hand reaches tended to be made with a lower reaction time than right hand reaches, especially in left hemispace; Carson *et al.* explain this result in terms of a right hemisphere dominance in the planning of nonballistic arm movements in a spatial context. The same explanation might account for the finding that there was a significant latency advantage for bisection over pointing in left hemispace.

Even though no overall hand effects were found in final error there seemed to be obvious spatial compatibility effects whereby the routes deviated more during contralateral than ipsilateral reaches (shown in the analyses of maximum and total deviations). However, this difference was compensated for prior to the final endpoint. These late corrections must have been particularly great with the left hand as this hand showed bigger compatibility effects than the right hand (on maximum and total deviation), yet its final accuracy did not differ from the right hand. It could be speculated that the right hand is more accurate initially but that if anything the left hand is more effective in making final corrections. Such a slight left hand superiority in the approach to the endpoint may be the reason for this hand showing a shorter deceleration time than the right hand, at least in right space.

On the kinematic measures of peak velocity, mean velocity, and time to reach peak velocity, reaches appeared to be more efficiently executed by each hand when operating in its ipsilateral as opposed to the contralateral hemispace.

This is a consistent finding reported by a number of authors (Prablanc *et al.*, 1979; Fisk & Goodale, 1985; Carson *et al.*, 1990; Carey *et al.*, 1990). The latency differences between contralateral and ipsilateral reaches could be interpreted in terms of interhemispheric transmission time, as suggested by Fisk and Goodale (1985), in that if reaches were initiated and controlled by the hemisphere contralateral to the hand used, then ipsilateral movements would be programmed within the same hemisphere initially stimuluated by target onset, whereas contralateral reaches would require that either information crosses to the opposite hemisphere. Therefore prolonged movement onset should be expected for contralateral reaches. The compatibility effects on the other temporal parameters however cannot be explained in such terms although for this experiment, it is possible that the increased movement times could be attributed to the longer paths being followed in contralateral reaches; but those more devious paths are themselves hard to explain.

No satisfactory explanation can be offered for the finding that male subjects showed faster reaches on both velocity measures than females. It is possible that male subjects were more motivated than females, and that the instruction to reach 'as accurately and fast as possible' was interpreted primarily as a speed instruction by them. No consistent sex differences have been reported by others.

As in the bisection experiments by Bradshaw *et al.* (1985; 1987a) small leftward displacements for reaches in central space were found in the bisection task. However, these were not significant from zero in any of the experimental conditions, nor was this bias significantly different from that in pointing at a single target. The findings of Carey and colleagues (Carey and Goodale, 1989; Carey *et al.*, 1990) of rightward errors in left hand open loop bisection were also not replicated. It is conceivable that their task might have been more taxing than this task due to their use of head restraint and the consequent absence of neck proprioception cues; there might thus have been more scope for systematic errors to appear.

The present study was, nonetheless, sensitive enough to reveal significantly greater centrifugal errors (i.e. overshoots) in bisection responses relative to pointing responses, in both left and right hemispace. Nichelli *et al.* (1989) reported the opposite result: they tested subjects with the traditional line bisection test, and found centri*petal* bisection, i.e. leftward in right hemispace, and vice-versa. However opposite results were found in Experiment 1 (chapter two) with centrifugal responses as in this experiment.

It should be noted that under open loop conditions the routes followed in the late portion of bisection reaches did not differ from pointing. Furthermore, the overshoot errors in the two tasks were only slightly different (20.6 vs 18.9 mm) in open loop. In contrast they differed markedly under closed loop conditions (10.5 vs 4.6 mm), though the task x loop interaction was nonsignificant. This tends to confirm the assumption that there is little useful visual feedback available for corrective purposes in open loop. However, closed loop conditions caused far smaller lateral route deviations than open, both early and late on. It is thus possible that visual feedback from the hand is important early in a movement as well as late.

Given the lack of difference in route deviations between the pointing and bisection tasks in these normal subjects, it could be predicted that with the use of open loop conditions, right hemisphere lesioned patients too will differ little in the routes taken in the bisection and pointing tasks. This would contrast markedly with the findings that have been reported in closed loop (Goodale *et al.*, 1990).

SUMMARY

Possible right hemisphere influences upon visually guided reaching were examined by asking normal subjects to point either directly to a single LED ('pointing'), or to the midpoint between two LEDs ('bisection'). On different trials, targets were situated centrally or in left or right spatial hemifield, and in all cases performance of the left hand was compared with that of the right. Subjects reached under both *closed loop* (with visual feedback of hand and arm) and *open loop* (no visual feedback) conditions.

It was found that subjects consistently deviated laterally in response to eccentrically-located targets ('overshooting'), making leftward errors in left hemispace and rightward errors in right hemispace. Movements towards central targets showed small and nonsignificant leftward errors. The overshoots were greater in open than in closed loop conditions, and greater for the bisection as opposed to the pointing task, being minimal in the closed loop pointing task. These effects were mirrored in curvilinear paths followed by the hand. There were no effects of target hemispace or hand on accuracy, though these interacted strongly in the kinematics of the reaching. These compatibility effects were more evident for the left hand than the right. Neither the type of task nor the feedback condition affected these kinematic measures.

CHAPTER FIVE

VISUOMOTOR ANALYSIS OF BISECTION UNDER RESTRICTED VISUAL FEEDBACK CONDITIONS IN NORMAL SUBJECTS

Contrary to most previous research (Fisk and Goodale, 1985; Flowers, 1975; Roy, 1983; Carey and Goodale, 1989) no hand differences (in favour of the right hand) were found for the visuomotor tasks carried out by the right-handed subjects in Experiment 9. The only indication of a possibly existing asymmetry occured with regard to movement onset time. Significant left hand latency advantages for reaches toward central and left space were reported, consistent with the findings of Carson *et al.* (1990) on normal right-handed subjects. Complementary clinical data on visuomotor tasks (Fisk and Goodale, 1988; Haaland and Harrington, 1989) have demonstrated prolonged movement onset times in patients with damage to the right hemisphere. Consequently both set of results seem to indicate a privileged role for the right hemisphere in movement preparation.

A left hand advantage for terminal accuracy was expected to be found for the bisection task under open-loop conditions, where no visual information on hand/target discrepancy was available. It is however possible that the increased visuospatial demands of this task, which should have favoured right-hemisphere participation, were simply not big enough to produce the expected effect. On the other hand the bisection task may have been too spatially complex to allow a right hand accuracy advantage to appear in closed loop performance (see also Carson and Goodman, 1992). However this explanation cannot be applied to the pointing task which, when performed under visual guidance, should have produced right hand advantages similar to those found in traditional aiming tasks (Fisk and Goodale, 1985; Roy, 1983; Watson and Kimura, 1989).

So although various investigators have suggested a special role of the right hemisphere in *perceptual localization* (Kimura, 1969; Levy and Reid, 1976; 1978; Robertshaw and Sheldon, 1976) empirical support for a right hemisphere contribution towards *visuomotor control* remains meagre (Guiard *et al.*, 1983). However Bracewell *et al.* (1990) carried out a study investigating whether differences in accuracy between hemifields could be demonstrated in the directing of saccadic eye movements. They found smaller variable errors for eye movements made to left as opposed to right hemifield targets, which they interpret as a right hemisphere advantage for *visuomotor localization*, although they also point out that the right hemisphere might simply be better for *remembering* the spatial location of visual targets (see also Bracewell *et al.*, 1987). It is interesting to note that in this study, in contrast to Experiment 9, in which the stimuli were visible throughout the movement, thus allowing unrestricted target feedback, targets were only briefly presented (100 msec). This may have had a facilitatory effect for the right hemisphere.

EXPERIMENT 10

So the next experiment was designed to reveal any possibly existing right hemisphere contributions regarding visuomotor tasks. In order to achieve this, only the bisection task was presented (in Experiment 9 this task proved more difficult overall than pointing, although it did not affect hand performance differentially). The number of target locations was increased and the central locations eliminated, as reaches towards central targets proved almost perfect for all conditions in Experiment 9. A chin rest was used as a head restraint and the consequent absence of neck proprioception cues might leave more scope for systematic errors to appear (see also Carey *et al.*, 1990). Similarly to Bracewell *et al.* (1987; 1990) briefly presented targets were randomly interspersed with targets visible throughout the movement, to assess whether this might have been a contributing factor for the lack of hand differences in Experiment 9.

Finally the range of target eccentricity was extended in order to elucidate whether the overshoot errors reported in Experiment 9 were simply due to a range effect (Brown *et al.*, 1948; Slack, 1953; Poulton, 1980), whereby subjects overshoot proximal targets and undershoot distal ones, or whether a greater activation of the contralateral hemisphere, due to lateral stimulus presentation could have led to the increased lateral responses, i.e. overshoots (see also **Discussion** Experiment 9, chapter four). The latter explanation would predict even larger overshoots for further laterally placed targets whereas the range effect would predict undershoot.

METHOD

Subjects. Eight male subjects ranging in age from 23 to 31 years (mean = 27) participated as unpaid volunteers in the experiment. All were fully right-handed as assessed both by self report and by administration of the Annett Handedness Inventory (Annett, 1967).

Apparatus and tasks. Again the subject was seated at a table facing a vertical panel on which the stimulus lights (green 4mm-diameter LEDs) appeared. For description of apparatus see Experiment 9, chapter four.

Two lights were presented simultaneously, being located either to the far right or left, i.e. 20 cm and 30cm from the centre of the panel on either side (approximately 33 and 45 degrees of visual angle), or to the midleft and midright, i.e. 10cm and 20cm from the centre on either side (approximately 17 and 33 degrees of visual angle).

Again reaches were recorded on Super VHS videotape. For description of the camera see Experiment 9, chapter four.

Procedure. Unlike Experiment 9 head movements were restricted through use of a chin rest attached centrally at a distance of 10cm from the start platform. All subjects performed the bisection task under both visually open and closed loop conditions (for description of open and closed loop see *Procedure* Experiment 9). In both conditions target lights remained illuminated throughout the movement (see also Experiment 9) on half the trials only. On the other half LEDs disappeared as soon as the finger was released from the microswitch (i.e. the reach was initiated). Before starting the experiment subjects were told that on some trials, the lights remained illuminated throughout the movement, whereas on others they would disappear after movement onset. However to prevent use of specific response strategies (i.e. short latencies and slow movements under constantly illuminated lights, or long latencies and fast movements with disappearing lights), they were not informed which condition was to be used on a particular trial.

A total of 256 trials was given with subjects being tested under each feedback condition (open and closed loop) for 32 trials on constantly illuminated lights (long presentation) and 32 trials on disappearing lights (short presentation), presented in pseudorandom sequence. This was repeated using each hand separately. In each of these 32 trials 8 reaches were directed towards the far left space, 8 towards the midleft, 8 towards the far right space and the remaining 8 to the midright space in pseudorandom sequence. The order of the open and closed loop blocks, as well as of the hand used, was counterbalanced as completely as possible. Six practice trials were given before each block and there were short rest intervals in the light between the four blocks. At the start of each trial, subjects rested their index finger on the starting platform. At a variable time interval following a 'ready' command the LEDs were either illuminated for 1 second (long presentation) or disappeared after movement onset (short presentation). Subjects were told to point as accurately and quickly as possible midway between the two lights presented on a given trial and not to correct the movement once the panel was reached.

The data were analysed as in Experiment 9. Again it should be noted that in all cases the measures refer only to medial/lateral deviations; neither vertical displacements nor proximal/distal errors were measured.

Statistical Analyses. As in Experiment 9, the mean of the 8 X,Y trajectories taken to a given target location within each block of trials was calculated for each subject following the 'slice' standardization. For each dependent variable these 8-trial means and also, where appropriate their standard deviations, were then subjected to four-way analyses of variance with conditions (open/closed loop), hands, presentations (long/short) and location (far left/midleft/midright/far right) as within-subjects factors. The significance of main effects and interactions involving repeated measures was assessed using the Geisser-Greenhouse adjustment to the degrees of freedom. Finally, significant main effects and interactions were examined in detail through the Newman-Keuls testing procedure, using the 5% level of significance.

RESULTS

Again a large number of analyses were carried out, so the presentation of the results is restricted to those findings that were consistent across related measures of performance. For full description of the significant ANOVA terms see Tables 5.1 and 5.3.

Spatial trajectory of the limb movement.

(i) Final Error.

The mean signed final errors of finger position showed a strong main effect of location (Table 5.1). Over all conditions subjects showed mainly

Table 5.1: ANOVA Results I: 8 normal subjects

ANOVA TERMS	Fin.Err.	Var.Err.	Max.Dev.	Tot.Dev.	Early Dev.	Late Dev.
Loop (Open, Closed)		***		***		***
Hand (Left, Right)	**					
Presentation (Long, Short)						
Space (Lt., Mlt, Mrt, Rt)	***	***	***	***	***	
Loop x Hand						
Loop x Presentation						
Loop x Space	***		***			
Hand x Presentation			*			
Hand x Space			*		***	
Presentation x Space		**				
Loop x Hand x Presentation		*				
Loop x Hand x Space						
Loop x Presentation x Space						
Hand x Presentation x Space						
Lp x Hd x Pre x Spc		***				

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Fin.Err.= Final Error, Var.Err.= "Variable Error", Max.Dev.= Maximum Deviation
Tot.Dev.= Total Deviation, Early Dev.= "Early Deviation", Late Dev.= "Late Deviation"
Lt= Left, Mlt= Midleft, Mrt= Midright, Rt= Right

leftward displacements regarding the two targets in left space (negative values) and rightward displacements regarding the two targets in right space (positive values), i.e. on both sides they overshot the target (Table 5.2). Only for the far left and far right targets however, were the deviations significantly different from zero ($t= 2.78$, $p< 0.05$, far left target; $t= 4.30$, $p< 0.01$, far right target). Comparison of the average errors in left and right hemispace [far left and midleft target (-12.6 mm) against far right and midright target (+17.2)], showed no significant differences in absolute magnitude ($t= 1.98$). Averaging all errors algebraically revealed a nonsignificant mean rightward error of +2.2 mm.

Because final error was measured as a signed quantity and occurred in opposite directions in the two halves of space, greater errors in open loop would cancel out if tested for in a main effect of loop. Instead a difference between the feedback conditions had to be sought as a loop x location interaction. As is illustrated in Figure 5.1, open loop reaching did result in more overshooting than closed, the interaction being significant (see also Table 5.1).

There was also a significant main effect of hand, reflecting leftward displacements for the left hand (-5.3 mm) and rightward displacements for the right hand (+9.9 mm) over all conditions. However these errors did not differ from one another in absolute magnitude ($t< 1$).

No other effects of hand were found although the right hand showed considerably larger average overshoot errors than the left hand in open loop (+14.7 mm versus -6.2 mm), but overshoots of similar magnitiude in the closed loop condition (+5.1 mm versus -4.4 mm). The direction of these differences is in line with the theoretical expectations (see beginning of this chapter).

No effects of stimulus presentation were found although there was a trend ($p< 0.067$) to produce smaller errors in the long than the short

Table 5.2: Final Error (Deviation in mm) for the 8 subjects for left (LH) and right hand (RH) in far left, midleft, far right and midright spatial locations, averaged across both presentations and both feedback conditions.

Subject	Far Left Space		Midleft Space		Midright Space		Far Right Space	
	LH	RH	LH	RH	LH	RH	LH	RH
1	-29.3	- 1.7	-24.4	0.3	9.5	28.4	11.2	- 3.6
2	-28.2	0.2	-13.5	27.1	8.3	31.5	8.7	30.5
3	11.9	11.8	- 5.4	13.2	-11.6	28.7	-45.1	- 0.9
4	-14.2	-30.6	-24.1	-33.2	0.2	- 2.7	- 4.6	7.8
5	-41.4	-16.7	-33.2	-22.0	22.5	26.8	26.3	24.5
6	-11.3	11.7	- 8.5	1.8	24.8	47.6	29.3	55.1
7	-26.9	-16.1	-14.4	- 8.5	16.3	11.2	19.9	20.9
8	-27.6	-18.4	-21.2	-12.5	7.7	46.9	16.6	58.8
Mean	-20.9	- 7.5	-18.1	- 4.2	9.7	27.3	7.8	24.1
SD	16.2	15.3	9.3	19.2	11.9	16.8	23.9	23.5

Negative scores indicate errors made to the left of the virtual target, positive scores indicate errors made to the right of the virtual target.

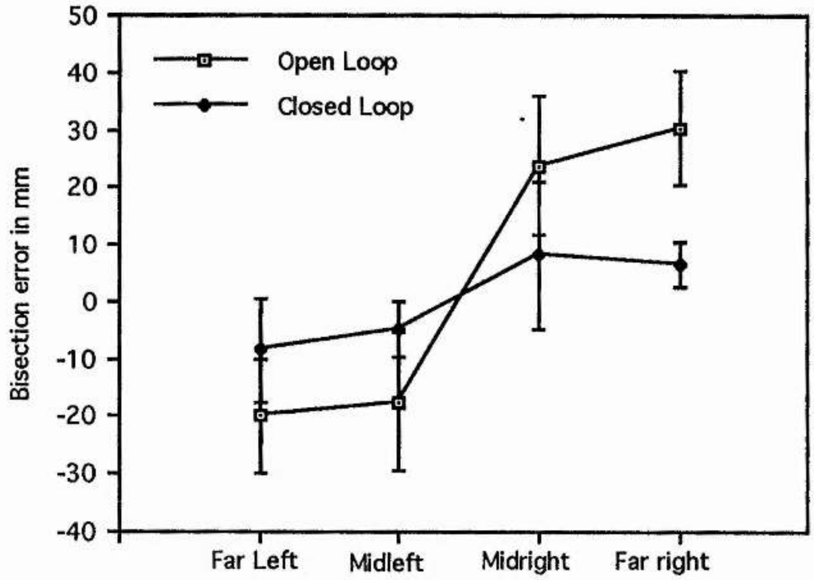

Figure 5.1: Mean final error for open and closed loop reaching toward each spatial location (far left, midleft, midright, far right). Negative values indicate displacements made to the left of the (virtual) target, positive values indicate displacements made to the right of the (virtual) target. Error bars indicate the intersubject variability.

presentation in closed loop (0.5mm vs 1.2 mm) but larger errors in open loop (6.2 mm vs 2.1 mm).

There was however no interaction of stimulus presentation with hand ($F < 1$).

(ii) Variable Error.

The 'variable error' defined as the standard deviation of the signed error scores, was computed as a measure of the variability of the subjects' accuracy under each of the experimental subconditions.

This variability proved not only greater in the open loop as compared to the closed loop condition but was also affected by hand and stimulus presentation, in that the left hand showed lower variability than the right hand for short stimulus presentation under open loop but not closed loop feedback conditions (see Figure 5.2). This finding was present as a significant loop by hand by presentation interaction (Table 5.1).

There was also a significant interaction of presentation by location (Table 5.1) reflecting the fact that the largest variations occured for reaches toward the far right target during short stimulus presentation.

(iii) Maximum Deviation.

The maximum lateral deviation of the mean route from the theoretical direct path similarly showed a strong main effect of location (Table 5.1), reflecting a significant leftward deviation regarding the targets in left space and a significant rightward deviation for the targets in right space. The effect occurred in both left and right hand reaching, as illustrated in Figure 5.3.

The extent of this deviation was significantly increased in the open loop condition with routes erring further laterally than in the closed loop condition.

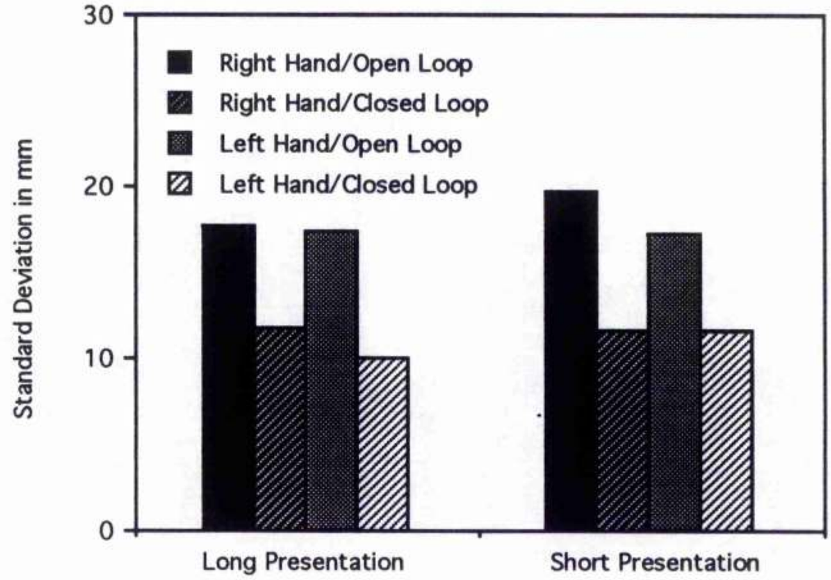

Figure 5.2: Intra-subject variability of the final error for long and short stimulus presentation as a function of loop condition (open, closed) and hand (left, right).

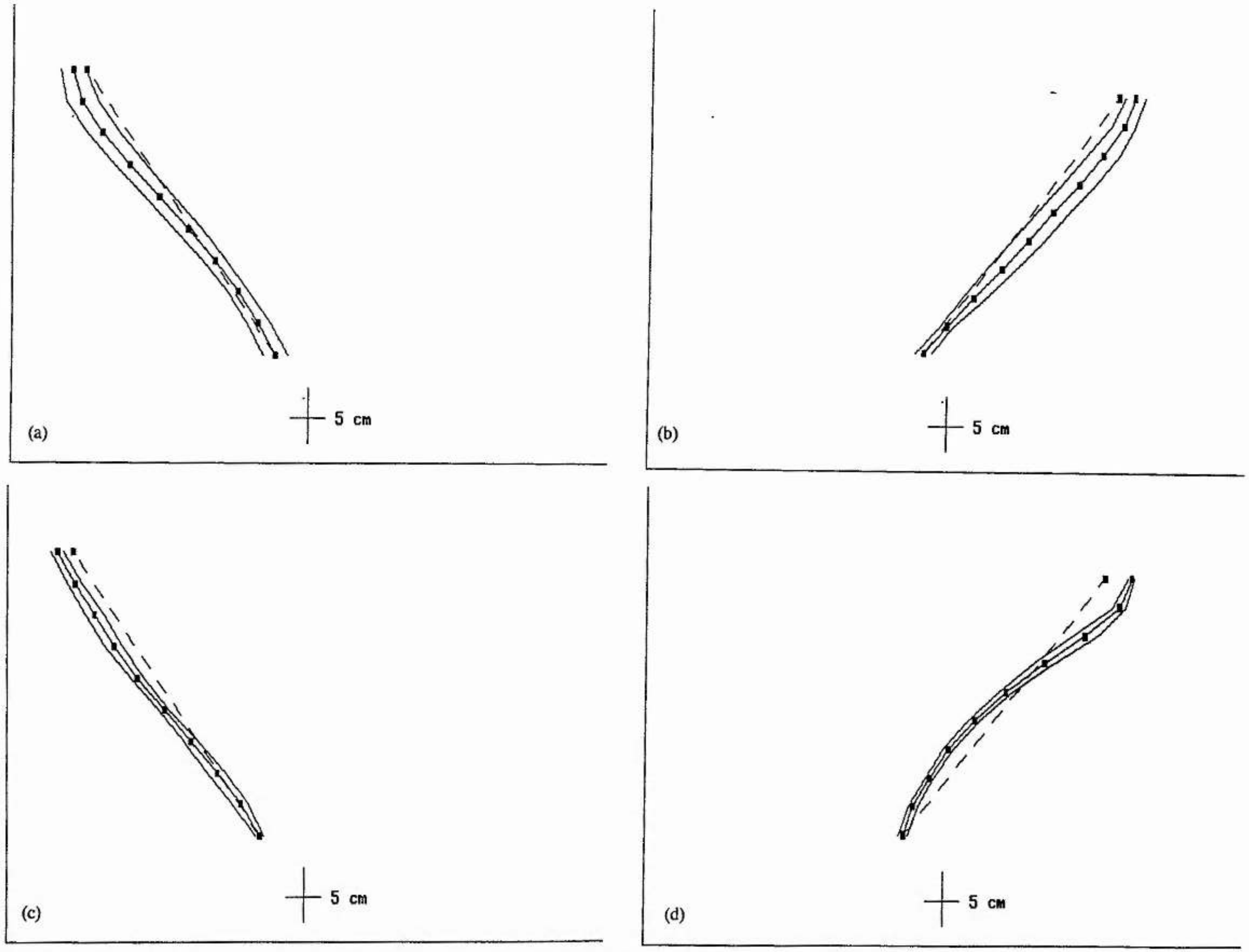

Figure 5.3: Averaged trajectories of a single subject performing the bisection task under closed loop reaching. Data are shown separately for a subject reaching with the left hand in far left space (a), the left hand in far right space (b), the right hand in far left space (c) and the right hand in far right space (d). For each mean trajectory 10 standardized data points (visible in each figure as black squares) were arrived at through interpolation, to allow averaging across 8 similar reaches. The thin lines at either side of the mean indicate the standard deviations across these 10 trials. The scale for both horizontal and vertical axes is indicated by the cross placed below each plotted trajectory.

