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Sensorimotor integration in the control of goal-directed hand action

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SENSORIMOTOR INTEGRATION IN THE CONTROL OF GOAL-DIRECTED HAND ACTION.

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Abstract

This thesis examines the integration of visual and somatosensory information in the planning and execution of goal-directed hand action by having subjects point, with or without vision, to targets that can be defined either by visual or by proprioceptive cues. The first experimental chapter examines the performance of healthy control subjects while subsequent chapters study patients with impairments to either the visual or somatosensory systems. Other chapters use prismatic displacement to distort the visual input of healthy normal subjects.

The study using patients with neglect reveals that the curvature of their reaches is abnormal only when visual cues are available and the conclusion is drawn that in these patients the basis of their neglect must be visual rather than spatial. In the cases of patients with somatosensory impairments performance was almost always improved by having visual cues available, despite the fact that these cues could not signal the location of the proprioceptively-defined target directly. The final chapter, a case study of a single patient with unilateral somatosensory impairment, reveals that being able to see the area of workspace immediately adjacent to the proprioceptively-defined target significantly improves proprioceptive localization of that target.

In all cases, and in particular after prism adaptation, performance varies according to whether visual and/or proprioceptive cues are available and a case is argued for a change in the frame of reference that is used to plan reaches under visual or proprioceptive conditions. In addition it is suggested that when planning a reach, information from each system is weighted according to the goodness of its source.

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Chapter One

1. An introduction to sensorimotor transformations with respect to reaching.

1.1 What is reaching and why is something so easy to do so difficult to understand?

Reaching out to touch something is a common everyday occurrence and most of us perform some form of reaching task several times a day. The definition of "reaching", in this sense, is to make a motion or effort to touch, get hold of, or attain something. This broad definition can include a multitude of functions, such as switching on a light, indicating a location or performing some other function, such as scratching, pressing or stroking. None of us normally have any problems in carrying out such tasks and can often do so without paying much attention to what we are actually doing. As will be outlined in this chapter, the sensorimotor transformations which must take place before we can perform an accurate reach are extremely complicated and, as yet, not fully understood. The neural basis and the underlying mechanisms which integrate visual information from the eyes and proprioceptive information from the body, necessary for the planning and control of reaching behaviour, are major issues within the field of human motor control.

In order to perform a reach we first need to know the whereabouts of the target (the object with which we wish to interact) in relation to our body so that the second part of the process, making a movement, or reach, towards the target, can be planned and then executed. We can use our eyes to look at, or fixate, the target, but the eye is mobile in the eye socket (also known as the orbit), the head is mobile on the trunk and the trunk is mobile about the hips and we can twist and turn our bodies without losing sight of an object. Thus, a seemingly infinite number of body/eye positions can indicate the same position of an object in space. (The term "space", for the purposes of this work, refers solely to the area immediately around the body into which the arm can be moved without locomotion of the whole body (also known as peripersonal space)). To this equation we need to add the problems concerning the location of the hand in space. This problem will be explained more fully later in this chapter, but simply put: because the hand can be moved about the wrist, and the forearm about the elbow, and the upper arm about the shoulder, the same hand position can be achieved by numerous different arm configurations.

The position of the target and the position of the hand are largely signalled by different systems (visual and proprioceptive) and the information from these separate systems must be put together in such a way that the hand can be moved to the target. This is the problem of sensorimotor transformation and the focus of this chapter will be to review some of the research into how visual and proprioceptive cues are brought together in order to formulate an accurate goal-directed motor plan.