Since maximum deviation is another signed quantity, this result was evident as a significant loop x location interaction (see Table 5.1).

The hand x location interaction (Table 5.1) showed smaller sideward deviations with ipsilateral reaches (e.g. left hand towards targets in left space) than contralateral reaches. Individual comparisons showed significantly greater deviations for the left hand than the right in far right space and greater deviations for the right hand than the left in far left space. Differences regarding midright and midleft spatial positions proved not to be significant.

There was an interaction of hand x presentation (Table 5.1) with the left hand demonstrating significantly larger deviations than the right for long stimulus presentation whereas the right hand did not differ between the two presentations. Additionally there was a trend ($p < 0.054$, Newman-Keuls) for the left hand to show smaller deviations than the right hand for short stimulus presentation.

(iv) Total Deviation.

The total summed deviations of each route (away from a hypothetical direct line) showed a significant main effect for location (Table 5.1). As Figure 5.4 shows, this reflected a superiority for mid-lateral targets as opposed to far lateral targets. Subjects tended to deviate much more from the hypothetical direct line in the open loop condition as opposed to the closed loop condition, as shown in a highly significant main effect of loop (Table 5.1).

No other effects were found.

(v) Subdivision of the Total Deviation.

As in Experiment 9 the total area was subdivided into an 'early deviation', defined as the area between the route taken and the direct line *up to the point of maximum velocity*, and a 'late deviation', defined as the summed

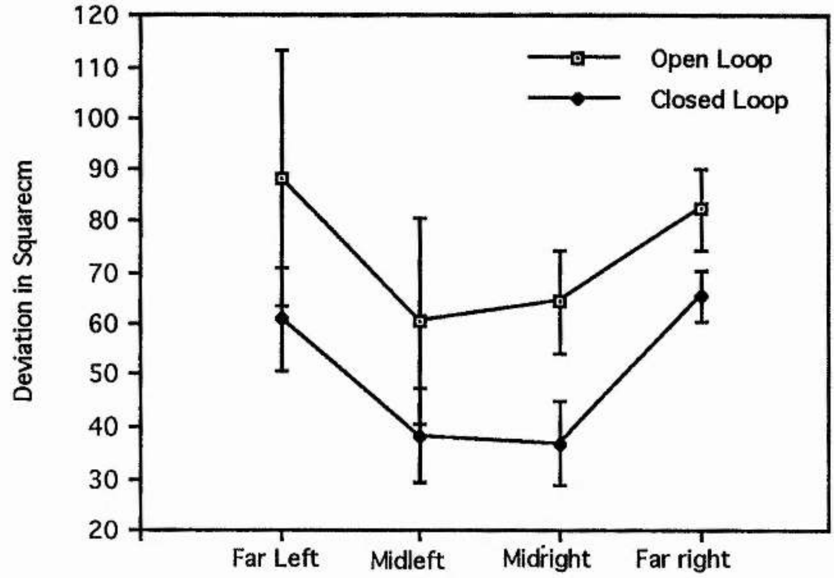

Figure 5.4: Total Deviation (areal departure of reaching trajectory from ideal straight line) for open and closed loop reaching toward each spatial location (far left, midleft, midright, far right). Error bars indicate the intersubject variability.

deviation from the point of maximum velocity until the end of the movement. Analyses of variance were then performed separately for these two measures.

Only in the late stage of the movement did subjects deviate more from the direct line in the open loop condition than in the closed loop condition (see Figure 5.5). Deviations in the early stage of the movement were not affected by loop condition (Table 5.1).

Ipsilateral reaches showed smaller deviations than contralateral movements though this only reached significance for 'early deviation' (interaction hand x location, Table 5.1). *Post hoc* analyses revealed that this was significant for both rightwardly located targets when the right hand was used but only for the far lateral targets when reaches were executed with the left hand.

No other effects were reported.

Latency and kinematic measures of the limb movement.

(i) Latency.

Latency (movement onset time) showed a highly significant loop effect (Table 5.3), with a much greater mean reaction time (391 vs 305 ms) in the open loop condition. However, as in Experiment 9 this difference is inflated due to the effectively lower intensity of the stimulus LEDs in the open loop condition, due to the use of a green filter in viewing.

There was no main effect of hands ($p > 0.50$), but a significant loop x hand x presentation interaction (Table 5.3) demonstrating that movement onset time was shortest with the right hand only during long stimulus presentation in closed loop. No other comparisons proved significant.

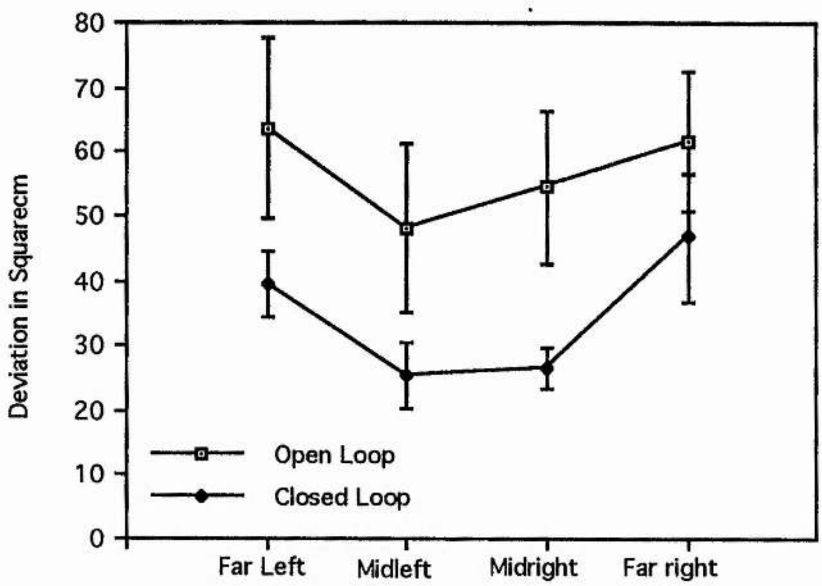

Figure 5.5: 'Late Deviations' (for definition, see text) for open and closed loop reaching toward each spatial location (far left, midleft, midright, far right). Error bars indicate the intersubject variability.

Table 5.3: ANOVA Results: 8 normal subjects

ANOVA TERMS	Latency	Max.Vel.	Mean Vel.	Time to P.	Deceleration Time
Loop (Open, Closed)	***				***
Hand (Left, Right)					
Presentation (Long, Short)					
Space (Lt., Mlt, Mrt, Rt)		***	***	**	***
Loop x Hand					
Loop x Presentation					
Loop x Space			**		
Hand x Presentation					
Hand x Space		***	***	***	
Presentation x Space		*			
Loop x Hand x Presentation	*				
Loop x Hand x Space					
Loop x Presentation x Space					
Hand x Presentation x Space					
Lp x Hd x Dur x Spc					

Significance Level after Greenhouse-Geisser adjustments; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Abbreviations: Max.Vel.= Maximum Velocity, Mean Vel.= Mean Velocity, Time to P.= Time to Peak
Lt= Left, Mlt= Midleft, Mrt= Midright, Rt= Right

(ii) Maximum Velocity.

The peak velocity measure showed a significant main effect of location, with higher velocities for the far lateral targets than the mid targets on both sides of space (Table 5.3). Ipsilateral reaches attained a higher peak velocity than contralateral reaches; this difference held for both hands and for both targets in left and right space (see Figure 5.6).

The presentation x location interaction (Table 5.3) revealed faster movements under long stimulus presentation for the far right target only. No other comparison proved significant.

No effects of loop were found.

(iii) Mean Velocity.

The mean velocity similarly proved higher for the far lateral targets than the mid targets on both sides of space (Table 5.3). Again ipsilateral reaches attained a higher peak velocity than contralateral reaches; this difference held for both hands and for both targets in left and right space (Table 5.3).

(iv) Time to Peak.

Ipsilateral reaches showed a shorter initial acceleration phase than contralateral reaches, as reflected in the hand x location interaction (Table 5.3); this difference held for both hands and for both targets on left and right sides.

(v) Deceleration Time.

The time from the velocity peak to the endpoint of the reach showed *no* significant hand x location interaction (Table 5.3). There was, however, a main effect of location with far lateral targets showing longer deceleration times than mid targets.

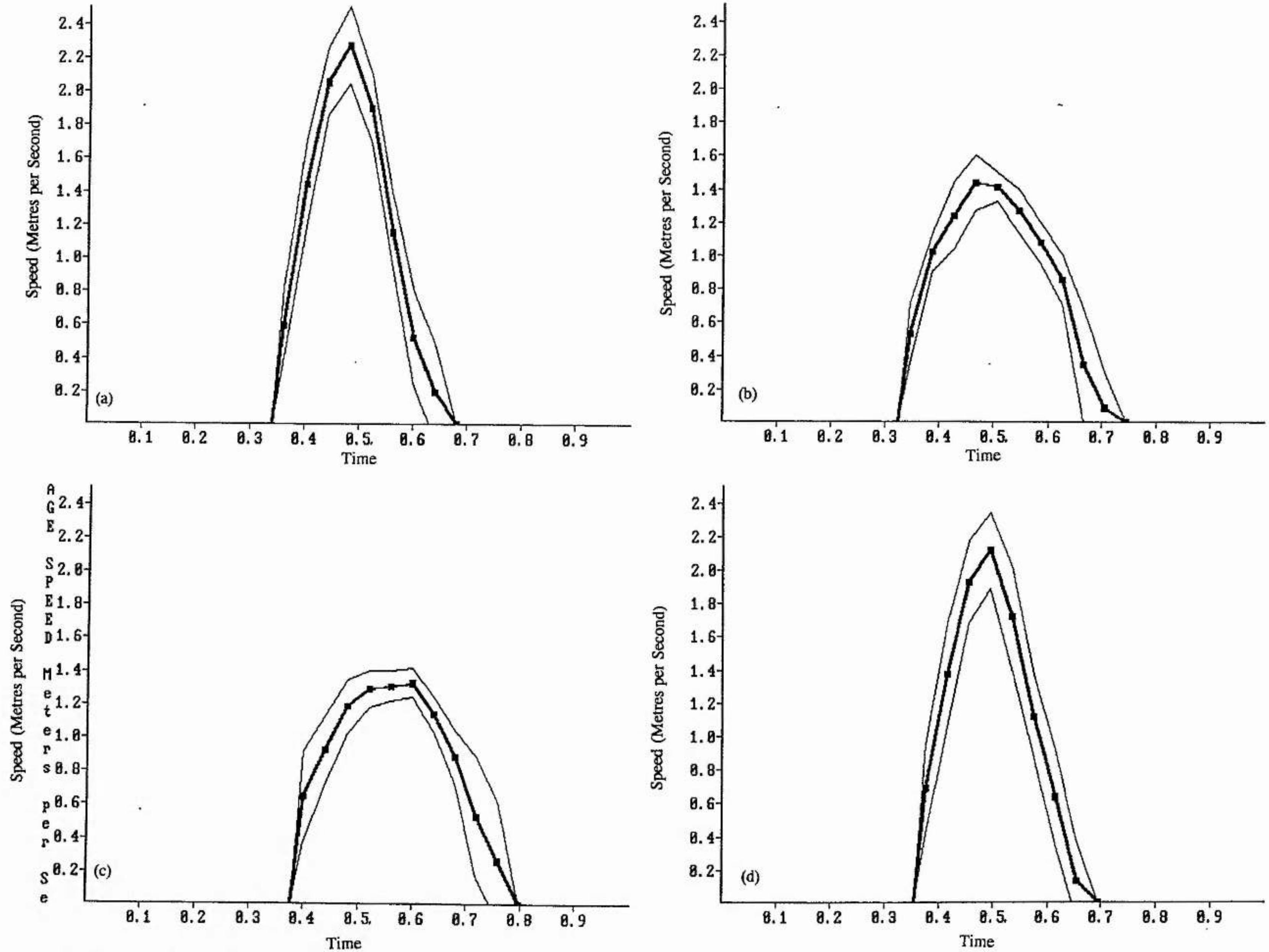

Figure 5.6: Average velocity profiles of a single subject performing the bisection task under closed loop reaching. Profiles were averaged across 8 trials for the left hand each in far left (a) and far right (b) hemispace and the right hand in far left (c) and far right hemispace (d). The markings around the profiles indicate the standard deviation across the 8 trials.

Finally there was a strong main effect of loop with faster deceleration movements in closed loop as opposed to open loop conditions. This was valid over all conditions (see Figure 5.7).

Summary of the data.

Subjects tended to overshoot all targets sidewards in all experimental conditions. These final errors were greatly exacerbated under open loop conditions and were closely associated with outwardly-curved reaching trajectories. Closer examination indicated that the increased path deviations caused by the removal of visual feedback tended to occur late in the movement.

Although no significant overall asymmetry on any accuracy measure in relation to hemispace or hand used was reported, reaches with the right hand showed considerably larger overshoot errors (+14.7mm) than those made with the left hand (-6.3mm) when visual feedback was not available.

There was also a significant finding of greater route variability in right hand reaches when movements were executed under short stimulus presentation in the absence of visual feedback. Additionally reaches were more variable when directed towards the far right targets, compared to all other targets, under short stimulus presentation.

In general, reaches tended to be more efficiently executed by each hand when operating in its ipsilateral hemispace. This was shown clearly for the kinematic measures of peak velocity, mean velocity, and the time taken to reach peak velocity; deceleration time however showed no such effect. The outward curvature of reach paths was also more marked in contralateral reaches as compared with ipsilateral. Closer examination revealed that this effect occured early in the movement rather than late.

Reaches toward the more laterally located targets reached higher maximum and mean velocities, but longer deceleration times than reaches to the

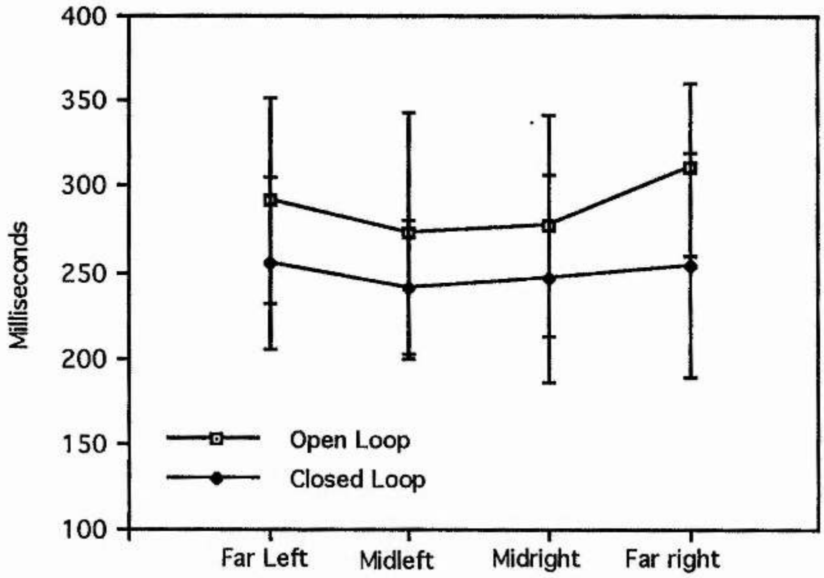

Figure 5.7: Deceleration time for open and closed loop reaching toward each spatial location (far left, midleft, midright, far right). Error bars indicate the intersubject variability.

more medial ones. In the absence of visual feeedback, deceleration times were much longer over all conditions. Finally right hand reaches demonstrated significantly quicker onset than left hand reaches, but only under long stimulus presentation in the closed loop condition.

DISCUSSION

Comparable to Experiment 9, there was a general finding that subjects tended to 'overshoot' stimuli located laterally in space. Again this occurred to some degree across all experimental conditions, but as final overshoot errors were significantly smaller under closed than open loop feedback (an average of 6.9mm vs an average of 22.9mm, respectively), this can not be discounted as an artefact of measurement. As in Experiment 9 there might have been a small residual error due to an outward rotation of the top of the finger as it moved over toward one side. This would have taken the LED further out than the midpoint of the finger but again it should be noted that this effect would be constant throughout the experiment and therefore could not account for the large effects observed under different conditions. Contrary to the suggestion made in the **Discussion** of Experiment 9, these overshoot errors cannot be wholly explained in terms of a range effect (Brown *et al.*, 1948; Slack, 1953; Poulton, 1980). This effect would have predicted overshoots for targets close to the midline only. In this experiment however, subjects overshot distal targets even more, although according to the range effect (Poulton, 1980) undershoots should have occured. These errors were exacerbated under open loop conditions, a finding which has also been reported by others (Prablanc *et al.*, 1979; Carey and Goodale, 1989; Carson *et al.*, 1990).

Again a partial explanation of the final overshoots and the observed curvilinear trajectories may ultimately be found in a consideration of the mechanics of the arm movement and/or in the optimization of late visual feedback that the curvature may provide. However none of these explanations could be appplied to the larger errors in open as opposed to closed loop reaching.

In addition however, as the overshoot responses were found to increase with target eccentricity they may be attributable to a tendency for the subjects to respond in the direction contralateral to the more activated hemisphere. Tressoldi (1987) suggests that although visual information is relayed to both hemispheres, a hemispace-hemisphere relationship still exists. Furthermore there is a possibility that each hemisphere has a map not only based on retinal co-ordinates but also on spatial co-ordinates with reference to the body midline (Bradshaw *et al.* 1987b). So the lateralized visual input could have produced an activation imbalance in favour of the hemisphere that was stimulated directly (see also Reuter-Lorenz *et al.*, 1990) resulting in exaggerated lateral turning tendencies, i.e. the reported overshoot. This explanation would also reconcile the finding that overshoot rather than undershoot errors were observed for the far lateral targets. As in Experiment 9, it could be argued that the larger overshoot errors reported for the open loop condition, might have been due to a greater salience of the stimuli in that condition, resulting in an even greater hemispheric activation and thus producing the increased lateral response bias.

Again comparable to Experiment 9, no hand differences in terminal accuracy were found. However, although not significant, terminal errors with the right hand (14.6mm) were larger than errors with the left hand (-6.3mm) when reaches were performed in the absence of visual feedback, similar to the findings of Guiard *et al.* (1983). The findings of Carey and colleagues (Carey and Goodale, 1989; Carey *et al.*, 1990) of rightward errors in *left* hand open-loop bisection were again not replicated. Moreover, right hand reaches showed greater route variability than left hand reaches, when movements were executed under short stimulus presentation in the absence of visual feedback. This finding also suggests that the left hemisphere is more dependent on visual information than the right hemisphere. This could also explain that reaches were more variable when directed towards the far right targets under short stimulus presentation. As none of these effects were found in Experiment 9, it is very likely that restricted target duration is indeed crucial in order to produce a right hemisphere advantage. Secondly, although variable error is generally attributed to errors of movement execution rather than of movement programming (Prablanc *et al.*, 1986; Schmidt *et al.*, 1979), Bracewell *et al.* (1990) argue that it is probable that the process of localizing targets is in itself not entirely accurate. This variability may add to that in the motor system which would indicate that variable error, as well as constant error, may be regarded as a measure of motor programming. So the findings on variable error could be interpreted as a right hemisphere advantage for *visuomotor localization* in the absence of visual feedback. However, it cannot be ignored that there was a slight memory component in the task, as targets disappeared after movement onset. Consequently there is the possibility that the right hemisphere is simply better for *remembering* spatial locations of visual targets (see also Bracewell *et al.*, 1987; 1990). There is evidence to suggest that spatial aspects of memory may be preferentially lateralized to the right hemisphere (De Renzi, 1982). Nevertheless it should be noted that the time between target offset and termination of the reach was very short in memory terms (overall mean 430msec).

Consistent with the findings of Fisk and Goodale (1985), right hand reaches proceeded with significantly quicker movement onset than left hand reaches under long stimulus presentation in the closed loop condition. The authors interpret this finding as a left hemisphere specialization for the integration of movements. Visual feedback seems to be a crucial part of this integration however, as this effect is no longer present under open loop conditions. In fact, in Experiment 9, a left hand latency advantage was found in the absence of visual feedback (see also Carson *et al.*, 1990). It is surprising that no right hand latency advantage for closed loop movements was found in Experiment 9, as the conditions were comparable to those under long stimulus presentation in this experiment. A possible explanation might be that the absence of a chin rest in Experiment 9 masked the left hemisphere advantage that might have been present.

Although hands were not differently affected, obvious spatial compatibility effects were found whereby the routes deviated more during contralateral than ipsilateral reaches (shown in the analysis of maximum deviation). However, this difference was compensated for prior to the final endpoint. Closer analysis ('early' and 'late' deviation) revealed that these compatibility effects were only apparent early in the movement and were corrected as the hands 'homed in' on the target.

A similar trend was observed regarding the kinematic measures of peak velocity, mean velocity, and time to reach peak velocity: reaches appeared to be more efficiently executed by each hand when operating in its ipsilateral as opposed to the contralateral hemispace. However no such effect was observed for deceleration time. Both these findings seem to suggest that the 'homing in' on the target is independent of hand or hemispace effects and therefore efficiently executed by *both* hemispheres. Deceleration time seems to be generally affected by visual feedback in that the 'homing in' takes longer when it is not available, but again there is no indication of differential hemispheric involvement. Although the compatibility effects reported on the velocity measures have also been described by a number of other authors (Prablanc *et al.*, 1979; Fisk and Goodale, 1985; Carson *et al.*, 1990; 1992; Carey *et al.*, 1990) explanations are difficult. Carson and Goodman (1992) argue that there is electrophysiological data to suggest that the firing patterns of single neurons in the motor cortex are highly correlated with specific directions of movement (see also, Georgopoulus *et al.*, 1982). Apparently the level of discharge is greatest for ipsilateral movements made forward into space and outward from the body. It may therefore be that spatially compatible movements are controlled by 'ready made' neural systems, while incompatible ones require special programming.

Movements toward the far lateral targets reached higher velocities than those toward less eccentric targets. This was independent of hand used, contrary to the findings of Fisk and Goodale (1985) and Carson *et al.* (1990). The latter authors reported higher velocities for the more eccentric targets in ipsilateral space but lower velocities for such targets in contralateral space.

Finally, it has now been shown repeatedly that bisection responses in left and right space reveal centrifugal rather than centripetal errors, contrary to the findings of Nichelli *et al.* (1989); see also chapters two and four.

SUMMARY

Again possible right hemisphere influences upon visually guided reaching were assessed by asking normal subjects to point to the midpoint between two LEDs (bisection). On some trials target feedback was limited as the LEDs disappeared after movement onset, on others targets remained illuminated throughout the reach. The targets were situated in left or right spatial hemifield with varying eccentricities, and in all cases performance of the left hand was compared with that of the right. Subjects reached under both *closed loop* (with visual feedback of hand and arm) and *open loop* (no visual feedback) conditions.

Again it was found that subjects consistently deviated laterally in response to all eccentrically-located targets (overshooting), making leftward errors in left hemispace and rightward errors in right hemispace. The overshoots were greater in open than in closed loop conditions and the effects were mirrored in curvilinear paths followed by the hand. There were no significant effects of target hemispace or hand on accuracy, but the right hand proved more variable than the left hand when movements were executed under short stimulus presentation in the absence of visual feedback. Additionally reaches were more variable when directed towards the far right targets, compared to all other targets, under short stimulus presentation.

The kinematic measures revealed again that reaches tended to be more efficiently executed by each hand when operating in its ipsilateral hemispace.

CHAPTER SIX

VISUALLY GUIDED REACHING AND BISECTION FOLLOWING UNILATERAL CEREBRAL STROKE

The experiments presented in the last two chapters were an attempt to elucidate the differential engagement of the cerebral hemispheres in motor control, by testing normal subjects on visuomotor tasks. In complementory fashion, a range of investigators have addressed this issue by using patient data. As one of the first, Liepmann (1908) demonstrated that patients with left hemisphere damage are not only more likely to show deficits in speech production but are also more likely to have trouble executing complex motor tasks. Similarly, Kimura and Archibald (1974) found that left hemisphere damaged patients were particularly impaired on sequential manual tasks involving transitions from one hand posture to another. Kimura (1977; 1982) argued that mechanisms within the left hemisphere play a special role in the sequential organization of complex movements and that whereas they are not responsible for sequencing the movement *per se* they are essential for selecting the correct posture and effecting an efficient transition from one posture to another. In a more recent study, however, Fisk and Goodale (1988) found direct evidence for a left hemisphere involvement in the much simpler task of visually guided reaching: in contrast to patients with right hemisphere damage, those with left hemisphere lesions took substantially longer than the control group to complete a pointing movement. This difference was primarily attributable to a prolonged terminal (deceleration) phase of the movement, suggesting that the patients with left hemisphere damage might be less able to make quick use of visual, proprioceptive and/or efference copy information to correct the trajectory of the reach.

In the same study, Fisk and Goodale found that patients with right hemisphere damage were slower to initiate a reach. Other investigators have implicated the right hemisphere in the initiation of motor acts (Heilman *et al.*, 1985b) with the demonstration of a selective leftward hypokinesia following right hemisphere damage. Somewhat earlier, Kimura (1969) provided tachistoscopic evidence for a right hemisphere involvement in visual localization, using normal subjects. In conjunction, these findings suggest that a right hemisphere involvement might be expected in reaching experiments that require accurate visual localization. This was indeed argued by Guiard *et al.* (1983) who, when testing normal subjects, found smaller constant errors for the left as opposed to the right hand when reaching was performed in the absence of visual feedback from the hand. Similar findings were reported in the present Experiment 10 (chapter five) with right hand reaches showing greater variability than left hand reaches under open loop conditions. Finally Bracewell *et al.* (1990) found subjects to be more accurate at directing their gaze to locations in the left visual hemifield than the right when asked to perform oculomotor saccades. Lesion evidence also indicates that the right hemisphere may be dominant in oculomotor control (Girotti *et al.*, 1983).

There have been findings that right hemisphere patients tend to bisect a horizontal line to the right of its true centre, and that this behaviour is more pronounced in the left than in central or right space (Schenkenberg *et al.*, 1980). Although these errors only occured in the patients with hemispatial neglect and not for the RCVA patients in Experiments 5 and 7, it is nevertheless possible that RCVA patients might show some additional abnormality in a visuomotor bisection task. This was indeed found by Goodale *et al.* (1990): they asked RCVA patients, who had *recovered* from visuospatial neglect, to point midway between two lights and found that the subjects made rightward terminal errors, which were significantly larger than errors shown in a direct pointing task. So it seemed that the visuomotor bisection task produced rightward errors that were no longer apparent in the traditional line bisection task.

EXPERIMENT 11

The next experiment was carried out to investigate more directly the involvement of the two hemispheres in visuomotor control by choosing tasks that should presumably affect performance of left and right hemisphere damaged patients differently. Again the bisection task was assumed to increase the complexity of visual feedback processing, with the finger's position having to be compared on-line to two as opposed to a single stimulus as the finger approaches its target. According to the findings of Fisk and Goodale (1988) one might therefore expect an impairment in patients with left hemisphere lesions during closed loop performance (i.e. with the hand visible). However the results of the Goodale *et al.* (1990) study suggest that under some conditions this effect may be outweighed by visuospatial demands that would tend to increase right hemisphere participation. This might be particularly apparent under open loop conditions, where no visual information on hand/target discrepancy is available (cf. Guiard *et al.*, 1983). Therefore a comparison between closed and open loop testing conditions was incorporated in the experiment. It was predicted that while bisection might maximize the expected impairment in left hemisphere damaged patients during closed loop reaching, it should also exaggerate the expected impairment of right hemisphere damaged patients during open loop reaching.

Targets positioned in left or right hemispace, as well as directly ahead of the subject were used. Differential engagement of the two hemispheres would be predicted as a function of hemispatial location (Heilman *et al.*, 1987) and this factor might therefore interact with the other variables. In particular, stimuli located in the left half of egocentric space might maximize the possibility of detecting right hemisphere influences on reaching.

Because of contralateral weakness, not all patients could be tested with both hands; so the main analyses were comparisons of the performance of the ipsilateral limb with the same limb of matched control subjects. However, 9 of the RCVA and 10 of the LCVA patients were able to perform the experiment with both hands, and so for these a direct comparison between the patient groups was possible.

METHOD

Subjects. Three groups of subjects were tested: 12 patients with unilateral right hemisphere infarct, 12 patients with unilateral left hemisphere infarct and 12 normal control subjects. For detailed description of the two patient and the control groups see *Subjects*, chapter three. It should be noted that although there was an age difference between the two full (N=12) groups of CVA patients, this difference was not significant between the two subgroups which could be compared directly on visuomotor measures (10 LCVA *vs* 9 RCVA: see *Statistical Analyses* below). For description of the neuropsychological tests applied see *Neuropsychological Tests,* chapter three.

Apparatus and tasks. Apparatus and tasks were the same as in Experiment 9, chapter four.

Procedure. As in Experiment 9 all subjects performed both the pointing task and the bisection task, and under both visually 'open' and 'closed loop' conditions. Head and eye movements were not restricted.

Under each feedback condition subjects were tested for 30 trials on direct pointing and 30 trials on bisection, and where possible this was repeated using each hand separately (two of the LCVA and three of the RCVA patients could only use their ipsilesional hand). In each of these 30-trial blocks 10 reaches were directed towards left hemispace, 10 towards right hemispace and 10 to the centre, in pseudorandom sequence. Both the order of the pointing and bisection blocks and of the hand used were counterbalanced as completely as possible. Six practice trials were given before each block and there were short rest intervals in the light between the blocks. At the start of each trial subjects rested their index finger on the starting platform and at a variable time following a 'ready' command the LED or LEDs were illuminated for 1 second for all the control subjects. For the patient groups illumination varied between 1 and 4 seconds in order to insure that the LED(s) remained illuminated throughout the duration of the reach. They were told to point as accurately and quickly as possible either directly to the light (pointing task) or midway between the two lights (bisection task) and not to correct their reach once the panel was touched.

Data analysis. Data analysis was the same as in Experiments 9 and 10.

Statistical Analyses. The mean of the 10 X,Y trajectories taken to a given target location within each block of trials was calculated for each subject following the 'slice' standardization (*see Data Analysis*, chapter four). For each dependent variable these 10-trial means (and also, where appropriate, their standard deviations) were then subjected to analyses of variance. Four separate sets of ANOVAs were performed. The two main sets of analyses were four-way ANOVAs comparing the performance of one patient group to the control group using the *ipsilateral* hand. In each case, the factors were: group (patients/controls) as a between-subjects factor, and conditions (open/closed loop), task (pointing/bisection) and location (left/right/centre) as within-subjects factors. However, as most patients were actually able to perform the experiment with both hands, additional five-way ANOVAs were carried out comparing both patients groups directly, with conditions, task, hand, and location as within-subjects factors. Finally four-way within-subjects ANOVAs were calculated for the control group alone, with conditions, task, hand and location as the factors. The significance of main effects and interactions involving repeated measures was assessed using the Geisser-Greenhouse adjustment to the degrees of freedom. Finally, significant main effects and interactions were examined in detail using the Newman-Keuls testing procedure, using the 5% level of significance.

RESULTS

Again a large number of analyses were carried out, so presentation of the results is restricted to those findings that were consistent across related measures of performance. For full description of the significant ANOVA terms see Tables 6.1 to 6.8.

12 RCVA patients vs 12 controls (right hand only)

Spatial trajectory of the limb movement.

(i) Final Error.

The mean final position of the forefinger in the RCVA patients erred significantly further rightward than in the control group (16.6mm vs 2.1mm). However, examination of the group x loop interaction revealed that this group difference was only significant for open loop reaching (Table 6.1, see also Figure 6.1). Patients and controls did not differ in closed loop reaching, and whereas the RCVA patients showed significantly larger errors in open than closed loop reaching, the control group did not differ between the two conditions (Newman-Keuls).

There was also a significant loop x location interaction, with subjects in both groups showing rightward errors at all three target positions in open loop,

Table 6.1: ANOVA Results I: RCVA patients vs controls (right hand only)

ANOVA TERMS	Fin. Err.	Var. Err.	Max. Dev.	Tot. Dev	Early Dev.	Late Dev.
Group (RCVA, Controls)	*		*		*	
Loop (Open, Closed)	***	***	***	***		***
Task (Pt, Bsct)		***		**	*	
Space (Lt, Ct, Rt)	***		***	***	***	***
Group x Loop	*	*	*			
Group x Task						
Group x Space						
Loop x Task					*	
Loop x Space	***		*	**	*	***
Task x Space	*					
Group x Loop x Task						
Group x Loop x Space			*		**	
Group x Task x Space						
Loop x Task x Space	***					
Group x Loop x Task x Space						

Significance Level after Greenhouse-Geisser adjustments; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Abbreviations: Fin. Err.= Final Error, Var. Err.= "Variable Error", Max. Dev.= Maximum Deviation
Tot. Dev.= Total Deviation, Early Dev.= "Early Deviation", Late Dev.= "Late Deviation"
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

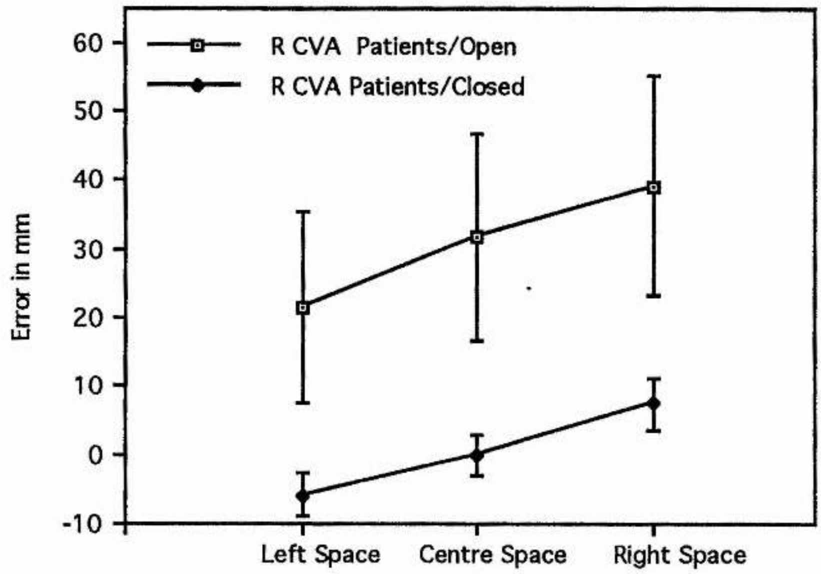

Figure 6.1 (a): Mean final error for open and closed loop reaching toward three spatial locations (left, centre, right). Results are presented separately for the RCVA patients (a) using their ipsilateral arm. The corresponding data of the control group are presented in Figure 6.1 (b). Negative values indicate displacements made to the left of the (virtual) target, positive values displacements made to the right. Errors bars indicate the intersubject variability.

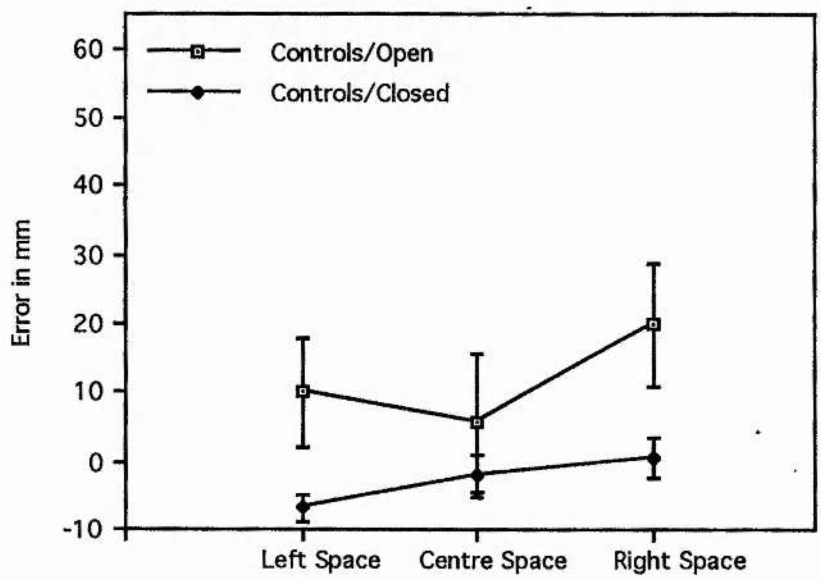

Figure 6.1 (b): Mean final error for open and closed loop reaching toward three spatial locations (left, centre, right). Results are presented for the control group using their right arm. Negative values indicate displacements made to the left of the (virtual) target, positive values displacements made to the right. Errors bars indicate the intersubject variability.

but leftward errors for centre and left locations in closed loop. Also, for open loop only, there were bigger rightward errors for bisection as opposed to pointing in both groups (revealed as a 3-way interaction of loop x task x spatial position, Table 6.1). *Post hoc* analyses demonstrated, however, that this was only significant for targets in right hemispace.

Terminal variability proved larger for bisection as opposed to pointing for both groups. No other effects were found to be significant. No discernible difference was present in the errors of either of the two recovered neglect patients as compared with the rest of the RCVA group.

(ii) Maximum Deviation.

The maximum lateral deviation of the mean route showed a group x loop x location interaction (Table 6.1). *Post hoc* analyses revealed that whereas the RCVA group showed rightward deviations in left space under open loop but not closed loop, the controls showed leftward errors there under both conditions. This pattern is illustrated in Figure 6.2.

(iii) Total Deviation and (iv) Subdivision of the Total Deviation. (see Chapter Four for description)

The two groups did not differ with respect to the total summed deviations of each route. Both groups showed larger deviations from the hypothetical direct line in the bisection as opposed to the pointing task and in the open as opposed to the closed loop conditions. The latter finding however was not significant for left space as shown by the significant loop by location interaction (see Table 6.1).

Closer examination of the total deviation indicated that RCVA patients deviated more than the control group early in the movement only. This was however modified by a significant group x loop x location interaction revealing

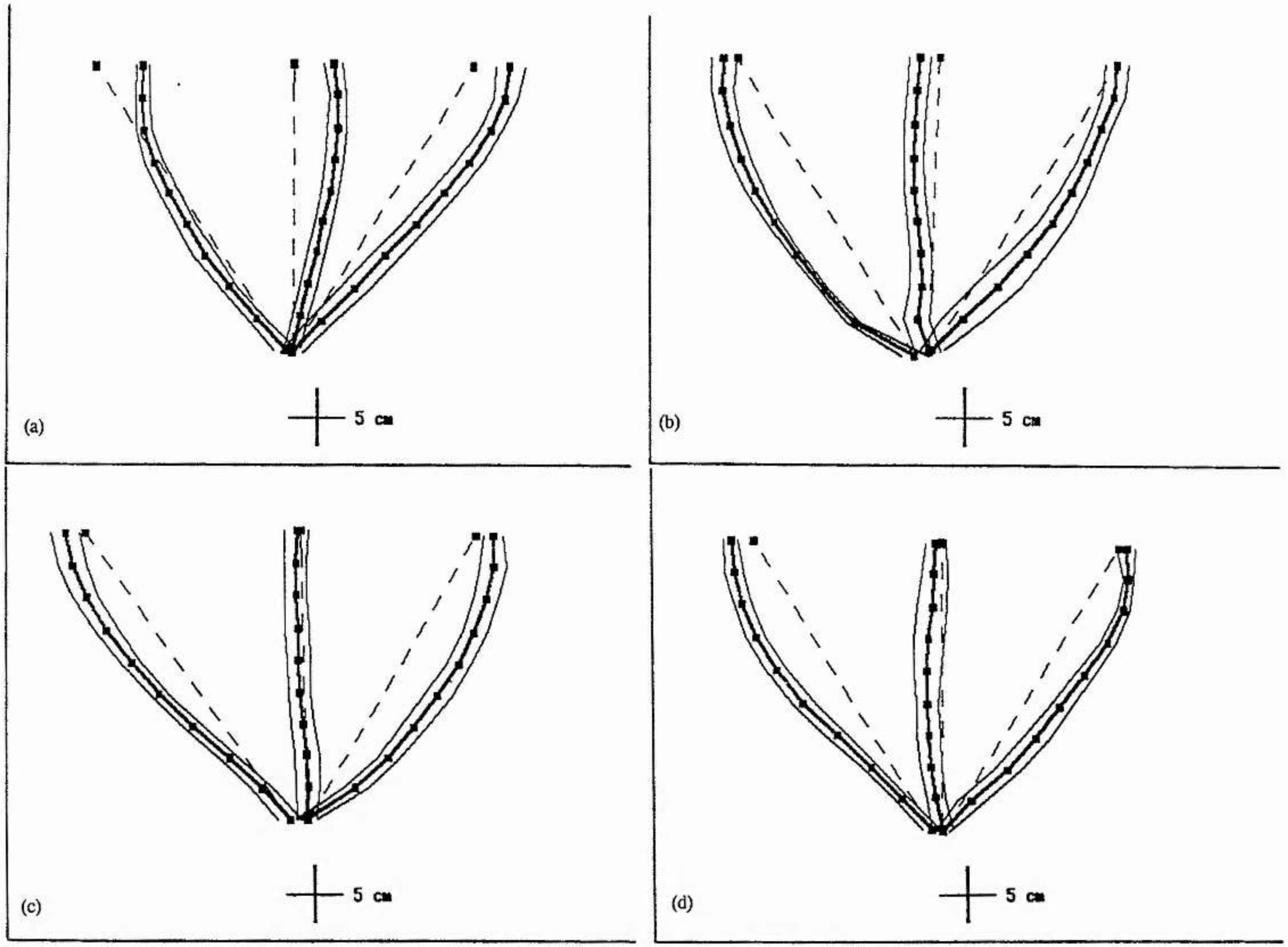

Figure 6.2: Averaged trajectories of single subjects performing the pointing task under open loop reaching. Data are shown separately for a RCVA patient reaching with the right hand (a), a control subject reaching with the right hand (b), a LCVA patient reaching with the left hand (c) and a control subject reaching with the left hand (d). Reaches are shown for the three target positions (left, centre, right). For each mean trajectory 10 standardized data points (visible in each figure as black squares) were arrived at through interpolation, to allow averaging across 10 similar reaches. The thin lines at either side of the mean indicate the standard deviations across these 10 trials. The scale for both horizontal and vertical axes is indicated by the cross placed below each plotted trajectory.

that this was only significant in open loop reaching towards targets presented in central and right space. No differences were found for 'late deviation' (Table 6.1).

Latency and kinematic measures of the limb movement

(i) Latency.

RCVA patients showed longer reaction times to movement onset than the control group over all target positions. Examination of a group x location interaction (Table 6.2) revealed further that their latencies were longer for left than for centre or right targets, whereas the latencies of the control group did not vary between spatial positions.

As shown in Table 6.2, both groups showed longer RTs in open than in closed loop reaching. However, this difference is inflated by the effectively lower intensity of the stimulus LEDs in the open loop condition, due to the use of a green filter in viewing. There were also longer latencies for bisection as opposed to pointing. This, however, was modified by a significant interaction of task x location, and *post hoc* analyses revealed that the task difference was not significant for left space.

(ii) Movement Velocity.

Over all conditions RCVA patients were slower in their reaches than the control group. This difference was highly significant both for average speed and for the maximum speed attained. The difference is illustrated in Figure 6.3(a).

Both groups showed higher velocities in closed than in open loop reaching, both on average and at maximum speed. This was however modified by a significant loop x location interaction in both analyses, and proved to be only significant in left hemispace.

Table 6.2: ANOVA Results II: RCVA patients vs controls (right hand only)

ANOVA TERMS	Latency	Mean Vel.	Max. Vel.	Time to P.	Dec. Time
Group (RCVA, Controls)	**	***	**		***
Loop (Open, Closed)	***			*	
Task (Point, Bisect)	*				
Space (Lt, Ct, Rt)	**	***	***	***	***
Group x Loop					
Group x Task					
Group x Space	*				
Loop x Task		***	*	*	***
Loop x Space		**	**		
Task x Space	*				
Group x Loop x Task					
Group x Loop x Space					
Group x Task x Space					
Loop x Task x Space					
Group x Loop x Task x Space					*

Significance Level after Greenhouse-Geisser adjustments; *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Abbreviations: Mean Vel.= Mean Velocity, Max. Vel.= Maximum Velocity, Time to P.= Time to Peak
Dec. Time= Deceleration Time
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

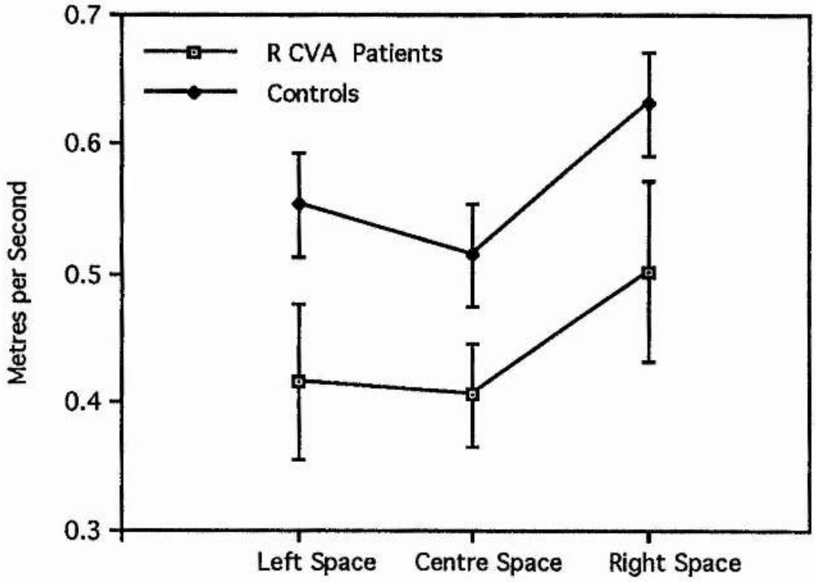

Figure 6.3 (a): Average speed of the RCVA patients using the ipsilateral arm in lateral space (left, centre, right). The control group data are for the right arm. Error bars indicate intersubject variability.

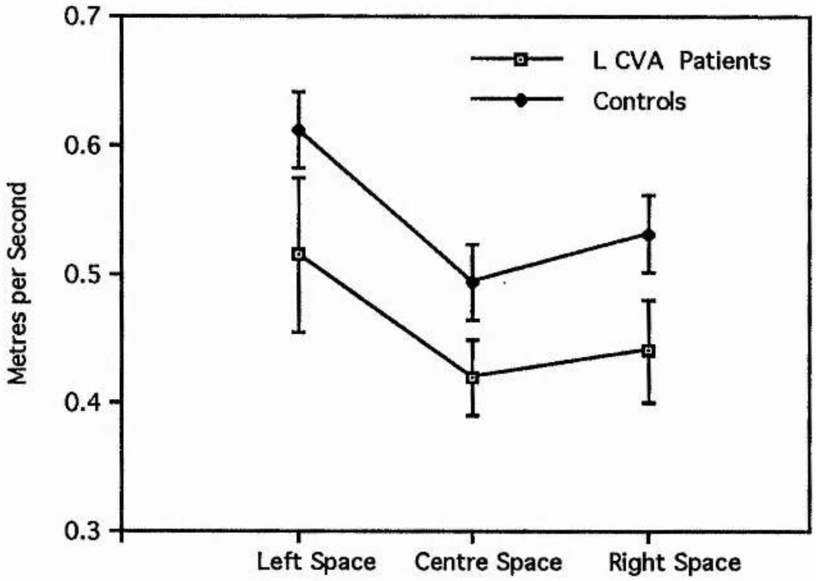

Figure 6.3 (b): Average speed of the LCVA patients using the ipsilateral arm in lateral space (left, centre, right). The control group data are for the left arm. Error bars indicate intersubject variability.

(iii) Time to Peak and (iv) Deceleration Time.

Although the two groups did not differ in the time taken to reach peak velocity, it proved that RCVA patients were substantially slower in their deceleration time than the control group (see also Figure 6.4). Thus their overall larger movement times are attributable to this later phase of the movement.

12 LCVA patients vs 12 controls (left hand only)

Spatial trajectory of the limb movement.

(i) Final Error and (ii) Maximum Deviation.

There were no significant differences between the groups on either the mean signed final errors or the maximum deviations. There was a significant loop x location interaction on both variables, such that both groups produced leftward errors in left space and rightward errors in right space; i.e. on both sides they 'overshot' the target (see Table 6.3 and also Figure 6.5). These overshoots were greater in open than closed loop reaching. *Post hoc* analyses of the loop x location interaction showed that this difference was not significant for reaches towards the centre for either final error or for maximum deviation.

Surprisingly, reaching errors were larger for pointing than bisection in open loop (significant on both measures except for reaches towards the centre). However there was also a significant interaction of loop x task x location, analysis of which revealed that closed loop pointing into left hemispace showed *smaller* errors than bisection (Table 6.3).

As before, terminal variability was overall significantly greater in bisection than in pointing. It was also greater in open than in closed loop reaching (Table 6.3).