1.2 The role of retinal inputs

In order to reach for a target we must know where that target is in relation to our own body. For visually-guided reaches the first source of sensory information is that provided by the retina as light reflected from the target reaches the photo-receptors at the back of the eye. Potential targets are localized more accurately if they are foveated (looked at directly). Due to the gradient of visual acuity away from the fovea, the accuracy of retinal information encoding a target location degrades the further into the periphery the target lies. This phenomena was aptly demonstrated in an experiment carried out by Bock (1993) who asked human subjects to point, without vision of the hand, to luminous discs presented stereoscopically at different distances, eccentricities and meridians with respect to the subjects' straight-ahead. The eccentricity (i.e. amplitude) of pointing errors to peripheral targets were greater when subjects fixated straight ahead (and the target fell in the periphery) than when they looked directly at the targets. Bock suggested that the eccentricity of targets in the peripheral visual field is overestimated (i.e. they appear to be further away from the fovea than they actually are) and that this overestimation is not proportionate to the amount of eccentricity as the effect diminishes the further from the fovea the target lies. A similar experiment was performed by Henriques and Crawford (2000) who noted that results in the Bock (1993) experiment may have been confounded because each of the targets was in a different spatial location requiring a different motor response. Henriques and Crawford (2000) always kept the target (and therefore the motor response) in the same place, but required the subjects to look in different directions so that the target's image fell on different parts of the retina. They too found that subjects tended to overestimate target eccentricity, but Henriques and Crawford (2000) argued that the systematic distortion of end-point errors that subjects exhibited was not totally independent and may have varied dependent upon the direction of gaze.

Even if retinal information were extremely accurate, it would not be enough, on its own, to pinpoint the location of a target in space with respect to the body. The retina can only provide information by way of signals which correspond to the angle between the target and the line of sight and as such gives null information about the targets actual location. Because the eye is mobile in the orbit, and the head mobile on the trunk, we are able to orient our eyes and bodies in such way that we can foveate any target in any number of ways. Thus, a given point in space may be encoded by many different retinal inputs and a given retinal input can encode an infinite number of points in space.

1.3 The role of eye position signals

Leaving aside for a moment the orientation of the head on the trunk, in order to localize a point in space we need to know the position of the eye in its orbit. Hallett and Lightstone (1976) showed that the saccadic system uses more than retinal information alone when determining the location of a visual target. In this study subjects had to make saccadic eye movements to follow a visual target across two locations. The target was presented (flashed) at two locations in rapid succession in such a way that the second target had disappeared before the saccade to the first location had been completed. If only retinal information was being used then the error in the end-point of the second saccade would have been equivalent to the disparity between the initial eye position and the retinal signal indicating the first target. This did not happen, however, and the second saccades landed close to the second target location indicating that the change in eye position during the first saccade must have been monitored and used to encode the location of the second target flash.

Eye position seems to be relatively coarsely coded by extraretinal signals as this experiment by Bock in 1986 indicates: Subjects were asked to point in the direction that their eyes were facing (i.e. point to where they were looking) without visual feedback from the pointing limb. Although they were accurate overall, the scatter of their pointing errors was characterized by a substantial inter- and intra-subject variability, highlighting the limitations of accurate target localization by extraretinal signals alone.

In 1995 Blouin et al. demonstrated that the acuity of extraretinal signals is improved if they are concomitant with retinal stimulation. In a perception study, designed to examine the contribution of retinal and extraretinal signals to the coding of eye position in the head, subjects made voluntary horizontal saccades in the dark from a central fixation point, returned their gaze to that fixation point and then positioned a laser spot at the location they thought they had made their saccades to. For some trials the retina was stimulated by a 200 ms laser flash <u>before</u> the subjects returned their gaze to the starting location. Perception of gaze direction was improved (in terms of the correlation of eye position with constant end-point error) in the condition when both retinal and extraretinal signals were available. Further evidence that retinal information serves to accurately define gaze angle comes from a Prablanc et al. study in 1986. In this study subjects pointed in the dark so that visual information about the reaching limb was not available. Peripheral targets were defined visually. In one condition the target remained illuminated for 2 seconds, long enough to complete the orienting saccade and pointing movement, whereas in another condition the target disappeared 120 ms after completion of the orienting saccade, but before the manual response could be completed. Pointing accuracy was reduced considerably (by three times) when retinal information about the target location was available during the manual response. This indicates that the internal representation of the target/goal which drives the hand can be updated on-line and that this internal representation requires a permanent retinal input in order for it to optimally updated.

It can be seen from the above studies that the acuity of eye position signals is relatively poor without concomitant information from the retina and also that retinal signals contribute more to target localization than would be expected given that foveal signals themselves define null information about the location of a target.