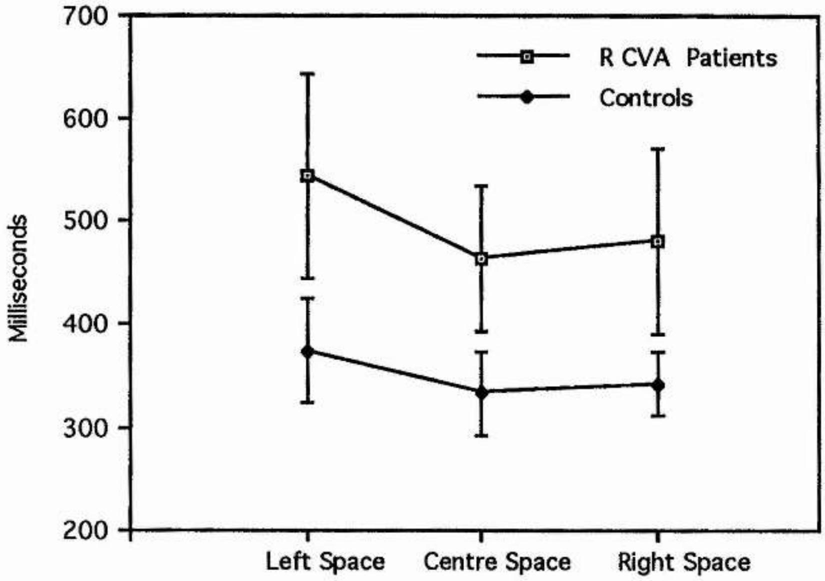

Figure 6.4: Deceleration time of the RCVA patients and the control group for the three spatial locations (left, centre, right). Error bars indicate intersubject variability.

Table 6.3: ANOVA Results I: LCVA patients vs controls (left hand only)

ANOVA TERMS	Fin. Err.	Var. Err.	Max. Dev.	Tot. Dev	Early Dev.	Late Dev.
Group (LCVA, Controls)					*	*
Loop (Open, Closed)		***		***	***	***
Task (Point, Bisect)		*		*	*	
Space (Lt, Ct, Rt)	***		***	***	***	***
Group x Loop					*	
Group x Task						
Group x Space				*		**
Loop x Task						
Loop x Space	***		***			
Task x Space						
Group x Loop x Task						
Group x Loop x Space						
Group x Task x Space						
Loop x Task x Space	***		***			
Group x Loop x Task x Space						

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Fin. Err.= Final Error, Var. Err.= "Variable Error", Max. Dev.= Maximum Deviation
Tot. Dev.= Total Deviation, Early Dev.= "Early Deviation", Late Dev.= "Late Deviation"
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

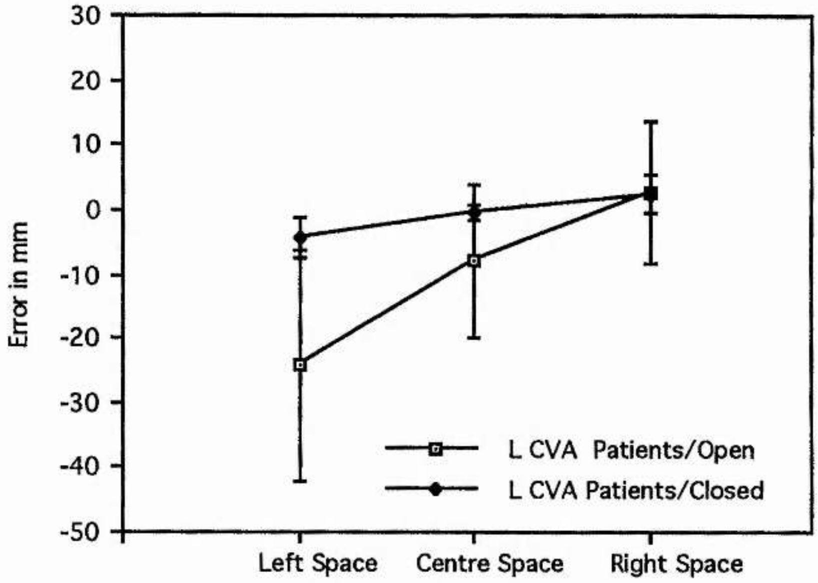

Figure 6.5 (a): Mean final error for open and closed loop reaching toward three spatial locations (left, centre, right). Results are presented separately for the LCVA patients (a) using their ipsilateral arm. The corresponding data of the control group are presented in Figure 6.5 (b). Interpretation of positive and negative values as in Figure 6.1. Errors bars indicate the intersubject variability.

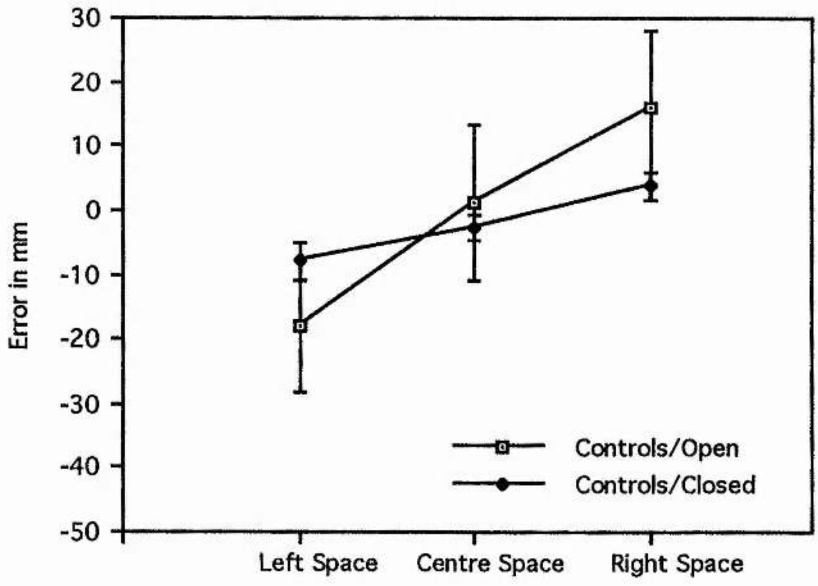

Figure 6.5 (b): Mean final error for open and closed loop reaching toward three spatial locations (left, centre, right). Results are presented for the control group using their left arm. Interpretation of positive and negative values as in Figure 6.1. Errors bars indicate the intersubject variability.

(iii) Total Deviation and (iv) Subdivision of the Total Deviation.

The group x location interaction revealed larger total deviations for the LCVA patients as opposed to the control group. This proved significant for left hemispace only.

Closer examination demonstrated that the LCVA group deviated more than the control group early in the movement only (main effect, see Table 6.3). Late deviation on the contrary, revealed smaller errors for the LCVA group than the control group. This proved significant for right hemispace only (group by location interaction, see also Table 6.3). It should be noted that these effects may simply reflect the shorter acceleration phase (Time to Peak) found in the control group compared to the LCVA group (see findings on Time to Peak below).

Latency and kinematic measures of the limb movement

(i) Latency.

Although there was no main group effect, there was a significant group x loop interaction, with LCVA patients showing longer latencies than the controls in open loop reaching.

As before, latencies were longer for bisection than pointing (see Table 6.4). They were also longer to targets in right hemispace as opposed to centre or left space.

(ii) Movement velocity.

Like RCVA patients, the LCVA patients were slower overall than the control group, as illustrated in Figure 6.3(b). Again this proved significant for both average speed and maximum speed. Finally, there was a spatial effect,

Table 6.4: ANOVA Results II: LCVA patients vs controls (left hand only)

ANOVA TERMS	Latency	Mean Vel.	Max. Vel.	Time to P.	Dec. Time
Group (LCVA, Controls)		*	**	**	*
Loop (Open, Closed)	***		**		*
Task (Pt, Bsct)	*				
Space (Lt, Ct, Rt)	*	***	***	***	***
Group x Loop	*				**
Group x Task				**	
Group x Space					
Loop x Task		***			***
Loop x Space					***
Task x Space			*	*	
Group x Loop x Task				*	
Group x Loop x Space					*
Group x Task x Space					
Loop x Task x Space					
Group x Loop x Task x Space					

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Mean Vel.= Mean Velocity, Max. Vel.= Maximum Velocity, Time to P.= Time to Peak
Dec. Time= Deceleration Time
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

with subjects in both groups reaching fastest toward targets in left hemispace and slowest toward the centre, on both measures (see Table 6.4).

(iii) Time to Peak and (iv) Deceleration Time.

Contrary to the RCVA group, LCVA patients were slower than the controls in *both* the time to reach peak velocity and the time from peak velocity to endpoint.

The control group reached peak velocity earlier in the pointing than the bisection task whereas no such difference was found for the LCVA group. Regarding deceleration time, LCVA patients took longer to decelerate under open loop than closed loop, whereas the control group did not differ with respect to loop.

9 RCVA patients versus 10 LCVA patients (both hands)

Spatial trajectory of the limb movement.

(i) Final error and (ii) Maximum Deviation.

On both final error and maximum deviation, RCVA patients made large rightward errors, while LCVA patients made small leftward errors. Student's t-tests showed that final error did not differ significantly from zero in the LCVA group [$t(11) = -0.65$], but was highly significant for the right hemisphere damaged patients [$t(11) = 3.71$, $p < 0.01$].

As before, however, analyses of a group x loop interaction (see Table 6.5) showed that the RCVA patients only made significantly larger final errors in open loop reaching. This interaction is plotted in Figure 6.6. Again as before, only the RCVA patients showed larger errors in open than closed loop; LCVA patients showed no such difference.

Table 6.5: ANOVA Results I: 9 RCVA patients vs 10 LCVA patients (both hands)

ANOVA TERMS	Fin. Err.	Var. Err.	Max. Dev.	Tot. Dev	Early Dev.	Late Dev.
Patients (RCVA, LCVA)	*		*			
Loop (Open, Closed)		***		***	***	***
Hand	**					
Task (Point, Bisect)		*		*		
Space (Lt, Ct, Rt)	***		***	***	***	**
Patients x Loop	*					
Patients x Hand						
Patients x Task						
Patients x Space				*	*	*
Loop x Hand	**		*			
Loop x Task				*		*
Loop x Space	***		*			
Hand x Task						
Hand x Space			**		***	***
Task x Space						
Patients x Loop x Hand						
Patients x Loop x Task						
Patients x Loop x Space			*			
Patients x Hand x Task						
Patients x Hand x Space						*
Patients x Task x Space						
Loop x Hand x Task						
Loop x Hand x Space				*	**	
Loop x Task x Space						
Hand x Task x Space					*	
Pts x Loop x Hand x Task						
Pts x Loop x Hand x Space						***
Pts x Loop x Task x Space						
Pts x Hand x Task x Space	*					
Loop x Hand x Task x Space						
Pts x Loop x Hand x Task x Space						

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Fin. Err.= Final Error, Var. Err.= "Variable Error", Max. Dev.= Maximum Deviation
Tot. Dev.= Total Deviation, Early Dev.= "Early Deviation", Late Dev.= "Late Deviation"

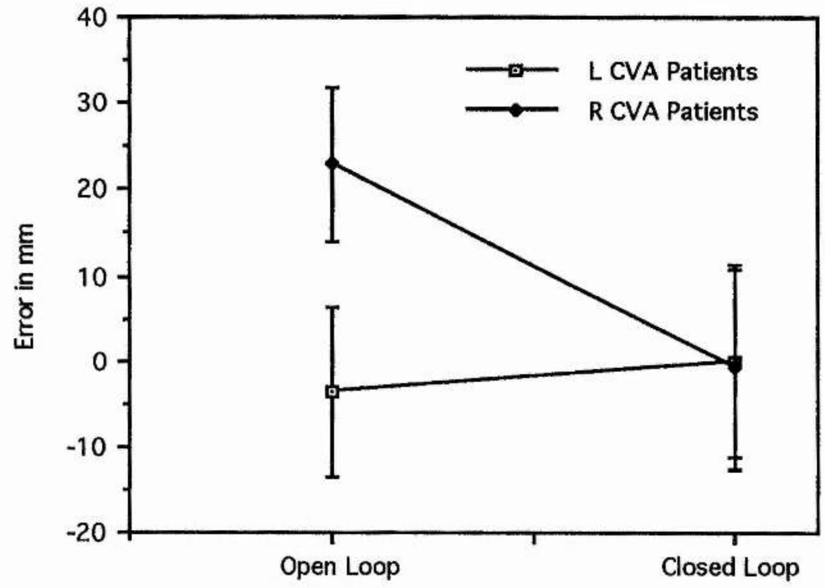

Figure 6.6: Mean final error for open and closed loop reaching for those RCVA and LCVA patients who were tested with both hands. Interpretation of the positive and negative values as in Figure 6.1. Error bars indicate intersubject variability.

In both groups, performance with the left hand was unaffected by feedback conditions, while the right hand showed bigger errors in open than closed loop. Left and right hand did not differ in closed loop. This was found for both variables, with both measures showing a significant interaction of loop x hand.

Again, terminal variability was overall significantly greater in bisection than in pointing. It was also greater in open than in closed loop reaching (Table 6.5). No differential group effects were found on this measure.

(iii) Total Deviation and (iv) Subdivision of the Total Deviation.

Again LCVA patients showed large deviations from the hypothetical direct line in left hemispace. The opposite trend for RCVA patients to show larger deviations than the LCVA group in right hemispace proved not significant (see Table 6.5). However, closer examination revealed that the large deviations for left hemispace in the LCVA group occured only early in the movement. In fact, in the late part of the movement RCVA patients showed larger deviations than LCVA patients for central and right hemispace whereas deviations regarding left space did not differ between the two groups (interaction group x location, Table 6.5).

Both groups showed smaller total deviations when pointing rather than bisecting under closed loop feedback. No differences emerged for open loop reaching. However this proved relevant for late deviation only, no effects were reported early in the movement.

Latency and kinematic measures of the limb movement

(i) Latency.

RCVA patients showed much longer latencies than LCVA patients (see Figure 6.7). Furthermore, whereas LCVA patients showed no differences

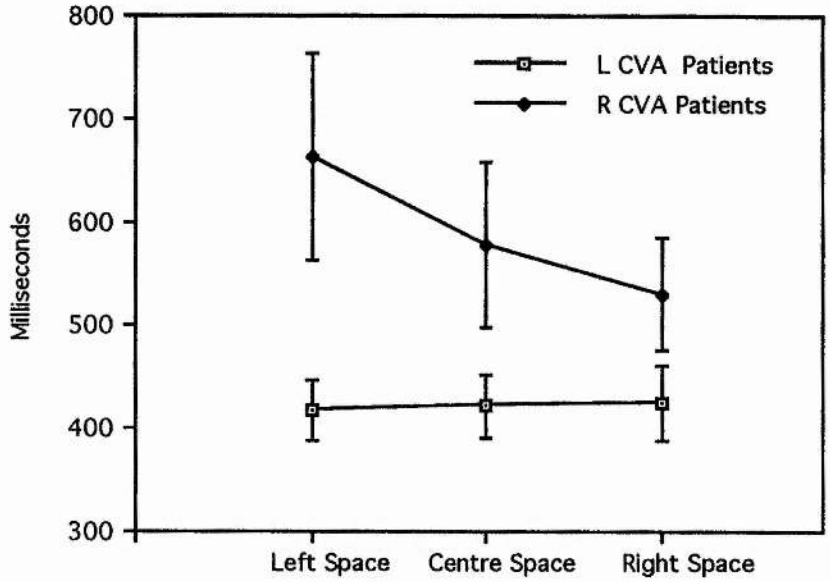

Figure 6.7: Latency to initiate a reach in lateral space (left, centre, right). The data are for those RCVA and LCVA patients who were tested with both hands. Error bars indicate intersubject variability.

between target locations, RCVA patients were slower to move toward left as opposed to centre or right space, giving a significant interaction of group x location.

Overall, there proved to be a significant interaction of hand x location (see Table 6.6), such that left hand RTs were shorter than right in left space whereas the hands did not differ significantly in right space. This effect was present in both patient groups.

(ii) Movement velocity.

RCVA patients moved the arm more slowly on average than LCVA patients in left and central space (yielding a group x location interaction). On maximum speed, this was again true, and in addition the LCVA patients were slower than the RCVA in right space. In other words, patients tended to move either arm more slowly towards targets in contralesional hemispace.

Both groups showed a spatial compatibility effect (significant hand x location interactions) on both speed measures. Reaches into ipsilateral hemispace attained a higher peak velocity than contralateral reaches, and this difference held for both hands and on both sides of space.

(iii) Time to Peak and (iv) Deceleration Time.

Analyses of the time to reach peak velocity revealed no differential group effects. However both groups took less time to reach peak velocity when movements were made into ipsilateral hemispace. Again this difference held for both hands and on both sides of space (see Table 6.6).

Regarding deceleration time, interpretation of the group x hand x location interaction (Table 6.6) indicated shorter deceleration times for LCVA than RCVA patients for all conditions, apart from reaches that were performed with the right hand while reaching into right hemispace. Although LCVA

Table 6.6: ANOVA Results II: 9 RCVA patients vs 10 LCVA patients (both hands)

ANOVA TERMS	Latency	Mean Vel.	Max. Vel.	Time to P.	Dec. Time
Patients (RCVA, LCVA)	*				
Loop (Open, Closed)	***		*		***
Hand					
Task (Point, Bisect)	**		*		*
Space (Lt, Ct, Rt)		***	***		***
Patients x Loop					
Patients x Hand					
Patients x Task					
Patients x Space	*	**	**		
Loop x Hand					
Loop x Task		***			***
Loop x Space					*
Hand x Task		*			
Hand x Space	*	***	**	***	**
Task x Space					
Patients x Loop x Hand					
Patients x Loop x Task					
Patients x Loop x Space					
Patients x Hand x Task					
Patients x Hand x Space					**
Patients x Task x Space					
Loop x Hand x Task					
Loop x Hand x Space					
Loop x Task x Space					
Hand x Task x Space	*				
Pts x Loop x Hand x Task					
Pts x Loop x Hand x Space					*
Pts x Loop x Task x Space					**
Pts x Hand x Task x Space					
Loop x Hand x Task x Space					
Pts x Loop x Hand x Task x Space					

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Mean Vel.= Mean Velocity, Max. Vel.= Maximum Velocity, Time to P.= Time to Peak
Dec. Time= Deceleration Time

patients took less time to decelerate in this condition as well, this failed to be significant (Newman-Keuls). Furthermore LCVA patients showed no spatial compatibility effects, whereas the RCVA group demonstrated shorter deceleration times with the left hand in left space and the right hand in right space.

Control group (both hands)

Spatial trajectory of the limb movement.

(i) Final Error and (ii) Maximum Deviation.

There was a significant loop x location interaction on both variables, such that the control subjects produced leftward errors in left space and rightward errors in right space; i.e. on both sides they 'overshot' the target (see Table 6.7). These overshoots were greater in open than closed loop reaching but did not differ between the hemispaces in absolute magnitude. Reaches toward the centre were equally accurate in open and closed loop, though errors tended to be leftward in closed loop reaching and rightward in open loop. These tendencies were present for both final finger position and maximum deviation, but did not reach significance.

Subjects showed much greater terminal variability during open than closed loop reaching, and in bisection than in pointing. However no effects of hand, nor interactions with hand, were found.

(iii) Total Deviation and (iv) Subdivision of the Total Deviation.

Total deviation simply revealed main effects for loop, task and space with larger errors in open than closed loop reaching, bisection as opposed to pointing and smallest deviations for movements towards the central targets compared to targets in left and right hemispace.

Table 6.7: ANOVA Results I: Control group (both hands)

ANOVA TERMS	Fin. Err.	Var. Err.	Max. Dev.	Tot. Dev	Early Dev.	Late Dev.
Loop (Open, Closed)		***		***		***
Hand						
Task (Pt, Bsct)		***		**	**	
Space (Lt, Ct, Rt)	***		***	***	***	***
Loop x Hand						
Loop x Task						
Loop x Space	***		***			
Hand x Task						
Hand x Space			**		***	
Task x Space						
Loop x Hand x Task					*	
Loop x Hand x Space						
Loop x Task x Space	**	***	**			
Hand x Task x Space						
Loop x Hnd x Task x Space						

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Fin. Err.= Final Error, Var. Err.= "Variable Error", Max. Dev.= Maximum Deviation
Tot. Dev.= Total Deviation, Early Dev.= "Early Deviation", Late Dev.= "Late Deviation"
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

However, whereas the effect of task was apparent early in the movement but not late, the effect of loop was found only late in the movement (see Table 6.7). Additionally both hands showed a spatial compatibility effect early in the movement but not late.

Latency and kinematic measures of the limb movement

(i) Latency.

As demonstrated before, movement onset latency was strongly affected by loop. There were also shorter latencies for pointing over bisection, significant for both loop conditions (Table 6.8). The hand x task interaction reflected slower RTs in the left hand than the right for bisection, in the absence of a hand difference for pointing.

(ii) Movement velocity.

On average the right hand moved faster than the left hand (Table 6.8). A highly significant compatibility effect (hand x location interaction) was found for both measures of speed. Reaches into ipsilateral hemispace attained a higher peak velocity than contralateral reaches, and this difference held for both hands and on both sides of space.

(iii) Time to Peak and (iv) Deceleration Time.

Again a compatibility effect was found but only for the time to reach peak velocity. Analysis of the deceleration time revealed no such effect, but the right hand was found to take less time decelerating than the left in right hemispace whereas the two hands did not differ in left hemispace (see Table 6.8).

Table 6.8: ANOVA Results II: Control group (both hands)

ANOVA TERMS	Latency	Mean Vel.	Max. Vel.	Time to P.	Dec. Time
Loop (Open, Closed)	***		*		
Hand		*			
Task (Pt, Bsct)		*		**	
Space (Lt, Ct, Rt)		***	***		***
Loop x Hand				*	
Loop x Task	*	**			*
Loop x Space					
Hand x Task	**				
Hand x Space		***	***	***	*
Task x Space					
Loop x Hand x Task					
Loop x Hand x Space					
Loop x Task x Space					
Hand x Task x Space		*	*	*	
Loop x Hnd x Task x Space					

Significance Level after Greenhouse-Geisser adjustments; *** p< 0.001, ** p< 0.01, * p< 0.05

Abbreviations: Mean Vel.= Mean Velocity, Max. Vel.= Maximum Velocity, Time to P.= Time to Peak
Dec. Time= Deceleration Time
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

Finally there was a loop x hand interaction reflecting shorter times to peak velocity for the right than the left hand in open but not closed loop. No such effect was found for deceleration time.

Summary of the data.

LCVA patients and control subjects tended to overshoot laterally-placed targets sidewards in all experimental conditions. As in the other experiments (chapter four and five) these final errors were exacerbated under open loop conditions and were closely associated with outwardly-curved reaching trajectories. The RCVA group however, although also showing outward curvature, demonstrated substantial rightward errors with regard to all three target positions when reaches were performed in the absence of visual feedback.

RCVA patients also showed slower movement onset times than the control group, and than the LCVA group when compared directly. LCVA patients did not differ from the control group when visual feedback was available but were slower in movement initiation under open loop conditions. All three groups showed lower latencies for pointing compared to bisection and the control group was also quicker in initiating the bisection response when using the right rather than the left hand.

Both patient groups were slower in the execution of their reaches than the control group. Similarly both patient groups moved more slowly in their contralesional hemispace, although all patients who were able to use both arms showed spatial compatibility effects. They were faster reaching with the right than the left hand in right space and with the left than the right hand in left space. This was also the case for the control group.

Closer examination of the velocity profiles revealed that LCVA patients were slower on both acceleration and deceleration times when compared to the control group. RCVA patients on the contrary seemed to be selectively slower on deceleration time, as they did not differ from the control group on the time taken to reach peak velocity. Their slowing in the deceleration phase however, must have been rather substantial as it was also significant when LCVA and RCVA patients were compared directly; i.e. it caused an overall greater movement time than in the LCVA patients despite the latter being slower in the acceleration phase.

DISCUSSION

Accuracy of reaching

It was found that patients with right hemisphere damage showed an impairment in terminal accuracy when reaching was performed in the absence of visual feedback (open loop). This was not true of left-hemisphere damaged patients, who were unimpaired (see Figure 6.2). Analysis of subsets of the two patient groups who were able to use either hand showed that these asymmetrical effects of lesions were present regardless of the hand used in reaching. However under closed loop conditions, no significant deficit in accuracy was found in either patient group. These findings indicate a strong right hemisphere role in the visuomotor guidance of open loop reaching, whilst the left hemisphere's contribution to terminal accuracy is minimal. The data are thus in agreement with Guiard *et al.* (1983), who found smaller constant errors for the left as opposed to the right hand when normal subjects reached under open loop conditions.