1.4 What is the nature of extraretinal eye position signals?

How does the central nervous system (CNS) know the position of the eye in its orbit? Early studies suggest that proprioceptive afferents (incoming nerve signals) do not play a major role in eye position sense. Passive movements of the eye, for example, do not give rise to conscious perception of eye displacement (Brindley and Merton, 1960). That is not to say that proprioceptive afferents do not contribute to the localization of objects in space as Gauthier et al. demonstrated in 1990. Subjects who viewed targets monocularly while the other (covered) eye was passively rotated in its orbit (i.e. without an efferent motor command) mislocalized those targets, by pointing, in the direction of the rotation of the covered eye.

Ocular efferent signals (signals sent from the CNS to the voluntary eye muscles), on the other hand, have been shown to play a larger role in coding eye position sense. The perceived location of a fixated target can be altered by pressing on one eye while the other eye remains covered. Pressing on the eye increases the effort required to maintain fixation, bringing about a change in the related efferent signals (Stark and Bridgeman (1983); Bridgeman (1986); Bridgeman and Stark (1991)). Furthermore, there is good evidence for the existence of a non-sensory eye position signal. In the absence of proprioceptive input, monkeys with deafferented eyes can compensate for electrically induced ocular perturbations (Guthrie et al., 1983). The CNS of the monkey is also able to compensate for electrically induced ocular perturbations when performing double-step saccadic responses in the absence of visual feedback (i.e. in the dark) (Mays and Sparks, 1980). Recordings of single neurons in the cortex of the inferior parietal lobule in primates showed that the visual sensitivity of the retinotopic receptive fields changes systematically with the angle of gaze. According to Andersen et al., (1985) the activity of many of the neurons in this area can be described by the product of a gain factor that is a function of the position of the eye and the response profile of the visual receptive field and that this produces a tuning for locations, relative to the position of the head, that is dependent upon eye position.

1.5 The role of head position

Because the eyes are located in the head and the head can be moved independently of the trunk, the transformation of an extrinsic target location into a coordinate system based around the body must take into account information about head position as well as eye position and retinal signals. The mechanisms responsible for encoding head position have not been as well investigated as those for eye position coding. What is known, however, is that afferent proprioceptive input is crucial for providing accurate head-to-trunk information. Pointing errors to visual targets can be induced by the injection of local anaesthetics to the neck, removing proprioceptive neck afferents (De Jong et al., 1977). Vibration applied to the neck muscles (which induces the sensation of head movement) also produces impaired reaching as well as creating the sensation of movement in a fixated visual target (Roll et al., 1991; Taylor and McCloskey, 1988; Karnath et al., 1994). It is generally thought that vestibular input (from the cavity in the middle ear) contributes to proprioceptive information by sensing the position of the head relative to the trunk. Evidence for this is that the perception of passive movements of the head relative to the stationary trunk have been found to be better than passive trunk movements relative to the stationary head (Taylor and McCloskey, 1988; Mergner et al., 1991).

1.6 Are all target positions encoded equally?

The central part of the retina achieves the most detailed sampling of the visual scene and just as the optimal position for target localization is in the central visual field (Prablanc et al., 1979; Bock, 1993; Bock, 1986) so there are optimal positions/angles for the head and eyes. Target localization degrades the further target presentation is from the central retina, the normal eye resting position and the normal head resting position (Biguer et al. 1984). Biguer et al. tested healthy normal subjects pointing to visual targets without visual feedback of the moving hand. The head was either fixed or free to move during pointing. They found that pointing errors were reduced in the head-free condition and that the reduction in errors was greatest for the more eccentric targets. In the head-free condition the head was displaced towards the target by no more than 2/3 of the distance. Accuracy was not affected by the amplitude of the head movement. They concluded that coordinated head and eye movements could improve the encoding of target position. Vanden Abeele et al. (1993) hypothesized that changes in reaching performance, from those which do not allow coordinated eye and arm movements to those which do, may be due to a change in the frame of reference used to encode reaches from an oculocentric reference frame to one which is head-centred. Theories concerning frames of reference will be covered later on in this chapter.

1.7 The role of initial hand position

When planning a goal-directed reaching movement, localizing the target in relation to the body is only part of the task. In order to effectively plan an action towards that target it is thought that the CNS must also know the position of the hand (as well as the configuration of the limb) relative to the target before movement initiation. But, if the CNS knows the location of the target in relation to the body, then does it really need to know where the hand is prior to movement? Can the CNS not simply move the hand, wherever it is, to that point in space? Prima face, it would seem that it should not be possible to plan a movement from A (the initial position of the hand) to B (the target) without first knowing where A was. There is evidence, however, to suggest that this may, in fact, be the case. Polit and Bizzi (1979), for example, showed that monkeys deprived of proprioception can still point accurately. They trained three monkeys to point, without vision of the limb, to visually-defined targets (17 light emitting diodes arranged at 5 degree spacings). Pointing movements consisted of horizontal rotations about the forearm, as the upper arm and body were fixed. Accuracy constraints were to point to within 15 degrees of the target LED. Performance was tested before and after bilateral dorsal rhizotomy (surgical interruption of a spinal or cranial nerve root) of the arm territory (C2-T3). After training, the forearm was unexpectedly displaced 150-200 ms before movement. Even with this displacement, the monkeys still accurately attained the target posture both before and after rhizotomy. Polit and Bizzi concluded from this that what is controlled in monkey arm movements is an equilibrium point which results from the interaction of agonist and antagonist muscles so when the equilibrium point is changed, this results in a movement to the new equilibrium point posture. However, if the deafferented monkey's body posture was changed in relation to the arm they missed the target, something they didn't do when intact. One of the major functions of afferent feedback therefore, they argued, is in the adaptive modifications of a learned motor programme. Further evidence for the equilibrium point hypothesis was provided by Bizzi et al. in 1991 and Giszter et al. in 1993 who demonstrated that excitation of certain nerves in the frog spinal cord induced leg movements to particular locations in the workspace, regardless of where the leg was positioned prior to excitation.

There is a considerable body of experimental and neuropsychological evidence, however, that argues that in order for a reach to be programmed accurately and efficiently the CNS does need to know the initial configuration of the upper limb and the initial position of the hand. This evidence will be discussed below in relation to the needs for vision and proprioception (knowledge about the position/orientation of parts of the body). Whereas with a visual target there is only one source of sensory information available about the target location (vision), this is not the case for localising the hand. With the hand we can both see where it is and feel where it is (by proprioception). The mechanisms responsible for this may be different depending on whether the limb is stationary or moving. Throughout this work the term "proprioception" will refer to knowledge of the limb position, independent of visual cues, when either stationary or moving.

1.8 The need for proprioception

Evidence that accurate proprioception of the initial limb configuration is required for accurate reaching can be found in an experiment performed by Larish et al. in 1984. They asked healthy subjects to accurately reproduce arm flexion movements while tendon and muscle vibration was applied to the lower 1/3 of the biceps muscle.

Vibration produced increased movement reproduction error, relative to control conditions, demonstrating that accurate knowledge about the initial limb conditions is a necessary component in positioning a limb. Another method of examining the role of proprioception is to study patient groups who have little or no proprioceptive information available to them. The majority of reaching studies involving deafferented humans have focused upon motor deficits brought about by the loss of proprioceptive feedback for the on-line control of movement, rather than as a result of the loss of knowledge regarding the initial limb position. These studies have, however, highlighted the fact that severe motor impairments in deafferented humans indicate a reliance upon proprioceptive afferents for normal movement. Rothwell et al. (1982), for example, reported the motor performance of a patient deafferented by a severe peripheral sensory neuropathy. Without the aid of vision, this man was unable to sustain constant levels of muscle contraction, nor could he maintain long sequences of simple motor programmes, suggesting that knowledge of hand and limb configuration (by proprioception) is necessary to be able to perform such tasks. Jeannerod et al., 1984 reported a patient with hemianaethsesia, following a parietal lesion, who could only perform prehension tasks poorly in the absence of visual feedback.