Nonetheless no group differences in the variability of reaching performance were found. These data are at variance with the results of Bracewell *et al.* (1990) who found a smaller variable error for eye movements made to left hemifield targets. They also differ from the findings of Experiment 10 where smaller variable errors were reported for the left hand in open loop under short stimulus presentation. It may be that the right hemisphere has a more fine-grained coding of retinal location than the left (cf. Kimura, 1969, Levy and Reid, 1976; 1978) which favours eye and hand movements to *brief* targets in the left hemifield. (In Experiment 10 variance was lowest for stimuli in left hemispace. Nevertheless this was difficult to interpret as it was apparent in the four way interaction of loop x hand x presentation x location only.) This asymmetry may not extend to the visuomotor localization of longer-duration targets.

The major result instead was that the RCVA patients erred systematically to the right of the true target over all three spatial positions in open loop. In contrast, under closed loop conditions, the errors were made to the left in left and central space and to the right in right space. Indeed, such overshoot errors with respect to stimuli located laterally in space were found in both normal and left hemisphere CVA patients, whether tested in open or closed loop conditions. This result is in full agreement with Experiments 9 and 10 where overshoot errors were also consistently reported. As illustrated in Figure 6.2(b,c,d), these overshoot errors were associated with outwardly curving reach trajectories, again comparable to those reported in Experiments 9 and 10.

As argued before, one way of accounting for the 'bowed' pattern of trajectories itself is to suppose that a lateralized stimulus tends to activate or arouse the contralateral hemisphere; this might cause an initial exaggeration of the sideward vector of the arm movement. Supposing this view was correct, it could be assumed that when the left hemisphere is damaged, it should be less activated than the intact hemisphere and should therefore produce less exaggeration of the sideward vector. Although not significant this was indeed the case: LCVA patients produced larger overshoot errors in left than right space (-14.2mm vs 2.6mm) and also showed less overshoot in right space when compared to the control group (2.6mm vs 9.8mm respectively).

As target eccentricity was rather limited one might also interpret the overshoot errors in terms of a range effect (Brown *et al.*, 1948, Slack, 1953, Poulton, 1980). However as shown in Experiment 10, overshoots in normal subjects remained when targets were located with greater eccentricity. In any case, as argued before (see **Discussion**, chapter four) range effects provide only a redescription rather than an explanation.

Figure 6.2 also illustrates that the outward curvature was present in the open-loop trajectories even of RCVA patients, but that a rightward shift was superimposed on to the standard pattern. In other words, the errors of these patients were the result of (at least) 2 additive factors: a normal overshoot and a uniform rightward shift. Furthermore the bisection task caused no greater impairment of these patients than did the simple pointing task, irrespective of feedback condition. This is contrary to the findings of Goodale *et al.* (1990) whose right hemisphere damaged patients showed larger rightward terminal errors for bisection as opposed to pointing under closed loop reaching. The discrepancy might be explained by the fact that Goodale *et al.*'s patients had all shown neglect in the past, though this had recovered by the time of testing. Only 2 out of the 12 subjects of the present RCVA group were known to have ever shown symptoms of neglect.

The generalized rightward displacement observed under open loop reaching in the present study, then, seems not to be directly related to neglect. And indeed none of the patients showed any abnormality when subjected to a variety of line bisection and landmark tests (see chapter three and also Milner *et al.*, 1993). Furthermore, the rightward shift was no greater in the left than right half of space, while a larger effect in left space is generally found in neglect (Heilman and Valenstein, 1979; Milner *et al.*, 1992).

It is therefore difficult to explain the data by any means other than by hypothesizing the operation of a 'directional hypokinesia' in rather pure form, in the RCVA patients (Heilman *et al.*, 1983). Presumbly this would have free rein under conditions where no visual feedback on limb position is available. But if this is correct, then contrary to Heilman *et al.*'s views, it would seem from the present data that directional hypokinesia is dissociable from neglect (though no doubt often present in neglect cases).

In the presence of visual feedback, no deficit in reaching accuracy after left or right hemisphere lesions was seen, even in the visually-taxing bisection condition. This finding differs from the data of Fisk and Goodale (1988) who found that both left *and* right hemisphere lesioned patients were less accurate than the control group in their pointing movements. It is possible that the patient pool of Fisk and Goodale's study is not directly comparable to the patients presented here: not all of their subjects had lesions of vascular origin and some patients demonstrated hemispatial neglect at the time of testing. There were also higher incidences of hemiplegia and aphasia compared to the patients of this study. So the clinical data seem to indicate an overall greater neurological impairment for their patient groups compared to the population presented here, which in turn could have been responsible for the overall reduction in accuracy.

Latency of response

In agreement with Fisk and Goodale's study (1988), however, prolonged reaction times were found in the RCVA group as compared with both the control group and the LCVA group. The finding that the RCVA patients had particularly long latencies in reaching for targets on the left as compared with ones in centre or right space (see Figure 6.7) may indicate that a good part of the slowing in these patients should be interpreted as due to the hypothesized directional hypokinesia: Heilman *et al.* (1985b) found delayed reaction times for movements towards left as opposed to right hemispace in six neglect patients and attribute this to directional hypokinesia. Fisk and Goodale (1988) provide another plausible explanation in that RCVA patients have difficulty determining the position of a target in extrapersonal space and thus require a greater period of time in which to access the neural systems responsible for programming a movement to that position.

It could alternatively be argued that partial visual field defects were responsible for the long latencies in left space. However, no comparable slowing was found for movement initiation into right space for the LCVA group; as the groups did not differ with regard to presence of hemianopia, this explanation seems unlikely. Nonetheless a generalized slowing of reaction times after right hemisphere lesions is well established in the literature (Howes and Boller, 1975; Benton, 1986), and may perhaps be attributed to lowered cortical arousal levels (Heilman and Van den Abell, 1980).

Also like Fisk and Goodale (1988), no evidence of prolonged latencies in closed loop reaching in the LCVA group in comparison with the control group was found. However, the left hemisphere damaged patients did show prolonged reaction times in making *open* loop reaches. Nonetheless this was a small effect, and may only have reflected an exaggeration of the detectability difficulty present for all subjects in the open loop condition. No additional RT slowing occurred when the reaching task required bisection; yet a role of the left hemisphere in bisection is suggested by the intriguing finding that normal controls were quicker to initiate the bisection response when using the right hand than the left, while there was no hand asymmetry for pointing. However no such effect was reported for the younger subjects in Experiment 9. If anything there was a contrary effect with latency advantages for the bisection task in left hemispace. Further research needs to be done to clarify this point.

Movement kinematics

Both patient groups were slower in the execution of the reaches than the controls (on both average and maximum velocity), and this was true for both open and closed loop performance. Furthermore, no overall group difference in movement time was found between the two subgroups of LCVA and RCVA patients who were able to reach with either hand, and thus could be directly compared. One possibility to explain this result is that patients in both groups were slowed as a result of direct or indirect damage to primary motor cortex or its outputs. But in neither patient group was there any evidence of a relative slowing of the contralesional hand: the interactions of group x hand were never significant. This suggests that the slowing effects were not due to any direct interference with primary motor systems. In contrast, the direct comparison of lesioned subgroups indicated that both groups moved more slowly toward targets in their contralesional hemispace than toward ipsilesional space, using *either* arm. This could have been due to a disordered visual guidance of the arm, which might result from damage to parieto-frontal systems for visuomotor control (Milner and Goodale, 1993). Certainly most of the patients tested had CT evidence for parietal and/or frontal infarcts.

Additionally to the general slowing of arm movements in both patient groups, RCVA patients proved specifically impaired with respect to deceleration time: they took considerably longer to terminate the movement than the control group (see Figure 6.4) and the LCVA group when compared directly. However, they did not differ from the control group with regard to the time to reach peak velocity and tended to be faster on this measurement than the LCVA group when compared directly, although this last finding was not significant. These data are in direct contrast to those of Fisk and Goodale (1988), who demonstrated no impairment on any of the kinematic measures for their right hemisphere damaged subjects, while pointing under closed loop conditions.

Nonetheless the results presented here indicate a right hemisphere impairment as the hand 'homes in' on the target, both in the presence and absence of visual feedback. It is during this portion of the trajectory that modifications normally occur on the basis of information by foveal and parafoveal vision (Goodale, 1988). If one accepts the assumption that the RCVA patients had difficulty in determining the target position (see also *Latency of response*, above), it could be that this deficit might also have been present in the 'homing in' phase of the movement as well as in the initiation phase. Maybe the initial direction of the movement while accelerating was only of 'ball park' accuracy and lacked on-line control. Consequently modifications of the trajectory would need to occur during deceleration. It is possible that through use of visual guidance, target determination problems were overcome in the closed loop condition, in that reaches were modified during this final phase, thus leading to increased deceleration times but accurate target location. In contrast in the open loop condition, where the visuospatial deficit could not be compensated through use of visual feedback, it became apparent in both speed and accuracy measures. On the other hand, it is unlikely that LCVA patients were impaired with regard to target determination as their latency times were not increased when compared to the control group. Nonetheless they showed a marked disruption in the organization of their reaching movements which was not only apparent for the deceleration phase but throughout movement. Goodale (1989) has pointed out that the left hemisphere is crucial for *on-line error-corrections* and timing and sequencing of visually guided aiming movements which consequently leads to a left hemisphere involvement in the control of complex motor behaviour (Kimura, 1982) and coupling of eye and hand movements (Fisk and Goodale, 1985). If one accepts that left hemisphere damaged patients have deficits in the on-line control of simple movements, apraxic patients should demonstrate the same deficits. This was indeed suggested by Goodale (1989) '...although

Kimura (1982) has argued that the deficit in apraxia is one of movement selection, it is possible that many of the complex sequences of postures that are used clinically to reveal apraxia may often require on-line monitoring and updating of the motor program as it unfolds...If one were to use more detailed kinematic analyses to....tests of apraxia, deficits might become apparent.' The findings of Harrington and Haaland (1992) might give some evidence for this: they tested 17 left hemisphere stroke patients and found that both the apraxic and the nonapraxic group were slower than the control group on the execution of *single* hand postures.

All three groups of subjects showed strong hemispace-hand compatibility effects, with ipsilateral reaches attaining higher velocity than contralateral reaches (for both hands and on both sides of space). These effects were present for both average speed and maximum speed, time to peak and, less consistently, for latency. However, no compatibility effects occured for deceleration time. The same effects have been noted in Experiments 9 and 10 and by others (Prablanc *et al.*, 1979; Fisk and Goodale, 1985). As argued before (see **Discussion**, chapter five) they presumably reflect a more direct 'wiring' of ipsilateral visuomotor response systems, such that reaches are more efficiently executed by each hand when operating in its 'own' hemispace. As argued by Fisk and Goodale (1985), this suggests that the visuomotor systems for guiding reaching are lateralized with respect to action space rather than with respect to either retina or limb. This view is supported by physiological evidence (e.g. Georgopoulus, 1982).

SUMMARY

Groups of patients with left or right unilateral cerebral stroke were tested for their ability to reach either toward a single target or midway between 2 targets. The tasks were performed either in free vision or in the absence of visual feedback from the hand. It was found that only the right CVA patients were inaccurate in reaching, and only in the absence of visual feedback. This effect of right hemisphere lesions was present regardless of the hand used in reaching, and took the form of a rightward bias, regardless of the hand used or task performed. It was present in the trajectory of the hand during the reach, and was of similar magnitude irrespective of target location. The bias is interpreted as a pure example of 'directional hypokinesia'. Since, however, the bias was present despite the absence of neglect, it must be concluded that directional hypokinesia is separable from neglect.

Both patient groups were slower in the execution of their reaches than the controls, and this was true for both open and closed loop performance. Unlike the LCVA group, this slowing was not present throughout the movement for the RCVA patients; they proved specifically impaired with respect to deceleration time, taking considerably longer to complete the movement than the control group and the LCVA group when compared directly. Similarly they also showed prolonged reaction times as compared with both the control and the LCVA group. No such impairment was reported for the LCVA group and it was suggested that the RCVA group had difficulty in determining the target position.

As in the other experiments strong hemispace-hand compatibility effects, with ipsilateral reaches attaining higher velocity than contralateral reaches were found for all three groups of subjects.

CHAPTER SEVEN

PRELIMINARY STUDY OF VISUALLY GUIDED REACHING AND BISECTION IN PATIENTS WITH HEMISPATIAL VISUAL NEGLECT

Although various investigators have discussed the differential engagement of the two hemispheres in motor control by using patient data (see chapter six), very few systematic studies have been done with patients showing unilateral spatial neglect. To substantiate their theory of directional hypokinesia, Heilman and colleagues (1983) asked five patients with left visual neglect and five aphasic control subjects to close their eyes and point to an imaginary point in space perpendicular to the midline of the chest. They found that, although both patient groups deviated into the hemispace ipsilateral to the lesion, the patient group with neglect showed significantly larger (rightward) deviations. As these findings cannot be explained in terms of impaired spatial attention, occular exploration or memory they seem indeed to be compatible with directional hypokinesia.

Nevertheless Jeannerod (1988) fits these results in the framework of Kinsbourne's activational hypothesis (1970; 1987) which assumes that neglect is not restricted to one hemispace: rather it affects the capacity to shift attention toward the side contralateral to the lesion, whatever the absolute location in the visual field of the object toward which attention is directed. Furthermore (and this is more in line with Heilman *et al.*'s data) he claims that left brain activation generates strong rightward turning, whereas right hemisphere activation only produces weak leftward biases. Consequently right hemisphere damage should cause a greater ipsilateral orienting bias than left hemisphere damage. Indirect evidence for Kinsbourne's theory could be taken from a pointing task carried out by Joanette *et al.* (1986) on three patients with unilateral neglect. They reported that target detection improved in the left visual field when reaches were performed with the contralesional rather than the ipsilesional hand. Presumably this indicates that through use of the left hand the right hemisphere was activated, and hence enhanced attentional shifts could be made towards the left visual field.

Duhamel and Brouchon (1990) carried out a pointing experiment with one neglect patient. Unfortunately amount or direction of terminal errors were not reported but they found that, whereas transport time for the right hand was longer for reaches toward left than right targets there was no such difference for reaction times. However the results on reaction time differ from of the data of Girotti *et al.* (1983) who, in their neglect patients, reported increased RT's for oculomotor movements directed at targets on the side contralateral to the lesion. Heilman *et al.* (1985b) also reported increased movement onset times for manual movements towards the left hemispace in neglect patients, and unlike Duhamel and Brouchon (1990), found no directional asymmetry for movement times.

Interpretation of these studies seems to indicate that patients with unilateral spatial neglect show rightward turning tendencies when asked to reach to targets in space. This seems to be associated with a relative slowing of movements directed into left hemispace, although as argued in the **Discussion** of Experiment 11, this decrease in movement time can be dissociated from hemispatial neglect as it is also observed in RCVA patients without evidence of neglect. Furthermore LCVA patients show a comparable slowing for movements into right hemispace.

EXPERIMENT 12

In order to gain more systematic information on movement trajectories and kinematics in neglect patients, two single case studies were carried out in the last experiment. Two patients who demonstrated strong hemispatial neglect at the time of testing, were analysed using the same paradigm as in Experiments 9 and 11. The neglect syndrome should affect reaching performance in the bisection task specifically, as it can be regarded as a variant of the classical line bisection test, which produces rightward errors when performed by neglect patients (see chapter three). Additionally reaches toward stimuli in the left half of egocentric space would be expected to show larger errors than those into central and right space (Heilman *et al.*, 1987). Both these factors (task and spatial location) might interact with presence or absence of visual feedback. Experiments 9 to 11 gave little indication that the use of the bisection task increased right or left hemisphere involvement specifically. Nevertheless the two neglect patients might show an increased impairment on this task, similar to the findings of Goodale *et al.* (1990) with patients who had recovered from neglect.

The traditional line bisection test is restricted to an analysis of the 'final error' only (the bisection mark made by the patient is compared to the true centre). The present paradigm however, allows analyses of the target approach and kinematics involved. This might be particularly relevant for one of the patients described: when applying the traditional line bisection test, this patient (B.W.) showed *leftward* errors for all three spatial positions (mean left space: -29.3mm; mean centre: -12.2mm; mean right space: -27.3mm). Although dissociations within the neglect syndrome have been reported before (Cubelli *et al.*, 1991; Tegner and Levander, 1991b) analyses of the movement trajectory of this patient might illuminate this particular behaviour. The clinical details of this patient are listed below, as due to his atypical line bisection behaviour, he was not included in the experiments presented in chapter 3.

Because of contralateral weakness both patients could only be tested with their ipsilesional (right) hand. Analyses were performed separately for each patient as they differed with respect to age, time elapsed between onset of illness and testing, location of lesion and even neglect symptomatology (especially performance on line bisection). As it was not possible to test any of the other neglect patients presented in chapter three, the data reported here should be regarded as preliminary. No attempt to generalize the findings will be made.

METHOD

Patients. Two right-handed patients were recruited who had sustained right hemisphere stroke and who performed outside normal limits on the *Behavioural Inattention Test* (for description of the test see *Neuropsychological Tests*, chapter three).

M.J. is a 61-year-old woman who had sustained a right hemisphere stroke eight months prior to testing. A CT-scan performed ten days post-onset showed a patchy low attenuation in the right mid/anterior white matter. The patient had a left hemiplegia and also a left homonymous hemianopia. Her BIT score was 30/146 with 100% omissions in contralesional and central space for all cancellation tasks; in fact only stimuli on the extreme right of the page were attended to.

For further information on the patient's neuropsychological test results, see Table 3.5, chapter three.

B.W. is a 50-year-old insurance broker who had sustained a right middle cerebral artery infarct two months prior to testing. CT-scan evidence at 3 months post onset indicated an extensive right fronto-parietal lesion. The patient had a hemiplegia but no reported visual field defect. There was no history of neurological or psychiatric complaints, nor of excessive smoking or drinking. He was right-handed.

His NART score was 110 and there were no language deficits (perfect performance on the aphasia test). Use of the WAIS-R revealed an average score of 10 (11 on age adjusted sores) on the verbal subtests and a score of 4.3 (5.3) on the performance subtests. Assessment on the Benton Visual Form Discrimination Test revealed chance performance (21 out of 36 correct) which could have been due to the fact that designs on the left of the page were never attended to, although the test was presented in the right hemispace. His BIT score was 94/146 with all omissions occuring in contralesional space.

Apparatus and tasks. Apparatus and tasks were the same as in Experiment 9, chapter four.

Procedure. As in Experiment 9 both subjects performed both the pointing task and the bisection task, and under both visually 'open' and 'closed loop' conditions. Head and eye movements were not restricted.

Under each feedback condition they were tested for 30 trials on direct pointing and 30 trials on bisection. Both subjects could only use their ipsilesional hand. In each of these 30-trial blocks 10 reaches were directed towards left hemispace, 10 towards right hemispace and 10 to the centre, in pseudorandom sequence. Six practice trials were given before each block and there were short rest intervals in the light between the blocks. Again at the start of each trial subjects rested their index finger on the starting platform. At a variable time following a 'ready' command the LED or LEDs were illuminated for 3 seconds for patient M.J. and 2 seconds for patient B.W. in order to insure that the LED(s) remained illuminated throughout the duration of the reach. They were told to point as accurately and quickly as possible either directly to the light (pointing task) or midway between the two lights (bisection task).

Data analysis. Data analysis was the same as in Experiments 9, 10 and 11.

Statistical Analyses. The 10 X,Y trajectories taken to a given target location within each block of trials were calculated for both subjects following the 'slice' standardization. For each dependent variable these 10 trials were then treated as the random variable for purposes of analysis of variance and were treated as independent from one another. ANOVAs were performed separately for each patient. In each case, the factors were: conditions (open/closed loop), task (pointing/bisection) and location (left/right/centre) as between-subjects factors. Significant main effects and interactions were examined in detail using the Newman-Keuls testing procedure, using the 5% level of significance.

RESULTS

Again a large number of analyses were carried out, so presentation of the results is restricted to those findings that were consistent across related measures of performance. For full description of the significant ANOVA terms see Tables 7.1 and 7.2. Data for the two patients are presented separately.

Patient M.J.

(i) Final Error and (ii) Maximum Deviation.

The overall mean error displayed by patient M.J. was 14mm to the right of the (virtual) target. Nonetheless a chi-square test demonstrated that her final reaching position showed an equal distribution of right or leftwardly located diplacements from the midpoint ($Chi^2 = 0$). There was however a main effect of loop, indicating that the final position of the forefinger erred significantly further rightward during open than closed loop reaching (26.1mm vs 1.8mm). The same difference occurred for the maximum lateral deviation of the trajectory (50.0mm vs -0.5mm respectively). Surprisingly, examination of the significant loop x task interaction revealed that this rightward deviation was substantially larger in the pointing than the bisection task under open loop conditions. An opposite trend of leftward errors for pointing and rightward errors for bisection, proved not significant for closed loop reaching. Again this finding was repeated for maximum deviation (Table 7.1, see also Figure 7.1).

Both measures also showed highly significant loop x task x location interactions (Table 7.1) revealing that the larger rightward errors in pointing as opposed to bisection in the absence of visual feedback, occurred only in left hemispace. This was found for both measurements. Further analysis of this interaction with regard to final error revealed that, in the open loop condition, the pointing task showed larger rightward errors in left space as opposed to centre and right, which themselves did not differ. The bisection task revealed smallest errors toward the central targets and errors of similar magnitude regarding targets in left and right space. Surprisingly, in the absence of visual feedback, reaches in both task conditions showed rightward displacements in left space and (although smaller) leftward displacements in right space. However, this was not the case regarding the maximum deviation of the reaches: in the absence of visual feedback, reaches in both tasks, showed rightward displacements for all three spatial positions. Reaching under closed loop feedback proved essentially 'normal' with small leftward displacements in left space and small rightward displacements in right space for both measurements (see also chapters four, five and six).

(iii) Total Deviation

The total summed deviation of each route proved also larger in open than closed loop movements (Table 7.1). However, examination of the loop x space interaction revealed that this difference was only significant for reaches toward central and left but not right spatial locations. Furthermore the loop x task x location interaction indicated that this only applied to the pointing task (Figure 7.2). The bisection task was not affected by loop condition or spatial position.

Table 7.1: ANOVA Results : Patient M.J.

ANOVA TERMS	Fin. Err.	Max. Dev.	Tot. Dev.	Latency	Mean Vel.	Max. Vel.
Loop (Open, Closed)	***	***	***	***	***	
Task (Point, Bisect)	***		**		***	*
Location (Lt, Ct, Rt)	***		***		***	***
Loop x Task	***	***				
Loop x Location	***	***	**			
Task x Location	***	*	**			
Loop x Task x Loc.	***	**	*		***	*

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Fin. Err.= Final Error, Max. Dev.= Maximum Deviation,
Tot. Dev.= Total Deviation, Mean Vel.= Mean Velocity,
Max. Vel.= Maximum Velocity
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

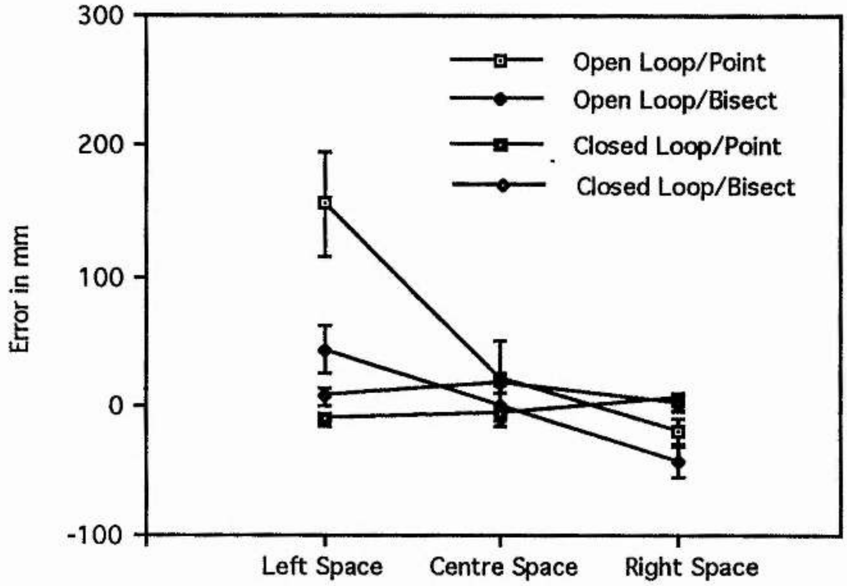

Figure 7.1(a): Mean final error toward each spatial location (left, centre, right). The data are of patient M.J. and plotted as a function of loop (open, closed) and task (pointing, bisection). Negative values indicate displacements made to the left of the (virtual) target, positive values indicate displacements made to the right. Error bars indicate intra-subject variability.