In 1985, Sanes et al. described a series of patients with large-fibre sensory neuropathies. This is a rare condition in which there is degeneration of large afferent fibres, notably those conveying proprioceptive information, with little or no effect on motor fibres. It is associated with impaired position, vibration and cutaneous sensation and the absence of deep tendon reflexes. Whereas muscular strength was normal in these patients, postural maintenance and movement accuracy (of wrist movements) were heavily dependent on visual guidance. The spatial paths of movement and end-point errors were abnormal. The defects were reflected in the inability to maintain constant levels of muscle activity. Sanes et al. (1985) concluded that whereas central motor commands were sufficient to initiate movement, proprioceptive afferents were important for the accurate maintenance of posture and the fine on-line control of movement.

Further experimental studies have shown that patients without proprioception who are allowed to view their static hand prior to movement point more accurately than if they are not. Ghez et al. (1990), studied both healthy control subjects and patients with large-fibre sensory neuropathies on a multi-joint reaching task in which subjects moved a hand-held cursor across a two dimensional surface. The cursor and target locations were displayed on a computer screen so the subjects did not view them directly and visual information about both target and cursor could be systematically manipulated. Whereas normal subjects, without visual feedback, exhibited stereotypical, relatively straight and accurate movements, the patients were highly variable and inaccurate. Ghez et al. (1990) concluded that proprioceptive input, provided largely by the spindles and tendon organs in our muscles and joints, is necessary to provide the CNS with an accurate on-line internal representation of the mechanical properties of the limb. This representation is used in both motor planning and execution and without sensory input from the limbs, the motor programmes of deafferented patients fail to compensate for the natural anisotrophies in the inertial properties of the arm (that is, the limb requires different forces to move it the same distance in different directions). Vision of the limb, Ghez et al. (1990), surmised, helps improve accuracy, largely by enabling a feedforward compensation for the anisotrophies of limb inertia.

1.9 The role of vision

There is considerable experimental evidence to suggest that the optimal conditions for accurate reaching require that accurate visual information about the initial position of the hand is available. Prablanc et al. (1979) found that pointing accuracy was significantly improved when subjects were allowed to see their hand prior to movement onset (vision was removed as soon as the hand started to move) compared to when reaches were performed without any vision of the hand before and throughout the movement .

In 1994(b) Rossetti et al. tested the pointing accuracy of 6 normal human subjects who were instructed to point to targets upon the visual onset of those targets. Subjects could not see their hand during movement execution, but were allowed varying amounts of visual information about the initial position of the hand prior to movement onset. The three conditions Rossetti et al. (1994b) used were: **T** - vision of the target only (i.e. no vision of hand before movement onset); **H-T** - vision of hand before target onset, but not after target onset. In this case the hand and target were seen sequentially, but never simultaneously; **H+T** - the hand was visible until movement onset so that the hand and target were seen simultaneously only during the planning of the movement. Pointing variability was reduced when the hand could be seen prior to movement onset compared to when visual information about the initial position of the hand was never available (**T**), Viewing the hand and target simultaneously (**H+T**) further reduced pointing variability compared to the **H-T** condition in which the hand and target were not seen simultaneously. Furthermore, the deceleration phase of reaches was longest in the **H+T** condition, suggesting that the reduced variability in this condition may have been due to feedback about the position of the hand based on kinaesthetic reafference. Rossetti et al. (1994b) suggested that using visual information to better encode the initial position of the hand relative to the target allowed for a calibration of arm position sense which was then used to drive the hand towards the target during the deceleration phase of the movement. These findings were further investigated by Desmurget et al. in 1995. They looked at only the **T** and **H+T** conditions, but extended the study by turning off the target light during the deceleration phase (at the moment velocity reached half the peak velocity of the movement). This made no difference to the **T** condition, but accuracy was better in the **H+T** condition. This supports the theory that vision of the static hand enhances the proprioceptive localization of the limb and allows for a better visual-to-kinaesthetic feedback.

Viewing the static hand prior to movement, therefore, might improve performance by allowing better encoding of the initial state of the motor apparatus. An alternatively explanation, however, might be that the observed improvement in reaching accuracy may instead be due to simultaneously being able to see the hand AND the target during movement planning. That is, that when subjects see both the hand and target prior to movement onset these initial cues regarding the hand and target improve the motor programme by better identification of the initial and final states (Prablanc et al., 1979; Proteau and Marteniuk, 1993; Rossetti et al., 1994b). Simultaneous vision of the hand <u>and</u> target may require, or involve, different types of planning to those when only the target can be seen (Redding and Wallace, 1996; Rossetti et al., 1994b).

Recent experimental evidence has been put forward to show that the benefits of seeing the hand prior to movement does not depend solely on simultaneous vision of hand and target (Desmurget et al., 1997b). This particular experiment will be discussed at some length in later chapters. That there <u>are</u> benefits for seeing the hand and target simultaneously was aptly demonstrated by Redding and Wallace (1996) in an experiment which used visually displacing prismatic goggles. They showed that when the starting limb and target location could be seen simultaneously whilst wearing prisms, reaching performance was accurate. In addition, after the removal of the prisms there was an absence of misreaching aftereffects. On the other hand when the starting position of the limb could not be seen through the prisms, but the target could, reaches were initially inaccurate, accurate performance was slow to develop and aftereffects were strong. They concluded that if the hand and target cannot be seen simultaneously then the CNS cannot detect any misalignment of visual and proprioceptive cues. (Redding and Wallace, 1996).

Perturbation studies, such as that detailed above, can be crucial in trying to understand how sensorimotor transformations take place. As we have already seen, it is clear from experimental studies in normals that disallowing visual information of the initial position of the hand reduces reaching accuracy and it is also clear from the neuropsychological studies that vision improves performance when proprioceptive information about the position of the reaching hand is not available. What happens when both visual and proprioception are available, but one or the other is distorted or perturbed, providing a positional mismatch between the two senses? This topic will be more fully investigated in a later chapter, but briefly, the apparent displacement of the limb - either visually (by use of displacing prisms) or proprioceptively (induced by tendon vibration) - produces inaccurate reaches in the direction opposite to the apparent displacement, especially in the absence of veridical visual feedback (e.g. Welch, 1986; Larish et al., 1984; Rossetti et al., 1995). Such directional errors can give valuable insight into how visual and proprioceptive information must integrated so that a single motor plan can be formulated.

1.10 Sensorimotor integration and the frames of reference problem

Thus far we have discussed what is necessary for optimally accurate and efficient goal-directed movement planning, but this does not tell us how different information regarding the positions of the target, the eyes, the head and the hand are integrated so that they can be used to create a single motor command. Spatial information can come from more than one sensory system (e.g. vision or proprioception) and the reaching movement itself may require the coordination of multiple body-segments (e.g. eye, head, arm). Planning a reach to a target requires the localization of the target and the arm in 3D space and the translation of this information into a coordinate system appropriate for the intended motor command (Lacquaniti and Caminiti, 1998; Jeannerod, 1988; Lacquaniti, 1997). An added complication is that there is probably no unitary map of space in the brain. Each body part, (eye, head, shoulder, hand) as well as the target has its own space or coordinate system associated with it. For the reach to be planned, the relative positions of the target and all relevant body parts must be translated into a common coordinate system using one or more coordinate system as a reference frame into which the various coordinate systems are translated (Simpson and Graf, 1985; Lacquaniti, 1997; Knudsen and Brainard, 1995). Determining the final state of the various sensorimotor transformations which must take place before an action can be performed is sometimes referred to as the frames of reference problem.

One commonly employed method to indicate which frame of reference is being used is the analysis of spatial end-point errors in pointing tasks to identify differences in the precision between the neural channels that process spatial information. If spatial information (e.g. distance and direction) is processed independently in different channels in the brain, then random noise in one channel should be statistically different from random noise in another channel. If the noise in two channels are different then this will be revealed by anisotrophy (different amounts in different directions) in the distribution of the end-points. The direction of the maximum and minimum variance (long and short axis of the ellipse) corresponds to the spatial orientation of the underlying independent channels.