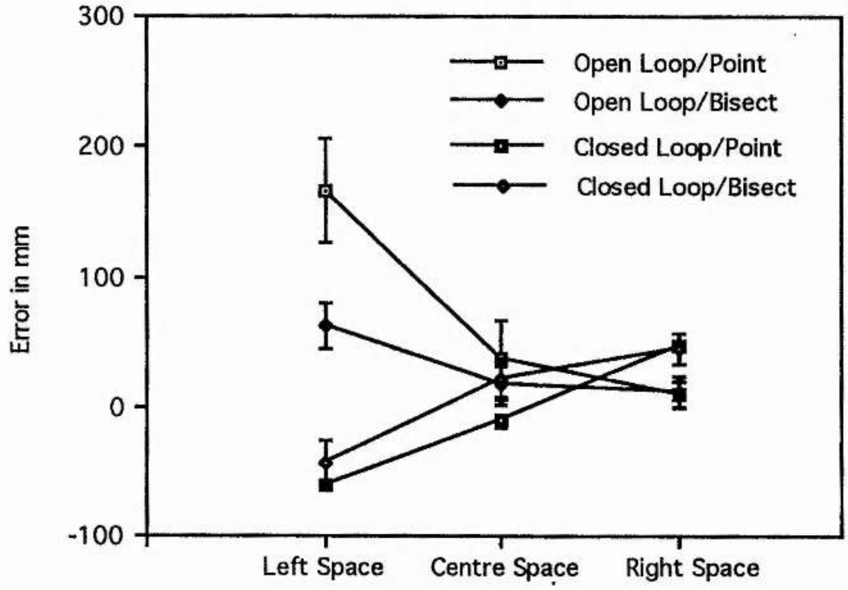

Figure 7.1(b): Maximum route deviation toward each spatial location (left, centre, right). The data are of patient M.J. and plotted as a function of loop (open, closed) and task (pointing, bisection). Interpretation of positive and negative values as in Figure 7.1(a). Error bars indicate intra-subject variability.

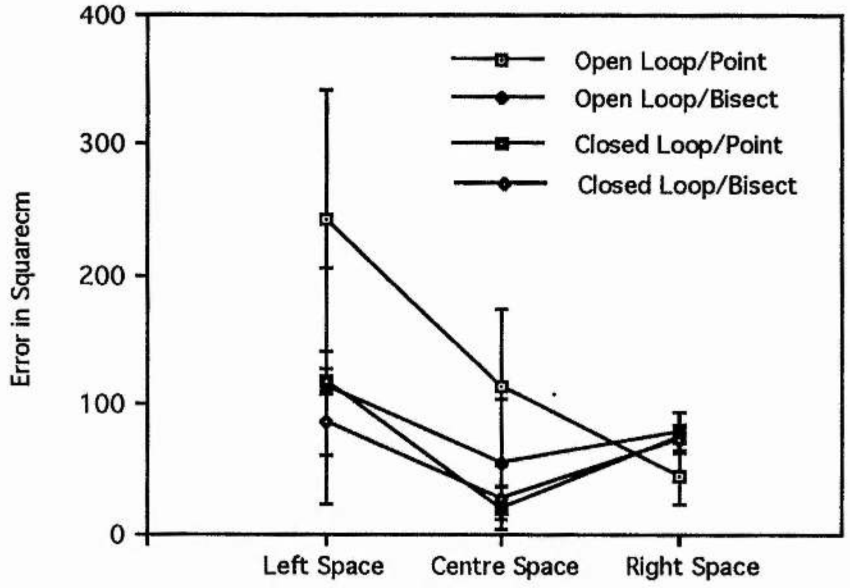

Figure 7.2: Total deviation (areal departure of reaching trajectory from ideal straight line) toward each spatial location (left, centre, right). The data are of patient M.J. and plotted as a function of loop (open, closed) and task (pointing, bisection). Error bars indicate intra-subject variability.

(iv) Latency.

Overall the patient showed very long latencies (grand mean: 1078 ms) compared to a mean of 595ms (SD = 225) for 12 RCVA patients without neglect (chapter six). However, only visual feedback affected movement onset time in that RT's proved shorter in closed than open loop reaching (Table 7.1). No other effects were found.

(v) Movement Velocity.

The patient also showed long movement times (mean maximum speed: 0.69 metres per second), which compares with a mean of 0.88 metres per second (SD = 0.13) for the 12 RCVA patients (chapter six). There were significant loop x task x location interactions for both maximum and average speed (Table 7.1) revealing fastest movement speeds towards right hemispace in the pointing task under open loop feedback. This was the case for both interactions, and no other comparisons proved significant (see also Figure 7.3).

Patient B.W.

(i) Final Error and (ii) Maximum Deviation.

The only significant effect found on both these measurements was a main effect of loop for final error. The final position of the forefinger erred rightward in open loop reaching (7.9mm) and leftward in closed loop reaching (-5.1mm). Chi-square tests revealed that, whereas there was a significantly higher occurence of rightward errors in the open loop condition ($Chi^2 = 8.3$), no significant difference was found for the closed loop condition ($Chi^2 = 2.0$). Including the effect of task (interaction loop x task, $F(2,108) = 2.9$, $p < 0.09$) closed loop reaching showed a trend for very accurate performance in pointing (0.4mm) but leftward errors in bisection (-10.7mm), whereas movements under open loop conditions revealed rightward errors for both tasks with slightly larger

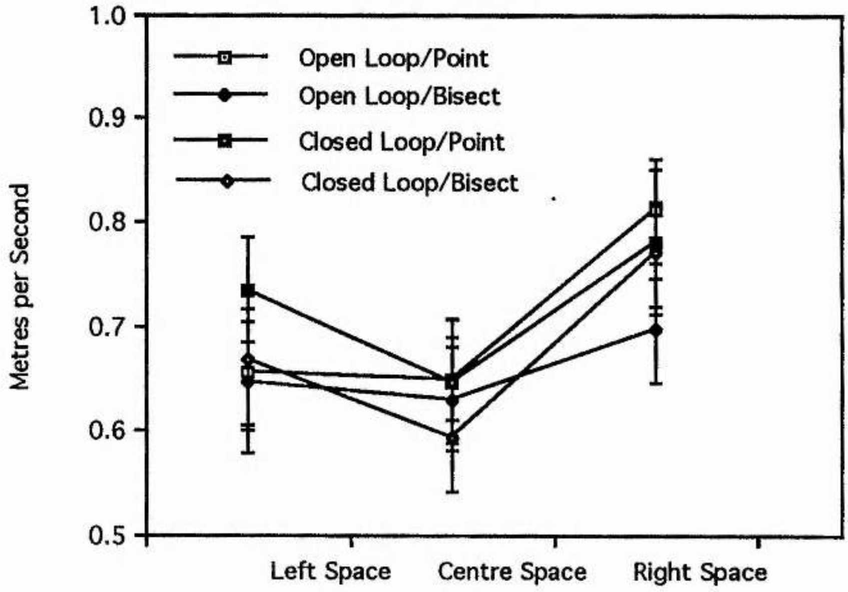

Figure 7.3: Maximum speed in lateral space (left, centre right). The data are of patient M.J. and plotted as a function of loop (open, closed) and task (pointing, bisection). Error bars indicate intra-subject variability.

TABLE 7.2: ANOVA Results : Patient B.W.

ANOVA TERMS	Fin. Err.	Max. Dev.	Tot. Dev.	Latency	Mean Vel.	Max. Vel.
Loop (Open, Closed)	**					
Task (Point, Bisect)			***			
Location (Lt, Ct, Rt)			***	***	***	***
Loop x Task						
Loop x Location						
Task x Location			**			
Loop x Task x Loc.				*		

Significance Level after Greenhouse-Geisser adjustments; *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

Abbreviations: Fin. Err.= Final Error, Max. Dev.= Maximum Deviation,
Tot. Dev.= Total Deviation, Mean Vel.= Mean Velocity,
Max. Vel.= Maximum Velocity,
Pt= Pointing, Bsct= Bisection, Lt= Left Space, Ct= Centre, Rt= Right Space

displacements in bisection (11.0mm) than pointing (4.7mm). Chi-square tests demonstrated that leftward displacements were significantly more frequent than rightward displacements in closed loop bisection ($Chi^2 = 4.5$). On the other hand rightward errors occured more often than leftwards errors for both tasks in open loop ($Chi^2 = 3.9$ for pointing, $Chi^2 = 4.1$ for bisection).

No significant differences were reported for maximum deviation but the average overall lateral deviation proved to be to the right (mean: 25.0mm) and deviations were unevenly distributed in the direction of rightward displacements ($Chi^2 = 28.0$).

(iii) Total Deviation

The total summed deviation of each route demonstrated a significant task x location interaction, indicating that the largest deviations occurred in the bisection task when movements were made into left hemispace. No other comparisons proved significant.

(iv) Latency

Over all, patient B.W. showed considerably lower RT's than M.J. (overall mean: 572 msec), indeed his RT's proved similar to those found in the RCVA patients in chapter six (overall mean: 595 msec) . Apart from a main effect of location which revealed longest latencies for reaches into left hemispace, movement onset time was greatest when bisecting in the absence of visual feedback, with movements being directed towards the left hemispace (interaction loop x task x location, Figure 7.4). No other comparisons were reported to be significant (Table 7.2).

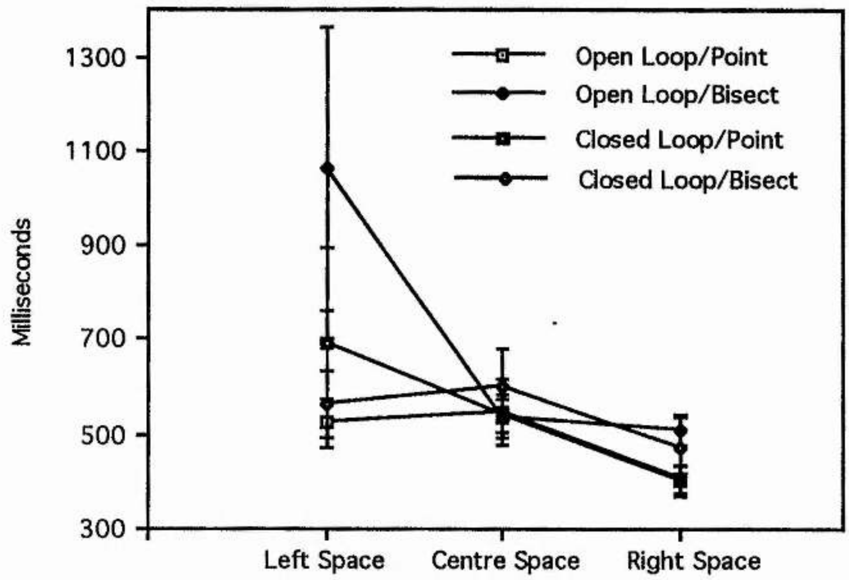

Figure 7.4: Latency to initiate a reach in lateral space (left, centre right). The data are of patient B.W. and plotted as a function of loop (open, closed) and task (pointing, bisection). Error bars indicate intra-subject variability.

(v) Movement Velocity

The patient also revealed higher velocities than M.J. (mean maximum speed: 0.94 meters per second) which, again, proved comparable to the RCVA patients in chapter six (mean maximum speed: 0.88 metres per second). Both average and maximum speed measures were fastest for reaches towards right space and slowest towards left space (main effect of space, Table 7.2). No other effects were found.

Discussion of Patient M.J.

Regarding the trajectory of the movement, the most consistent finding was that M.J. showed large rightward deviations when, in the absence of visual feedback, reaches were directed towards targets located in left hemispace. These rightward deviations proved significantly larger in the pointing than the bisection task (155.8mm vs 43.39). This is surprising as task did not affect the performance of the right hemisphere lesioned group in Experiment 11 (chapter six), although they too showed rightward deviations in the absence of visual feedback. Furthermore the data of Goodale *et al.* (1990) would lead one to expect the opposite result. It is possible that M.J. was showing extinction in the bisection task (in left space), resulting in rather accurate pointing towards the more rightwardly located LED. This seems plausible given the large amount of error demonstrated (43.3mm): a deviation of 50mm from the virtual midpoint would be equivalent to pointing directly to the rightwardly located stimulus. However the phenomenon of extinction alone can not explain the huge rightward deviation seen in the *pointing* task. There seems also to be a motor bias operating to shift reaches away from the left side of space. Nonetheless this shift is not universal across the spatial locations: rightward deviations proved substantially smaller for central reaches and although route deviation showed rightward shifts for right space as well, terminal errors were to the left of the true midpoint (although substantially smaller than those in left space; 155.8mm vs -19.8mm). It should be noted that all these effects were apparent in the absence of visual feedback only. Accuracy in closed loop reaching was comparable to those of the other elderly subjects tested (RCVA, LCVA patients and controls, see chapter six) with overshoot errors for left and rightwardly located targets.

The patient was very slow on both movement onset time and movement velocity. She did not, however, show any differential slowing as a function of hemispace or task. Although a generalized slowing of reaction times after right hemisphere lesions is well established in the literature (Howes and Boller, 1975; Benton, 1986) and movement velocity was also affected in the patients in Experiment 11 (chapter six), the amount of slowing reported in this patient was much greater compared to the profiles of the other patients. It is possible that M.J.'s lesion involved damage to the basal ganglia, especially the putamen and nucleus caudatus with a resulting inhibition of motor areas (Duus; 1987). This might have been responsible for the overall slowing of the hand.

Discussion of Patient B.W.

Patient B.W. who unexpectedly displayed leftward errors when asked to bisect a line in the traditional line bisection task, also showed leftward terminal errors when reaches were performed under visual guidance. In contrast, rightward terminal errors were made in the absence of visual feedback. Additionally, although route deviation was not affected by either loop, task or spatial location, an overall rightward bowing was found for all movements. These findings seem to indicate that B.W. made rightward directional errors at the outset of the reach which were corrected (indeed overcorrected into leftward errors) under visual guidance, but remained towards the right under open loop conditions. The only effect of task was that the areal discrepancy between the actual trajectory and the direct path to the target, was largest for reaches into left hemispace while bisecting rather than pointing. So contrary to the results of Milner and Goodale (1988) and Goodale *et al.* (1990), use of the bisection task only affected overall route discrepancy for reaches into left space, rather than producing across-the-board rightward errors. Nonetheless in closed loop conditions B.W. showed almost the same reaching pattern as observed for the pointing and bisection task in Goodale et al.'s data: in the presence of visual feedback B.W. made initial rightward directional errors, which were corrected in the pointing task but produced leftward errors in bisection. Although Goodale et al.'s patients produced rightward errors in the visually taxing bisection task, B.W. differed from these patients in that he showed leftward displacements when asked to bisect a line. Consequently his errors in bisection under closed loop feedback are consistent with this behaviour. Nonetheless he made rightward terminal errors in the absence of visual feedback, which is most likely what Goodale *et al.* would have predicted, had they tested there patients under open loop conditions.

Contrary to M.J. patient B.W. showed no overall slowing for movement onset time or movement velocity. Latency was longest for initiating reaches into left hemispace under bisection. Similarly movement velocities were also longest for reaches directed into left space. These findings are difficult to interpret as due to contralateral weakness, the patient was only tested with the right hand. Both these effects could be part of the hemispace-hand compatibility effect, with ipsilateral reaches attaining higher velocity and lower latency than contralateral reaches (see also previous chapters). Nevertheless the findings on latency could also be due to a directional hypokinesia (Heilman *et al.*, 1985b), and the reduced velocities a result of damage to fronto-parietal systems for visual guidance of the arm (Milner and Goodale, 1993).

GENERAL DISCUSSION

In the presence of visual feedback, both patients showed rather accurate reaching performance for both the pointing and the bisection task. This is surprising as substantial errors were found on the traditional line bisection test. In fact the data almost provide a double dissociation with those presented by Goodale *et al.* (1990) who found that right hemisphere lesioned patients, who had *recovered* from hemispatial neglect and showed no abnormality on the traditional line bisection test, nevertheless made rightward terminal errors in the bisection task. It is hard to explain why the two neglect patients presented here showed no serious reaching errors in closed loop bisection. An assumption might be that the two LED's, which remained illuminated throughout the movement, induced conscious orienting towards the side with the stimuli and a subsequent online comparison of the finger as it approached the target. It is possible that neglect patients find this easier than first scanning a long line and then placing a mark. Nonetheless this does not explain the impairment of Goodale *et al.*'s (1990) patients unless their subjects did not have continuous target feedback (no explicit information with regard to target duration is given).

Like the RCVA patients in Experiment 11 (chapter six), both subjects showed an impairment in terminal accuracy when reaching was performed in the absence of visual feedback from the hand. This finding adds more evidence to the hypothesis of a right hemisphere contribution to the accuracy of visually guided open loop reaching (cf. Guiard *et al.* 1983). On the other hand, the presented data give little evidence for a specific right hemisphere involvement in the bisection task.

Patient B.W. erred systematically to the right of the true target over all three spatial positions. Indeed B.W.'s reaching behaviour seems very similar to *both* the performance of the RCVA patients in Experiment 11, and Heilman's neglect patients (1983) who erred rightwards when pointing to an imaginary 'straight ahead' point in space. This strongly suggests that rather than being apparent in neglect only, 'directional hypokinesia' seems to be associated with right hemisphere lesions as such, independent of neglect. This possibility is indeed pointed out by Heilman and colleagues in a later paper (Heilman *et al.*, 1985b). M.J. also showed rightward turning tendencies but unlike B.W. these were largest for reaches into left hemispace, moderate for central reaches (although still significantly different from zero) and indeed leftwards for reaches into right space. Although in neglect patients larger rightward shifts would be expected for reaches into left hemispace (Heilman and Valenstein, 1979) no explanation can be given as to why, in M.J., these deviations become leftward for reaches into right hemispace, giving a centripetal reaching pattern.

The reported overall tendency of reaches deviating into the hemispace ipsilateral to the lesion in the absence of visual feedback has also been demonstrated in patients with optic ataxia. Optic ataxia is defined as the inability to reach for objects in extrapersonal space, in the absence of gross motor, visual or somatosensory deficits (Jeannerod, 1988). Patients with optic ataxia misreach for objects located within their contralesional field and misreaching can occur for movements with the hand contralateral to the lesion (Castaigne *et al.*, 1971) or either hand (Garcin *et al.*, 1967) or the contralateral hand in both hemifields (Levine *et al.*, 1978; Ferro, 1984). In a systematic reaching experiment Vighetto (1980) found that optic ataxia patients performed comparably to normal subjects when they could see their moving hand during reaching. Nonetheless in the absence of visual feedback misreaching occurred with systematic deviations to the side of the lesion. Indeed Jeannerod (1988) has argued that hemispatial neglect and optic ataxia may reflect disruption of a common functional substrate in that the patients' egocentric coordinates (those relating the spatial position of objects to the body axis and serving as a reference for directing the movements) are biased in one direction.

As both patients could only be tested with their ipsilesional hand, interpretation of latencies and kinematics with regard to hemispace is unsafe as the data could merely reflect compatibility effects. Nonetheless patient B.W. showed longest movement onset times while performing the bisection task in left hemispace under open loop conditions. These data could suggest an impairment in determining the target position which became apparent under this taxing condition only. Like the Duhamel and Brouchon patient (1990) M.J. showed no specific RT slowing for reaches toward leftwardly located targets. This is surprising, as her movement trajectories for reaches into left hemispace were substantially distorted.

It seems that, although both these patients illustrate behaviour patterns which can be subsumed in the overall category of hemispatial neglect, no simple visuomotor account is likely to be applicable to all such patients. Both these patients differed remarkably with respect to trajectory and kinematics of the movement. The only consistent finding was that they were both fairly accurate in closed loop reaching, a finding which in turn differs from Goodale *et al.* (1990).

SUMMARY

Two right hemisphere lesioned patients with symptoms of hemispatial neglect were tested for their ability to reach either toward a single target or midway between 2 targets. The tasks were performed either in free vision or in the absence of visual feedback from the hand. It was found that both patients were rather accurate in closed loop reaching. In the absence of visual feedback reaching was inaccurate, but whereas patient B.W.'s errors took the form of a rightward bias, regardless of task or spatial position of the target, M.J. showed largest errors for reaches into left space, especially in the pointing task. M.J.

also proved very slow in movement initiation latency and execution of her reaches, whereas patient B.W. proved comparable to the other RCVA patients tested in chapter six. No attempt to generalize the findings was made.

CHAPTER EIGHT

GENERAL DISCUSSION AND CONCLUSIONS

Implications of the line bisection and landmark experiments

In chapters two and three an attempt was made to examine the nature of the displacements found in the traditional line bisection test when applied to normal (right-handed), as well as brain lesioned subjects. Three main phenomena have been repeatedly reported in the literature: firstly, there seems a be an overall leftward displacement, when normal subjects are asked to bisect a centrally presented line (Bisiach *et al.*, 1976; Bowers and Heilman, 1980; Bradshaw *et al.*, 1985; 1987a; Scarisbrick *et al.*, 1987), and although other authors fail to demonstrate such an effect (Werth and Poeppel, 1988; Manning *et al.*, 1990; Halligan *et al.*, 1990, Nichelli *et al.*, 1989) this leftward bias is generally explained in terms of a right hemisphere advantage on visuospatial tasks. Moreover, there is complementary evidence that right hemisphere lesioned subjects, in particular patients with symptoms of hemispatial neglect, display rightward bisection errors when asked to bisect a centrally presented line (Schenkenberg *et al.*, 1980; Heilman and Valenstein, 1979; Riddoch and Humphreys, 1983; Halligan and Marshall, 1988; 1989), thus giving further indication of a right hemisphere involvement in this task.

Secondly, there is now evidence that normal right-handed subjects make bisection errors towards whichever end of a line is explicitly cued (Dudgeon, 1988; Nichelli *et al.*, 1989; Reuter-Lorenz and Posner, 1990). Similarly, various investigators have demonstated that providing a neglect patient with a left cue, significantly reduces the amount of rightward bisection error typically shown in these patients (Riddoch and Humphreys, 1983; Halligan and Marshall, 1989; Halligan *et al.*, 1991; Reuter-Lorenz and Posner, 1990) suggesting the relevance of attentional components.

Finally, spatial location has been found to affect bisection errors although, so far, the results are inconsistent for both normal right-handed and brain lesioned subjects: Nichelli *et al.* (1989) found that normal subjects bisect to the left in right hemispace and to the right in left hemispace, whereas Fukatsu *et al.* (1990) found no effect of spatial location. Regarding neglect patients, Heilman and Valenstein (1979) demonstrated that these subjects show larger rightward displacements in left than central or right space, whereas Riddoch and Humphreys (1983) reported no significant effect of space.

However, as already pointed out in chapters two and three the problem with the standard bisection task is that it invariably confounds perceptual and motor factors. In contrast, use of the 'landmark task' enables an examination of perceptual effects in isolation. In other words, the landmark test can quantify whether the overall rightward bisection errors in neglect patients are due to directional hypokinesia (Heilman and Valenstein, 1979; Heilman *et al.*, 1985b) or perceptual/attentional biases (Riddoch and Humphreys, 1983; Milner, 1987). The same problem applies to the normal subjects: a right hemisphere dominance for spatial processing could cause either/or both of an increased motor response or a perceptual asymmetry. Analogous logic can be applied to an analysis of the effects of cueing or of spatial location. A perceptual overestimation of the cued side should result in judging the side opposite the cue as shorter. A motor bias due to the presence of the cue however, would be expected to elicit responses toward the cued end of a line, perhaps due to activation of the contralateral hemisphere. Finally, presenting stimuli in left or right space should cause motor biases toward the lateral ends of the lines due to such activational effects, whereas a perceptual overestimation of the lateral part of the lines would result in a manual indication of the medial end as shorter. So if the independent variable causes a bisection error in a given direction, then the manual landmark task will always place the two alternative accounts of that error in opposition.

Regarding the *overall bisection error*, the findings on both the young (Experiment 1) and elderly subjects (Experiment 3) repeated the results of Bradshaw *et al.* (1985; 1987a) in that significant leftward displacements were found for bisection responses in the central presentation condition. Both groups also showed an overall leftward bisection error averaged over all locations of presentation, but this proved significant for the elderly subjects only. However, differences between the two groups emerged in the landmark task which illuminated whether these leftward errors reflected a relatively magnified percept of the leftward part of the line (Milner, 1987) or a response bias in the form of a predominantly leftward orienting tendency (Heilman *et al.*, 1985b). The landmark data of the elderly subjects indicate that the bisection errors reflect leftward orienting responses, as judgements remain toward the left in this task (Experiment 4). On the other hand, no consistent bias was found for the younger subjects. There are two possible explanations for this: one is that both factors (perceptual and motor) were operating together in the younger subjects and thus cancelled each other out. This explanation would be consistent with a dual role of the right hemisphere in both enhancing the perceptual salience of spatial stimuli in the left hemispace, and also in activating leftward orienting response tendencies. Nevertheless, it could also be argued that the overall effect (and the effect in central space) was simply not strong enough in the younger subjects to be replicated in the landmark task (Experiment 2). It was certainly statistically weaker in the original bisection experiment (Experiment 1) than the overall effect found in the elderly subjects (Experiment 3).