An excellent example of this procedure can be found in the work of Soechting and Flanders' group (Soechting and Flanders, 1989; Flanders and Soechting, 1990; Flanders et al., 1992) who, in a series of experiments, assessed the spatial end-point errors in pointing in normal subjects. Their analysis revealed that the observed errors were in the sensorimotor transformation rather than errors of perception. The error was most consistent when evaluated using a spherical coordinate system around the right shoulder (the pointing limb). Another fine example of this style of psychophysical analysis technique can be seen in Gordon et al. (1994a) who examined the variability of pointing on a horizontal digitising tablet in six normal subjects to see if the pattern of variable errors would reveal the nature and origin of the coordinate system in which the movements were planned. The target and cursor positions were displayed on a computer screen, vision of the hand and arm was blocked and the screen cursor was blanked during movement to prevent visual corrections. They found that the spatial distributions of movement end-points were elliptical in shape and that the major axes of these ellipses were systematically oriented in the direction of hand movement with respect to its initial position. Furthermore, variability along the axis of movement, representing extent variability, increased markedly but non-linearly with distance. Variability perpendicular to the direction of movement, which results from directional errors, was generally smaller than extent variability, but it increased in proportion to the extent of the movement.

They concluded from this that directional variability, in angular terms, was constant and independent of distance. Because the patterns of variability were similar for both slow and fast movements, as well as for movements involving different joints, they concluded that they result largely from errors in the planning process. They also argued that they cannot be simply explained as consequences of the inertial properties of the limb. Rather the data provided evidence for an organising mechanism that moved the limb along a straight path. They further concluded that reaching movements were planned in a hand-centred coordinate system, with direction and extent of hand movement as the planned parameters. Since the factors which influenced directional variability were independent of those that influence extent errors, they proposed that these two variables could be specified separately by the brain.

As can be seen from these two studies alone, the frame of reference used by the CNS may vary depending upon the task constraints and variously eye-, head-, shoulder-, hand-, and viewer-centred reference frames have been proposed for different pointing tasks (McIntyre et al. 1997; McIntyre et al 1998). In addition to there being a number of proposed end-state frames of reference there have also been a number of hypothesized transformation stages. For example, Vanden Abeele et al. (1993) suggested a transformation to the most stable body-centred reference frame whereas Andersen et al. (1993) proposed a more hierarchically-based transformation as did Carrozzo et al., (1999) who suggested that there is a gradual transformation from viewer-centred to body-/arm-centred coordinates with retinal, extraretinal and arm-related signals being progressively combined. Kowato and Wolpert (1998) suggest that the CNS may learn and store a number internal models for sensorimotor transformation. The aim of this work is not to test or discuss in detail the validity of these, or similar, models. The main purpose of this work will be to examine the end product of sensorimotor integration, regardless of the order of events of transformation, and to explore the possible mechanisms involved.

Chapter Two will outline the basic experimental procedure used throughout this work and will examine the performance of normal healthy individuals on a proprioceptive matching task which requires the integration of vision and proprioception. Later chapters will investigate how and why disorders and perturbations of either the proprioceptive or visual systems can affect performance on this task.

Chapter Two

2. Pointing performance on a visual and proprioceptive matching task in normal subjects

2.1 Introduction

In this, and subsequent chapters, we will investigate the integration of visual and proprioceptive information by making use of a proprioceptive matching paradigm in which the main aim of the task is to match the felt position of the index finger of one hand with the index finger of the other hand. Matching paradigms in this vein have been used previously, mainly as a methodology for studying the perceived position of the hand in space. In general (e.g., Wann (1991); Von Hofsten and Rosblad (1988); Haggard et al., (2000)), the three main experimental conditions employed have required subjects to match the finger of an unseen hand with: a) a target defined by vision alone, b) a target defined by vision AND proprioception (by placing the target finger where it could be seen) or c) a target defined by proprioception alone. Haggard et al. (2000), referred to these three conditions as **V:P**, **VP:P** and **P:P** respectively. The letters before the colons represent visual or proprioceptive information available about the target and the letters after the colons denote information available about the matching hand. This is the notation that will be used throughout this chapter when describing paradigms with equivalent conditions.