Moreover, no significant rightward displacements in bisecting lines were found for the RCVA patients, who did not show any evidence of neglect at the time of testing. Indeed the overall error score of this group proved not significantly different from perfect performance. This is contrary to the findings of Schenkenberg *et al.* (1980) who found significant rightward displacements in their right hemisphere damaged patient group. Bisiach *et al.* (1976) also reported rightward bisection errors in their right hemisphere damaged group. Nevertheless, the data of both these studies might be biased, as no attempt was made to analyse patients with hemispatial neglect separately. The more recent literature gives little information regarding the bisection behaviour of right or left hemisphere damaged subjects as most studies compare the performance of neglect patients with that of normal controls (Halligan and Marshall, 1991; Halligan *et al.*, 1990; Reuter-Lorenz and Posner, 1990). However in very recent work, Halligan and Marshall (1992) point out that, although some people in the field seem to think that right hemisphere lesions will invariably provoke an abnormal shift to the right on line bisection, this is not always the case. They quote the performance of two right hemisphere lesioned patients with neglect symptoms as evidence against this assumption. Indeed Tegner and Levander (1991b), who tested 25 neglect patients on lines of varying length and used right and left hemisphere lesioned patients and normal subjects as controls, found very similar displacements to those presented here: on lines of 20cm length, both right hemisphere lesioned patients and controls showed small leftward displacements (-0.22mm and -1.mm respectively). The left hemisphere lesioned group also made leftward errors (-3.3mm) but these were only slightly larger. This was also the case for the LCVA group presented in chapter three (Experiment 5A): they averaged an overall error of -2.26mm which proved significantly different from zero. Nonetheless these deviations were no greater than those shown by the control group when using their left hand. The bisection results of the right and left CVA groups on lines of varying length (Experiment 7A) also confirm that neither group differed significantly from the control group. Finally, both groups also showed an overall equal distribution of left and rightward judgements in the landmark tasks (Experiments 6A and 8A). Consequently, although the data of both the young and elderly normal subjects seem to give an indication of right hemisphere involvement in both the bisection and landmark task, this is not confirmed by the findings on the RCVA patients, who did not show any neglect symptoms at the time of testing. Neither in the bisection nor the landmark task, did these patients differ from the control group. Not surprisingly there was also no difference between the LCVA and control group on either task. So it seems that unilateral brain lesions, including lesions in the right hemisphere are not sufficient to produce an overall impairment in either bisection or landmark tasks, and it is likely that most impairments reported in the literature are due to patients who, apart from right hemisphere lesions *per se*, also concurrently showed symptoms of hemispatial neglect (Schenkenberg *et al.*, 1980; Heilman and Valenstein, 1979; Riddoch and Humphreys, 1983; Halligan and Marshall, 1988; 1989).

Unfortunately (but comparable to the literature), it turned out that the data on *spatial location* proved rather inconsistent. First of all, the *bisection* data of the younger subjects (Experiment 1) confirmed most previous reports (Bradshaw *et al.*, 1987a; Dudgeon, 1988; Reuter-Lorenz, 1990) that the leftward error of normal subjects in bisection tends if anything to increase in the left half of egocentric space, but to reverse direction in the right half. That is, there was a tendency to bisect too far laterally. However, in the elderly subjects, significant leftward bisection errors were found in all three spatial positions (Experiment 3) and this was also the case for the right and left CVA groups (Experiment 5A and 7A), although their errors proved insignificantly different from zero.

In the *landmark* task, however, younger subjects (Experiment 2) showed no consistent bias regarding spatial location. Again this could be due to a failure to replicate a weak effect. On the other hand, it is possible that in the landmark task, which required a motor response, a perceptual bias toward the midline (indicating that part of the line as being shorter because of a lateral overestimation) may have been counteracted by a motor- orienting bias in terms of a lateral overshoot (pointing towards the lateral part of the line), independent of the actual perception. However, this interpretation would be in direct opposition to the location effect reported in the landmark data of the elderly subjects (Experiment 4) who indicated the *lateral* part of laterally presented lines as being shorter. So if a perceptual bias is at work in the elderly subjects it seems to enlarge the *medial* rather than the lateral part of laterally presented lines. On the other hand, it can be argued that the main effect of spatial location in the elderly subjects cannot have been very strong as it disappeared when they were analysed (as controls) with the brain lesioned patients (Experiment 6A). Moreover, the opposite effect was found when all three groups (LCVA, RCVA and controls) performed the landmark task on lines of varying length. In this experiment (8A) all subjects showed significantly more rightward judgements in left than central and right space, thus indicating a relative overestimation of the *lateral* part of laterally placed lines.

So regarding the effects of space in young and elderly subjects, it is not at all clear why elderly subjects should overscale the *medial* extent of long lines and the *lateral* end of lines of varying length, while younger subjects if anything overscale the *lateral* extent (these subjects were only tested on long lines). As already pointed out in the **Discussion of Experiments 8A and 8b**, it is possible that another factor might be responsible for these diverging results: as eye movements were neither restricted nor recorded, little is known about the scanning patterns adopted by the subjects. Nonetheless it has been consistently shown that focusing a subjects attention to a particular side (by cueing) produces a perceptual overestimation of that part of the stimulus (Milner *et al.*, 1992; see also Experiments 2, 4, 6A and 8A). Consequently it seems possible that whatever part of a line is scanned longest is perceived as largest. Indeed Manning *et al.* (1990) also claim that normal subjects who adopt a predominantly left-to-right scan strategy should produce leftward errors in bisection, whereas a predominant right-to-left scan should result in rightward errors. It is possible that younger subjects adopt different scanning strategies than elderly subjects. It might also be important whether lines do or do not vary in length from trial to trial. In Experiments 4 and 6A, in which all lines were of 20 cm length subjects might have scanned the medial part of laterally presented lines more than the lateral part, this causing them to indicate that the lateral end was closer to the central mark. In Experiment 8A in which lines differed in length they might have scanned the lateral end more (as part of a strategy for line length estimation) thus indicating the medial part as being shorter. However, data on eye movements need to be available before any such claims can be substantiated.

However, unlike spatial location, *cueing procedures* provided consistently clear and robust results throughout the whole set of experiments. For all subject groups (young, elderly, LCVA and RCVA without neglect) and both tests (bisection and landmark), use of a single visual cue biased judgements in a manner consistent with a relative overscaling of the cued end of the line. It seems that unilateral cueing directs selective attention unevenly to one or other end of the line (perhaps due to visual areas within the contralateral hemisphere being especially activated), and that the perception of relative size is subject to systematic distortion as a function of this selective attention within the visual field. So it may be inferred that the influence of cueing upon active line bisection (see also Nichelli *et al.*, 1989; Reuter-Lorenz and Posner, 1990) seems to operate principally at the perceptual level (overestimation of the cued half-line) and little if at all at the level of any putative orienting response bias. As predicted these effects proved the same for the two patient groups (LCVA, RCVA) and the control group, suggesting that most patients with unilateral brain damage have no deficit in consciously attending to targets. Biases to overestimate the cued end of the line remain strong even when a directional motor response is made in the opposite direction, i.e. in the landmark task.

As reported by other investigators (Riddoch and Humphreys, 1983; Halligan and Marshall, 1989a; Halligan *et al.*, 1991; Reuter-Lorenz and Posner, 1990) highly significant cueing effects were also found for the neglect patients in the bisection task (Experiment 5B): unilateral left cues decreased the magnitude of rightward displacements shown, whereas unilateral right cues increased the amount of error. It is interesting, however, that bilateral cues were as effective in reducing rightward deviations as single left cues, while on the other hand, single right cues produced no larger displacements than the no-cue condition. Riddoch and Humphreys (1983) also reported a reduction in neglect with a single left cue (in their first experiment) and (in their second experiment) a similar reduction in the bilateral cue condition when the patient was asked to report the left letter only. Nonetheless the neglect patients presented in chapter three, contrary to Riddoch and Humphreys' patients, did not produce larger rightward displacements in the single right cue as opposed to the no-cue condition. According to the covert orientation argument (Posner *et al.*, 1982), neglect should increase with a right-side cue, as the patient has difficulty in shifting attention (disengaging) once that has been oriented to the right. On the other hand, it is possible that in the absence of any cues, the patient's attention is already prebiased to the right thus producing bisection responses equivalent to those made in the presence of a right side cue: certainly Kinsbourne (1987) argues that ...'the patient with neglect turns ever to the lesioned side when negotiating his environment'.

As cueing could be successfully demonstrated in the bisection task, it seems that patients with neglect are capable of consciously orienting to stimuli although they may not do so automatically (Riddoch and Humphreys, 1983). Consequently cueing in the landmark experiment should produce similar effects to those reported for all other subjects, i.e. judging the half-line *without* the cue as *shorter* than the cued half. Surprisingly though, all neglect patients pointed towards the *cued* half of the line. It should be noted that this effect was embedded in an overall tendency to indicate the left half of a line as being shorter: judgements differed significantly from chance performance in a leftward direction in all four conditions (no-cue, bilateral cue, single left and right cue). Nonetheless it seemed that in these neglect patients cueing produced motor rather than perceptual effects. This bias is different from a directional hypokinesia as it operates towards the cued side rather than producing a general rightward bias independent of cueing conditions (Heilman and Valenstein, 1979). It seems therefore that the cueing effects reported for the bisection task (Experiment 5B) were due to increased motor response amplitudes, which shifted marks closer towards the cued sides, thus reducing errors with a left cue but increasing rightward deviations with a right cue. As other authors who demonstrated cueing effects in neglect patients (Riddoch and Humphreys, 1983; Halligan and Marshall, 1989a; Halligan *et al.*, 1991; Reuter-Lorenz and Posner, 1990) never explicitly distinguished between perceptual and motor components of the effect, it cannot be ruled out that the cueing effects in their patients were also mainly due to an increased motor response 'attracted' by the cue. The only proposal which can be made at present to explain these increased motor responses, is to assume that the lateralized cues produced an activation imbalance in favour of the directly stimulated hemisphere (see also Reuter-Lorenz *et al.*, 1990) which in turn facilitated turning towards the cued side. Presumably the attentional structures damaged by neglect-causing lesions were not able to mediate a normal effect of cueing on size perception (Milner *et al.*, 1992).

However, the main question the experiments in chapter three address is whether *neglect patients* perceive the midpoint of a horizontal line to be subjectively shifted to one side. Neither the space-compression hypothesis (Halligan and Marshall, 1991; see also introduction, chapter three), nor the directional limb hypokinesia hypothesis (Heilman *et al.*, 1985b), would predict this, since neither account predicts any nonlinear distortion of perception. Halligan and Marshall's account (1991) predicts only that the whole line should be subjectively shifted rightwards in space, along with a uniform shrinkage in its size. Thus both of these previous hypotheses can only explain bisection errors as due to a misdirection of response. Neither would predict that the two halves of a line should appear different in length to a neglect patient. Yet, through use of the landmark task (Experiments 6B and 8B), it has been demonstrated that out of six patients with manifest hemispatial neglect, each showing large rightward bisection errors, five patients consistently indicate the left end of a centrally pre-bisected line as appearing closer to the objective midpoint. This misperception occurred for long as well as short lines. Indeed, even 20cm lines pre-transected as far as 5 mm to the right of centre were predominantly judged in this way, i.e. as if leftwardly transected (Experiment 6B). So it can be concluded that, in these five hemispatial neglect patients, there was indeed a bias to perceive the left half of a line as shorter than the right half.

The experiments also address the frequently noted trend in neglect patients to show greater line bisection errors in contralateral space than in ipsilateral visual space. Again Halligan and Marshall's model (1991) could explain this, since it predicts that the subjective location of a line should be shifted rightwards to a greater extent within left hemispace than within right hemispace (see also introduction to chapter three). This hypothesis alone, however, predicts no variation in the perceived appearance of a transected line placed in different parts of visual space. In contrast, Milner (1987) suggested that patients with left hemineglect might perceive leftwardly-located spatial extents as shrunken relative to more rightward ones, and that the gradient of this distortion might be greater within left than right hemispace. If this is correct, then the tendency to judge the left halves of lines as shorter than the right, which was reported here for the two landmark tasks, should become particularly pronounced in left hemispace. This was indeed found for the second landmark task (Experiment 8B), in which neglect patients showed significantly more leftward judgements in left than in right hemispace. The same trend occurred in the first landmark study (Experiment 6B) but failed to prove significant, possibly due to the fact that there were fewer trials. The landmark results are thus consistent with the hypothesis that neglect patients tend to judge the left half of a centrally bisected line as shorter, and that the gradient of distortion may be particularly pronounced in left hemispace. Neither of the other two theories can explain these landmark data.

So it can be argued that in at least some patients suffering from hemispatial neglect, there is a perceptual factor operating which renders left-side stimuli subjectively smaller than rightwardly located ones. This phenomenon seems (at least in one of the present neglect patients) to be particularly pronounced in the perception of horizontal extent (Milner *et al.*, 1993). Consequently this distortion of size perception must play an important role in the causation of line bisection errors in such patients. Moreover, it was consistently shown that cueing strongly influenced both line bisection and landmark judgements in normal subjects as well as brain lesioned subjects (without neglect) in that it caused the subjects to overestimate the cued part of the line. It was argued that the perception of relative size is subject to systematic distortion as a function of this selective attention within the visual field. The rightward bisection performance of five of the neglect patients could consequently be interpreted as documenting an abnormal example of this attentionally-induced illusion. In such 'perceptual' neglect, the distribution of attentional resources may be assumed to be abnormally biased in a way that is only partially reversible under voluntary control. The result of this imbalance may be to cause, quite directly, a gross abnormality of size perception, which in turn is manifest in disordered bisection behaviour. Indeed there is know accumulating evidence for the assumption that attention is abnormally biased in neglect patients and that these patients not only experience difficulties in disengaging attention (Posner *et al.*, 1984; 1987), but that there is early automatic orienting toward the half space ipsilateral to the lesion and that this tendency is tightly linked to the presence of behavioural manifestations of hemispatial neglect (Gainotti *et al.*, 1991; Isiai *et al.*, 1989; 1992).

Nonetheless one of the neglect patients (E.L.) did show *rightward* responses in the landmark as well as in the bisection tasks (Experiments 5B, 6B, 7B and 8B) and this behaviour extended to asymmetrically bisected lines as well (Experiment 6B). Consequently her rightward bisection errors seem to have been most likely due to a directional hypokinesia, i.e. a spatially misdirected action possibly due to an underactivation of the right hemisphere premotor system which would normally initiate action in a leftward direction (Heilman *et al.*, 1987). So although the majority of the patients presented here demonstrated a perceptual distortion of their subjective space, nonetheless one of them showed no such effect, but instead a directional hypokinesia.

Still other investigators have recently pointed out that a useful distinction can be made between neglect patients showing mainly symptoms of directional hypokinesia and others experiencing perceptual forms of neglect. For example, Bisiach *et al.* (1990) showed that some neglect patients would move a manipulandum *leftwards* from the spatial midline in order to set a transection pointer *rightwards* from the midpoint of a line that they were asked to bisect. Like the present data, this behaviour could not be explained by a leftward directional hypokinesia, or by a spatially misdirected aiming movement. Other patients, however, did give evidence for the operation of such a factor. Coslett *et al.* (1990) found similar results when testing four patients with neglect syndrome on a line bisection task, preventing direct viewing of the line by using a video-camera and monitor, each of which could be moved independently into right or left hemispace. They report that two patients performed in a manner consistent with the hypokinesia hypothesis and the other two consistent with the attentional/perceptual hypotheses. In a comparable experiment, Tegner and Levander (1991a) tested 18 neglect patients on a line cancellation task which was presented either in normal view or through a 90 degree angle mirror, preventing a direct view. They found that in the mirror condition, 4 out of the 18 patients cancelled lines in right hemispace only, thus indicating symptoms of directional hypokinesia, whereas 10 patients cancelled lines in left hemispace only i.e., showing a perceptual form of neglect. The remaining patients cancelled only central lines, a finding which the authors believe to be due to a combination of motor and perceptual forms of neglect. More indirect evidence might be drawn from a study by Marshall and Halligan (1989) reporting a patient (PP) who, when shown centrally pre-bisected lines, indicated on 94% of trials that they were 'wrongly' bisected and generally then 'corrected' them toward the right. It is possible that this patient also experienced a distortion of her subjective space and that a centrally bisected line appeared to be offset to the left. Indeed it would be expected that the neglect patients of Bisiach *et al.* (1990); Coslett *et al.* (1990) and Tegner and Levander (1991a) who did not demonstrate directional hypokinesia but some kind of 'perceptual' deficit, all show this effect in that they would have perceived the left half-line of a centrally pre-bisected line as shorter than its right half.

So in the recent literature, there have been a number of independent studies suggesting that a useful classification can be made between neglect patients showing mainly symptoms of directional hypokinesia and others experiencing perceptual difficulties (Coslett *et al.*, 1990; Bisiach *et al.*, 1990; Tegner and Levander, 1991a; Liu *et al.*, 1992, Bottini *et al.*, 1992) and the experiments presented in chapter three further substantiate the appropriateness of this distinction.

In relation to this distinction, Mesulam (1981) proposed some years ago, that anterior lesions may be associated with 'intentional' neglect while posterior lesions cause attentional/representational deficits. Bisiach *et al.* (1991) did indeed find an association between directional hypokinesia and anterior lesions, and the single case studies by Liu *et al.* (1992) and Bottini *et al.* (1992) both report that a patient with directional hypokinesia had a frontal lesion, and a patient with perceptual neglect, parietal damage. The data of Tegner and Levander (1991a) also seem to support this hypothesis: of the four patients with directional hypokinesia, three had a frontal and one a central lesion. On the other hand, all patients with isolated posterior lesions showed a perceptual pattern. However, the authors also point out that their results must be regarded with caution, as patients with directional hypokinesia tended to have larger lesions and no patients with isolated anterior lesions were examined. There is a similar problem with Coslett *et al.*'s patients (1990): although the lesions of the two patients with symptoms of directional hypokinesia appear to preserve the parietal areas, they were not isolated anterior lesions. Secondly, the lesions of the two patients with 'perceptual' neglect did not only involve parietal areas. Lesion analysis of the six neglect patients presented here is also ambiguous: E.L. who showed symptoms of directional hypokinesia had a large fronto-parietal lesion. Four out of the five 'perceptual' patients did indeed have posterior (parietal) lesions but one of them (M.J.) had a lesion in the mid/anterior white matter, a finding which appears to contradict Mesulam's theory (1981).

Two of the experiments (7 and 8) presented in chapter three included testing of the effect of *line length* on the performance of patients with neglect syndrome. Halligan and Marshall (1988) were the first to demonstrate that neglect patients show *leftward* displacements when asked to bisect very short lines. This behaviour pattern has been demonstrated repeatedly since then (Marshall and Halligan, 1990; Tegner and Levander, 1991b) and although all authors point out that the displacements shown for lines of 2.5cm length were significantly different from those shown by normal control groups, the experiments described in chapter three demonstrated that these errors were indeed comparable to those made by the control groups. It is obvious that bisecting shorter lines is easier than bisecting long (say 20cm) lines. Consequently problems experienced by neglect patients should be diminished when the task becomes less difficult. It is feasible that reducing lines to a very short length (say 2.5cm) makes it as easy for neglect patients as other subjects to produce small insignificant errors.

As expected, four out of the six neglect patients tested in Experiment 7B (notably, E.L. was not one of them), showed leftward bisection errors on the shortest lines. However, the magnitude and variability of these errors did not differ from those of the RCVA and the elderly control group, neither over all or in any of the three spatial positions. Also, although the spatial position of the lines presented had an effect with longer lines (larger errors in left space), no such effect was found for very short lines (Experiment 7B). Again this could indicate that neglect patients found the task too easy to be influenced by spatial position. As all lines were arranged centrally on the sheet, shorter lines actually extended less into left (and right) space than longer lines. This could have contributed further to the lack of a spatial effect. Nonetheless the fact that leftward displacements were found in left hemispace disagrees with the idea of an attentional boundary: if, as argued by Halligan and Marshall (1988), neglect patients have an attentional boundary placed slightly to the left of the objective midline, lines in left hemispace should either be missed altogether or if anything, bisected to the right of the true centre. It can thus be argued that, for very short lines, most neglect patients experience no greater difficulty than other subjects. That is, there is no evidence for a disorder which requires special explanation. With longer lines, on the other hand, the operation of attentional biases may become more prominent because of the need to make successive ocular fixations.

The data also give an indication that the line-length effect may only be present in patients whose neglect is largely perceptual in nature: four out of the five 'perceptual' neglect patients demonstrated a *cross over* to the left of the true centre in all three spatial positions. On the other hand patient E.L. (the patient with symptoms of directional hypokinesia) showed significant rightward errors for short as well as intermediate and long lines in all three spatial positions. Maybe only 'perceptual' patients show a reduction in rightward displacements with shorter lines and eventually perform like controls on very short lines. The 'motor' neglect patients on the other hand, may be affected by directional hypokinesia when bisecting lines of any length. At the moment there seems to be no study which distinguishes between 'perceptual' and 'motor' neglect patients and then assesses their performance on lines of varying length separately. However Bisiach *et al.* (1983) also reported that some of their neglect patients showed rightward bisection diplacements which seemed independent of line length, whereas others produced far larger errors with the longer lines. It is conceivable that the patients whose displacements did not change, had mainly symptoms of directional hypokinesia, whereas the others showed more perceptual/attentional difficulties.

Future considerations evolving from the landmark and bisection data

The results of the neglect patients proved rather consistent across all landmark and bisection experiments, with the majority of patients giving evidence of misperceiving the left half of a centrally pre-bisected line as shorter than the right half. The gradient of this distortion proved steeper in left than in central and right space. As eye-movement studies of visual search, line bisection and picture inspection in neglect patients (Ishiai *et al.*, 1989; 1992; Huber *et al.*, 1988; DeRenzi *et al.*, 1989b, Gainotti *et al.*, 1989) have shown that their fixations tend to be crowded to the right of the stimulus, this tendency might have contributed to the consistent findings reported here. It was also shown that (for normal subjects) focusing a subjects attention to a particular side (by cueing) produced a perceptual overestimation of that part of the stimulus. Consequently it seems possible to argue that whatever part of a line is scanned longest is perceived as largest. Indeed Manning *et al.* (1990) also argue that normal subjects who adopt a predominantly left-to-right scan strategy should produce leftward errors, whereas a predominant right-to-left scan should result in rightward errors. So, as already suggested, the inconsistent findings on spatial location (in the normal subjects) might have been due to different scanning strategies employed between subjects or between tasks. It is possible that in experiments which monitor eye movements, a correlation could be found between subjects mainly scanning the medial part of laterally presented lines and indicating the lateral part as shorter, and others who mainly scan the lateral part and indicate the medial part as shorter. This would further substantiate the assumption that perception of relative size is subject to systematic distortion as a function of selective attention within the visual field. An experiment like this could also solve another problem: the provision of visual cues in all the experiments was *assumed* to draw attention to that part of the line. It is of course possible that adding a visual cue to the end of the line alters its physical appearance and shifts the perceptual point of balance of the figure in the direction of the cue. However, if perceptual overestimation could be achieved by simply asking subjects to scan one end of a line longer than the other, objections like this would no longer be valid. On the other hand providing an auditory rather than a visual cue should also address this problem and is probably an easier (and cheaper) task than monitoring eye movements.

Referring back to the patients with neglect, it seems that hardly anybody would argue nowadays that unilateral spatial neglect is a unitary deficit: too many dissociations have by now been demonstrated (Baxter and Warrington, 1983; Costello and Warrington, 1987; Bisiach *et al.*, 1986; Mark *et al.*, 1988; Halligan *et al.*, 1989, etc) and in a recent paper, Halligan and Marshall (1992) go as far as arguing that the concept of visuospatial neglect is a meaningless entity. However the experiments presented here and also a number of independent studies recently performed (Coslett *et al.*, 1990; Bisiach *et al.*, 1990; Tegner and Levander, 1991a; Liu *et al.*, 1992, Bottini *et al.*, 1992) suggest that a useful classification can be made between neglect patients showing mainly symptoms of directional hypokinesia and others experiencing perceptual difficulties. It also seems that the landmark test is by far the simplest means for classifying patients in either one of these groups, or even identifying patients who show a combination of motor and perceptual deficits. No complicated manipulandum devices or mirror images are necessary. It would be desirable to quantify the landmark test on a large sample of neglect patients and subsequently incorporate it in routine neuropsychological testing. It is no more difficult to apply than the line bisection test, but in association with it gives far more insight into the disorder involved. It is also possible that routine testing with the landmark task might indirectly confirm Mesulam's theory: patients with lesions involving the frontal lobes should demonstrate mainly rightward (motor) resonses, whereas patients with lesions involving the parietal lobes should show leftward (perceptual) responses. Finally, it would be interesting to study whether only 'perceptual' neglect patients show leftward bisection errors for very short lines and patients with symptoms of directional hypokinesia do not, as the results of the present studies indicate.

Implications of the visuomotor studies

The second part of the thesis (chapters four to seven) was designed to investigate any possible contribution the right hemisphere might make to visuomotor control. Various studies have indicated that this hemisphere is important for localizing stimuli in space (Kimura, 1969; Fisk and Goodale, 1988). Moreover, the findings of Goodale *et al.* (1990) suggest a right hemisphere role in programming initial heading direction in visual reaching in general, and a more specific role in feedback correction when the reaching task is performed in a spatially demanding context. So the experiments of both chapter four and chapter five were designed to detect possible visuospatial influences on hand asymmetries during reaches in normal subjects. With the experiment presented in chapter 6 an attempt was made to investigate the involvement of the two hemispheres more directly, by testing right and left hemisphere damaged patients and by choosing tasks that should presumably affect the performance of these two groups differently. Presenting the spatial 'bisection' task in the presence of visual feedback was assumed to increase the complexity of visual feedback processing, as the finger's position has to be compared on-line to two as opposed to a single stimulus as the finger approaches the target. According to the findings of various investigators on normal subjects (Flowers, 1975; Roy, 1983; Todor and Cisneros, 1985) and those of Goodale and co-workers on brain lesioned subjects (Goodale, 1989; Fisk and Goodale, 1988) one might therefore expect an impairment in patients with left hemisphere lesions during closed loop performance (i.e. with the hand visible). The efficiency of these patients in error correction and/or sequential processing of the movement should be affected.

On the other hand, the results of the Goodale *et al.* (1990) study suggest that this effect might be outweighed by visuospatial demands that would tend to increase right hemisphere participation. This should be particularly apparent under open loop conditions, where no visual information on hand/target discrepancy is available (cf. Guiard *et al.*, 1983). Consequently while the bisection task might maximize the expected impairment in left hemisphere damaged patients during closed loop reaching, it should also exaggerate the expected impairment of right hemisphere damaged patients during open loop reaching. Moreover, locating stimuli in the left half of egocentric space as opposed to central and right space, might maximize the possibility of detecting right-hemisphere influences on reaching (Heilman *et al.*, 1987).

Accuracy of reaching. Surprisingly, for both experiments on normal subjects (Experiments 9 and 10), no hand differences in terminal accuracy were in fact found, nor were there any significant interactions of hand with visual feedback or task. This outcome was rather unexpected as various investigators have repeatedly demonstrated a right hand advantage for visually guided reaching (Flowers, 1975; Roy, 1983; Fisk and Goodale, 1985; Carey and Goodale, 1989). It is, however, possible that the bisection task was too spatially complex to allow a right hand accuracy advantage to appear in closed loop performance, whereas on the other hand, the increased visuospatial demands of this task, which should have favoured right hemisphere participation, were simply not big enough to produce the expected left hand effect (see also Carson and Goodman, 1992). However this explanation cannot be applied to the pointing task which, when performed under visual guidance, should have produced right hand advantages similar to those found in traditional aiming tasks (Fisk and Goodale, 1985; Roy, 1983; Watson and Kimura, 1989). A possible interpretation might be that the hand asymmetry found by others is a small or unstable effect.

The lack of a *left* hand advantage in terminal accuracy in the absence of visual feedback, disagrees with the findings of Guiard *et al.* (1983), but other recent experiments have also failed to find hand differences in terminal accuracy in either open or closed loop pointing tasks (Haarland and Harrington, 1989; Carson *et al.*, 1990; 1992). It seems possible, however, that in Experiment 9, the failure to find clear asymmetries in final error was partly due to the fact that the stimuli were visible throughout the movement. This allowed unrestricted target feedback which might have counteracted any initial facilitatory effect the right hemisphere might have had. And indeed in Experiment 10, where target feedback was restricted, terminal errors with the right hand proved larger than errors with the left hand when visual feedback of the reaching hand was not available. Unfortunately this trend proved not significant. However in Experiment 10, right hand reaches also showed greater route variability than left hand reaches when movements were executed in the absence of visual feedback. This finding suggests that the left hemisphere is more dependent on visual information than the right hemisphere, and as none of these effects were found in Experiment 9, it is very likely that restricted target duration is indeed crucial in order to produce a right hemisphere advantage. Secondly, although variable error is generally attributed to errors of movement execution rather than of movement programming (Prablanc *et al.*, 1986; Schmidt *et al.*, 1978), Bracewell *et al.* (1990) argue that it is probable that the initial process of localizing targets is, in itself, not entirely accurate. This variability may add to that in the motor motor system which would indicate that variable error, as well as constant error, may be regarded as a measure of motor programming. So the findings on variable error could be interpreted as a right hemisphere advantage for *visuomotor localization* in the absence of visual feedback from the hand. Bracewell *et al.* (1987; 1990), who demonstrated a left hemifield advantage in the accuracy of directing saccadic eye movements, also interpret their results as a right hemisphere advantage for *visuomotor localization*. On the other hand, they also point out that the right hemisphere might simply be better for *remembering* the spatial location of visual targets.

It cannot be ignored that there was a slight memory component in the tasks employed in Experiment 10, as targets disappeared after movement onset. Consequently there is the possibility that the right hemisphere has a special role in memory for spatial locations of visual targets (see also Bracewell *et al.*, 1987; 1990), especially as there is also evidence to suggest that spatial aspects of memory may be preferentially lateralized to the right hemisphere (Milner and Taylor, 1972; De Renzi, 1982). Nevertheless it should be noted that, in Experiment 10, the time between target offset and termination of the reach was very short in memory terms (overall mean 430msec).

Finally, the strongest argument for a right hemisphere involvement in visuomotor localization comes from the finding that patients with right hemisphere damage showed an impairment in terminal accuracy when reaching was performed in the absence of visual feedback of the hand, but constant target feedback (Experiment 11). This was not true of the left hemisphere damaged patients, who were unimpaired. Analysis of subsets of the two patient groups who were able to use either hand showed that these asymmetrical effects of lesions were present regardless of the hand used in reaching. However under closed loop conditions, no significant deficit in accuracy was found in either patient group. These findings indicate a strong right hemisphere role in the visuomotor guidance of open loop reaching, whilst the left hemisphere's contribution to terminal accuracy in such tasks is minimal. The data are thus in agreement with Guiard *et al.* (1983). Nonetheless no group differences in the variability of reaching performance were found, a finding which is at variance with the results of Bracewell *et al.* (1990) and the data reported in Experiment 10 (smaller variable errors for the left hand in open loop under short stimulus presentation). It may be that the right hemisphere has a more fine-grained coding of retinal location than the left (cf. Kimura, 1969; Levy and Reid, 1976; 1978) which favours eye and hand movements to *brief* targets in the left hemifield. (In Experiment 10 variance was lowest for stimuli in left hemispace. Nevertheless this was difficult to interpret as it was apparent in the four way interaction of loop x hand x presentation x location only.) This asymmetry may not extend to the visuomotor localization of longer-duration targets.

The major result was that the RCVA patients erred systematically to the right of the true target over all three spatial positions in open loop. In contrast, under closed loop conditions, the errors were made to the left in left and central space and to the right in right space. Indeed, such 'overshoot' errors with respect to stimuli located laterally in space were found in both normal and LCVA patients, whether tested in open or closed loop conditions. This result is in full agreement with Experiments 9 and 10 where overshoot errors were also consistently reported. Also comparable to Experiments 9 and 10, these overshoot errors were again associated with outwardly curving reach trajectories. It seems plausible to interpret the greater part of the overshoot errors in terms of a range effect (Brown *et al.*, 1948; Slack, 1953; Poulton, 1980): subjects tend to overshoot proximal targets and to undershoot distal ones. So in Experiments 9 and 11, where target distance from the midline of the display was rather short (15cm), overshoots would be expected, and the fact that these overshoots are exacerbated under open loop conditions is in accordance with previous findings (Prablanc *et al.*, 1979). However range effects provide a redescription rather than an explanation and, as shown in Experiment 10, overshoots in normal subjects remain when targets are located with greater eccentricity (25cm). Although a full explanation of this phenomeneon may ultimately be found in a consideration of the mechanics of the arm movement and/or in the optimization of late visual feedback that the curvature may provide, it is an interesting suggestion that the 'overshoot' responses may be attributable to a tendency for subjects to respond more strongly in the direction contralateral to the more activated hemisphere. Lateralized visual input should produce an activation imbalance in favour of the hemisphere that is stimulated directly (Reuter-Lorenz *et al.*, 1990; Kaplan *et al.*, 1991). Therefore presenting a stimulus in right (or left) space should produce a *greater* activation of the contralateral hemisphere and a concomitant orienting shift to the stimulated side of space. In the present experiments this could have resulted in an increased lateral response ('overshoot'). In the same vein it could be argued that the larger overshoot errors in open loop might have been due to a greater salience of the stimulus in that condition, thus resulting in an even greater lateral response due to a more activated hemisphere. Supposing this view was correct, it could be assumed that when the left hemisphere is damaged, it should be less activated than the intact hemisphere and should therefore produce less exaggeration of the sideward vector. Although not significant this was indeed the case: LCVA patients produced larger overshoot errors in left than right space and also showed less overshoot in right space when compared to the control group .

For the RCVA patients it seemed that, in open loop conditions, a rightward shift was superimposed on to the standard pattern of outward curvature. In other words, the errors of these patients seemed a result of (at least) 2 additive factors: a normal overshoot and a uniform rightward shift. Furthermore the bisection task caused no greater impairment of these patients than did the simple pointing task, irrespective of feedback condition. This is contrary to the findings of Goodale *et al.* (1990) whose right hemisphere damaged patients showed larger rightward terminal errors for bisection as opposed to pointing under closed loop reaching. The discrepancy might be explained by the fact that Goodale *et al.*'s patients had all shown neglect in the past, though this had recovered by the time of testing. Only 2 out of the 12 subjects of the present RCVA group were known to have ever shown symptoms of neglect. Unfortunately, however, an examination of the data of these two patients showed that neither of them gave large rightward errors in closed loop bisection.

The generalized rightward displacement observed under open loop reaching in the present study, then, seems not to be closely related to neglect. And indeed none of the patients showed any abnormality when subjected to a variety of line bisection and landmark tests (see chapter three and also Milner *et al.*, 1993). Furthermore, the rightward shift is no greater in the left than right half of space, while a larger effect in left space is generally found in neglect phenomena (Heilman and Valenstein, 1979; Milner *et al.*, 1992). It is therefore difficult to explain the data by any means other than by hypothesizing the operation of a 'directional hypokinesia' in rather pure form, in the RCVA patients (Heilman *et al.*, 1983). Presumably this would have free rein under conditions where no visual feedback on limb position is available. However, if this is correct why did the RCVA patients not show symptoms of directional hypokinesia in the landmark and bisection experiments in chapter three? Presumably the landmark and bisection tests are closed loop tasks, so no disorder of reaching would be expected as indeed no impairment was found in the visuomotor tasks in the presence of visual feedback of the hand. On the other hand, as all the six neglect patients tested in chapter three had right hemisphere damage it would be expected that they would also show a rightward bias when tested in open loop reaching.

In the presence of visual feedback, no deficit in reaching accuracy after left or right hemisphere lesions is seen, even in the visually-taxing bisection condition. This finding differs from the data of Fisk and Goodale (1988) who found that both left *and* right hemisphere lesioned patients were less accurate than the control group in their pointing movements. As already pointed out in chapter six, it is possible that the patient pool of Fisk and Goodale's study is not directly comparable to the patients presented here. Nonetheless, it is still surprising that both the data on normal subjects (Experiments 9 and 10) and on left hemisphere lesioned patients (Experiment 11) give little indication of a left hemisphere involvement in motor control, although other authors have reported such findings.

Latency of response. However, consistent with the findings of Fisk and Goodale (1985), right hand reaches proceeded with significantly quicker movement onset than left hand reaches in response to a long stimulus presentation in the closed loop condition in Experiment 10. Goodale and colleagues interpret this finding as reflecting a left hemisphere specialization for the integration of movements. The data of Experiment 10 suggest, however, that visual feedback is a crucial part of this integration, as the hand difference is no longer present under open loop conditions. In fact, in Experiment 9, a *left* hand latency advantage was found in the absence of visual feedback (see also Carson *et al.*, 1990). It is surprising that no right hand latency advantage for closed loop movements was found in Experiment 9, as the conditions were comparable to those under long stimulus presentation in Experiment 10. A possible explanation might be that the absence of a chin rest in Experiment 9 masked the left hemisphere advantage that might have been present otherwise.

Regarding the patient data (Experiment 11), prolonged reaction times were found in the RCVA group as compared with both the control group and the LCVA group. Furthermore RCVA patients proved to show particularly long latencies in reaching for targets on the left as compared with targets in centre or right space. This could indicate that a good part of the slowing in these patients might be due the directional hypokinesia hypothesized in the previous section: Heilman *et al.* (1985b) found delayed reaction times for movements towards left as opposed to right hemispace in six neglect patients and attributed this to directional hypokinesia. On the other hand, Fisk and Goodale (1988) who also found prolonged latencies in their RCVA patients, provide another plausible explanation: they argue that RCVA patients have difficulty determining the position of a target in extrapersonal space and thus require a greater period of time in which to access the neural systems responsible for programming a movement to that position. As further evidence for this interpretation Goodale (1989) points out that, in another experiment, these RCVA patients were only slightly slower than the control group, when an auditory stimulus to begin moving was provided and the movement was to a constant spatial location. The fact that none of the RCVA patients tested in Experiment 11 showed symptoms of hemispatial neglect also makes it more likely that the delay in initiating a reach was due to a deficit in visuospatial processing rather than to a general problem in motor activation. Pierrot-Deseilligny *et al.* (1991) also found that for saccades towards suddenly appearing targets, patients with damage to the right posterior parietal cortex demonstrated prolonged latencies bilaterally, whereas patients with left parietal damage showed increased latencies for saccades contralateral to the lesion only. Again these data could argue for a right hemisphere involvement in the determination of target position in extrapersonal space. Indeed Pierrot-Deseilligny and colleagues argue that their finding could be related to the perception of the lateral targets but they put other explanations forward as well.

Movement kinematics. The data of the normal subjects (Experiments 9 and 10) on latency and the kinematic measures of peak velocity, mean velocity and time to reach peak velocity, show consistently that reaches are more efficiently executed by each hand when operating in its ipsilateral as opposed to the contralateral hemispace. This is a consistent finding reported by a number of authors (Prablanc *et al.*, 1979; Fisk and Goodale, 1985; Carson *et al.*, 1990; Carey *et al.*, 1990). The latency differences between contralateral and ipsilateral reaches could be interpreted in terms of interhemispheric transmission time, as suggested by Fisk and Goodale (1985), in that if reaches were initiated and controlled by the hemisphere contralateral to the hand used, then ipsilateral movements would be programmed within the same hemisphere initially stimulated by target onset, whereas contralateral reaches would require that the information crosses to the opposite hemisphere. Therefore prolonged movement onset should be expected for contralateral reaches. The compatibility effects on the other temporal parameters however cannot be explained in such terms and explanations are difficult. Furthermore interhemispheric transmission times are generally found to be less than 20ms (Milner and Rugg, 1989). Carson and Goodman (1992) argue that there is electrophysiological data to suggest that the firing patterns of single neurons in the motor cortex are highly correlated with specific directions of movement (see also Georgopoulus *et al.*, 1982). Apparently the level of discharge is greatest for ipsilateral movements made forward into space and outward from the body. It may therefore be that spatially compatible movements are controlled by 'ready made' neural systems, while incompatible ones require special programming. It is striking that all brain lesioned subjects who could use both hands also showed strong hemispace-hand compatibility effects, with ipsilateral reaches attaining higher velocity than contralateral reaches. Again, these effects were present for both average and maximum speed, time to peak and, less consistently, for latency. As argued before they presumably reflect a more direct 'wiring' of ipsilateral visuomotor response systems, such that reaches are more efficiently executed by each hand when operating in its 'own' hemispace. However, the direct comparison of lesioned subgroups indicated also that both groups moved more slowly toward targets in their contralesional hemispace than toward ipsilesional space, using *either* arm. This deficit present in both CVA groups could have been due to a disordered visual guidance of the arm, as a result of damage to parieto-frontal systems for visuomotor control (Milner and Goodale, 1993). Certainly most of the patients tested had CT evidence for parietal and/or frontal infarcts.

Nonetheless, both patient groups proved slower in the execution of all reaches than the controls (on both average and maximum velocity), and this was true for both open and closed loop performance. Furthermore, no overall group difference in movement time was found between the two subgroups of LCVA and RCVA patients who were able to reach with either hand, and thus could be directly compared. However, additionally to the general slowing of arm movements in both patient groups, RCVA patients proved specifically impaired with respect to deceleration time in both open and closed loop reaching: they took considerably longer to terminate the movement than both the control group and the LCVA group when compared directly. However, they did not differ from the control group with regard to the time to reach peak velocity and tended to be faster on this measurement than the LCVA group when compared directly, although this last finding was not significant. These data are in direct contrast to those of Fisk and Goodale (1988), who demonstrated no impairment on any of the kinematic measures for their right hemisphere damaged subjects, while pointing under closed loop conditions. Nonetheless the results presented here indicate a right hemisphere impairment as the hand 'homes in' on the target, both in the presence and absence of visual feedback. It is during this portion of the trajectory that modifications normally occur on the basis of information by foveal and parafoveal vision (Goodale, 1988). If one accepts the assumption that RCVA patients have difficulty in determining target positions, it could be that this deficit might also have been present in the 'homing in' phase of the movement as well as in the initiation phase. Maybe the initial direction of the movement while accelerating was only of 'ball park' accuracy and lacked on-line control. Consequently modifications of the trajectory would need to occur during deceleration. It is possible that through use of visual guidance, target determination problems were overcome in the closed loop condition, in that reaches were modified during this final phase, thus leading to increased deceleration times but accurate target location. In contrast in the open loop condition, where the visuospatial deficit could not be compensated through use of visual feedback, it became apparent in both speed and accuracy measures. On the other hand, it is unlikely that LCVA patients were impaired with regard to target determination as their latency times were not increased when compared to the control group. Nonetheless they showed a marked disruption in the organization of their reaching movements which was not only apparent for the deceleration phase but throughout movement. Goodale (1988) has argued that the left hemisphere is crucial for *on-line error-corrections*, and timing and sequencing of visually guided aiming movements. This consequently leads to a left hemisphere involvement in the control of complex motor behaviour (Kimura, 1982) and coupling of eye and hand movements (Fisk and Goodale, 1985). If one accepts that left hemisphere damaged patients have deficits in the on-line control of simple movements, apraxic patients should demonstrate the same deficits. This was indeed suggested by Goodale (1989) '...although Kimura (1982) has argued that the deficit in apraxia is one of movement selection, it is possible that many of the complex sequences of postures that are used clinically to reveal apraxia may often require on-line monitoring and updating of the motor program as it unfolds...if one were to use more detailed kinematic analyses to....tests of apraxia , deficits might become apparent.' The findings of Harrington and Haarland (1992) might give some evidence for this: they tested 17 left hemisphere stroke patients and found that both the apraxic and the nonapraxic group were slower than the control group on the execution of *single* hand postures. However, even if one accepts that left hemisphere lesioned patients might be impaired in monitoring and updating motor programs, it is still not clear why the LCVA patients presented here showed a slowing of their movements throughout the reach, while Fisk and Goodale's patients (1988) were specifically impaired in the deceleration phase. Moreover, their right hemisphere lesioned patients were not impaired once the movement was initiated, whereas the RCVA patients tested here demonstrated a substantial increase in deceleration time.

Future considerations evolving from the reaching data

All the present reaching experiments were designed to demonstrate any possible contribution the right hemisphere might make to visuomotor control, but the data on normal subjects gave little indication of a specific right hemisphere involvement in such tasks. Neither use of a spatial bisection task, nor absence of visual feedback of the moving hand or arm seemed to produce left hand advantages on the dependent measures. On the other hand, RCVA patients proved impaired in their reaching behaviour in the absence of visual feedback, thus suggesting a right hemisphere involvement in motor control. Some indications for such an involvement were also given by the finding of a smaller terminal variability for the left than the right hand in the absence of visual feedback, in one of the experiments on normal subjects. Carson and Goodman (1992) point out that, although the spatial component inherent in target aiming leads to a prediction of left hand advantage, empirical support remains meagre. Somewhat earlier Carson (1989) argued that a task which has a large spatial component, may nevertheless be performed by the preferred right hand because of other task constraints such as the need for fine endpoint accuracy or manipulation. Consequently, reaching movements which have a high spatial component are nonetheless mainly accomplished by the preferred right hand. He claims that in infants on the other hand, reaches are more often performed by the left hand and that this characteristic is exhibited prior to the acquisition of the facility for fine manipulative skills (de Schonen and Bresson, 1984; Gesell and Ames, 1947; Seth, 1973, cited by Carson, 1989). So in an attempt to elucidate the contribution of the right hemisphere to the regulation of movement, the challenge is to achieve adequate independent manipulation of spatial complexity. This challenge was obviously not met with the tasks presented here, but it should be noted that other authors have also failed to create tasks which elicit left hand/right hemisphere advantages explicitly (Carson et al., 1990; Carson and Goodman, 1992).

On the other hand, the task was sensitive enough to demonstate deficits in patients with right hemisphere lesions. All RCVA subjects proved impaired on latency, kinematics and accuracy, especially in the absence of visual feeedback of the hand, whereas the LCVA patients showed a slowing with respect to the kinematic measurements only. Although most of these findings agree with Fisk and Goodale's data (1988) they differ in so far as the RCVA patients presented here showed substantially prolonged deceleration times over all conditions, whereas Fisk and Goodale's patients did not differ from the controls on this measurement. Although explanations for this might be found in the different patient populations used, it seems that further research needs to be done to clarify this point as the implications are crucial for the interpretation of left and right hemisphere involvement in motor control.

Finally, although it was proposed that the rightward displacement observed in the right hemisphere damaged patients in the absence of visual feedback was due to a directional hypokinesia, this interpretation is not unequivocal. The visuomotor bisection task, unlike the landmark test, did not explicitly distinguish between hypokinesia and perceptual/attentional factors. And although none of these patients showed symptoms of spatial misperception in the experiments carried out in chapter three, it is not impossible that these might have been present in the reaching task. However, it is more plausible to assume that such factors would have produced phenomena such as extinction or at least a larger rightward deviation in left than central or right space. It would be ideal to create a visuomotor task which sets these two factors in mutual opposition.

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APPENDIX

<u>Numerical values of the kinematic measurements in Experiment 9</u>

	Left Hand/Left Space	Left Hd/Right Space	Right Hd/Left Space	Right Hd/Right Space
Pointing				
Mean Velocity (m/s)	0.82	0.73	0.72	0.80
Maximum Velocity (m/s)	1.49	1.31	1.30	1.46
Time to Peak Velocity (ms)	143	195	198	145
Deceleration Time (ms)	266	258	259	274
Bisection				
Mean Velocity (m/s)	0.79	0.71	0.71	0.77
Maximum Velocity (m/s)	1.45	1.31	1.28	1.47
Time to Peak Velocity (ms)	159	211	199	152
Deceleration Time (ms)	272	259	277	298

Numerical values of the kinematic measurements in Experiment 10

	Far Left Space	Midleft Space	Midright Space	Far Right Space
Left Hand				
Mean Velocity (m/s)	1.01	0.84	0.71	0.78
Maximum Velocity (m/s)	1.92	1.49	1.12	1.27
Time to Peak Velocity (ms)	138	135	172	182
Deceleration Time (ms)	263	251	255	291
Right Hand				
Mean Velocity (m/s)	0.80	0.71	0.82	0.98
Maximum Velocity (m/s)	1.26	1.09	1.56	1.94
Time to Peak Velocity (ms)	186	164	125	140
Deceleration Time (ms)	283	263	268	272

Numerical values of the kinematic measurements in Experiment 11

	RCVA Patients			*Controls*		
	Left Space	Centre	Right Space	Left Space	Centre	Right Space
Latency	679	568	538	405	390	393
Mean Velocity (m/s)	0.42	0.44	0.50	0.55	0.51	0.63
Maximum Velocity (m/s)	0.81	0.78	1.06	0.99	0.90	1.21
Time to Peak Velocity (ms)	231	185	175	173	154	141
Deceleration Time (ms)	543	463	480	374	333	342

	LCVA Patients			*Controls*		
	Left Space	Centre	Right Space	Left Space	Centre	Right Space
Latency	430	445	472	408	396	412
Mean Velocity (m/s)	0.52	0.42	0.44	0.61	0.49	0.53
Maximum Velocity (m/s)	1.03	0.77	0.83	1.17	0.85	0.95
Time to Peak Velocity (ms)	198	228	254	155	166	187
Deceleration Time (ms)	432	389	436	351	338	374