Von Hofsten and Rosblad (1988) tested 270 young children with ages ranging from 4 to 12 years. They recorded random, systematic and absolute end-point errors by measuring the position of pin-marks made by subjects placing a pin on the underside of a table (so there was no visual feedback about the reaching limb). The four conditions they used were the V:P, VP:P and P:P conditions (as described previously) and a visual memory condition. Overall they found that pointing performance was superior when visual information was available, especially in the VP:P condition. Von Hofsten and Rosblad (1988) tested subjects on their left and right hands and found that with both hands subjects tended to indicate the target position too far towards the contralateral side of the body (that is, the left hand indicated too far to the right and the right hand indicated too far to the left). Whether this effect varied according to target location (i.e. contralateral or ipsilateral) is not recorded.

That matching tasks can be useful in the examination of visuoproprioceptive integration is demonstrated by Wann's (1991) one-dimensional limb matching task. Designed to be understood by children with congenital Cerebral Palsy, this experiment used a simplified variation of the V:P, VP:P and P:P conditions. Normal adult subjects tested on this paradigm performed best (in terms of RMSE) in the VP:P condition, followed by V:P, then P:P - the same order of performance as found by Von Hofsten and Rosblad (1988). The CP students on the other hand found most difficulty with the V:P task. This condition, which involved matching the seen position of the target with the felt position of the unseen limb, is the only condition which requires the integration of visual and proprioceptive information whereas the VP:P and P:P (and a third condition - VP:VP, in which both limbs could be seen) could be performed simply by matching limb positions based on either purely visual information (VP:VP) or purely proprioceptive information (VP:P and P:P).

Both of the experiments described above showed the same pattern of results (i.e. VP:P < V:P < P:P). Thus, when two modalities specify the target location, performance is better than when only one modality specifies the target location These results provide good evidence that sensorimotor integration is taking place in these tasks. Another variation of the matching task, which also demonstrates that having both visual and proprioceptive information available about the target location facilitates performance on finger matching, was that reported by Plooy et al. in 1998. A target finger, either the participant's or the experimenter's was inserted through a hole in a specially constructed viewing box which allowed vision of the target finger, but not of the matching hand (Figure 2.1). The task was to position the finger of the unseen matching hand, on the outside of the viewing box, such that it was at the same distance as the perceived location of the target finger. Subjects viewed the target finger through 8-dioptre prisms, to create an illusion of greater visual depth, and performed four conditions: pointing to their own or the experimenter's finger respectively in normal lighting conditions or pointing in the dark to their own or the experimenter's finger to which was attached a light emitting diode. Clearly, when the target finger was the subject's own finger, proprioceptive as well as visual information was available whereas

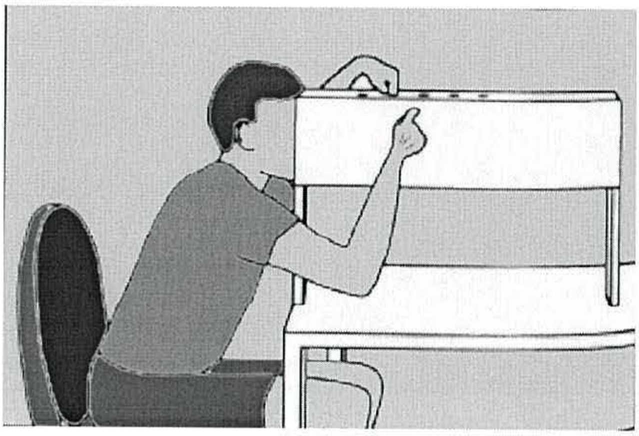

Figure 2.1: Experimental set-up used by Plooy et al., 1998.

when the target finger belonged to the experimenter, only visual information about the target was present. Participants were allowed as long as they felt necessary, with as many readjustments as they required, to accurately position their matching finger. The main purpose of this study was to determine whether a perceived increased vergence-specified distance, induced by the prisms, would be negated by the inclusion of veridical proprioceptive information about target distance. The findings specific to the purpose of the study will be discussed in greater depth in a later chapter where they will be seen to be of more relevance. For the purpose of this chapter it is more pertinent to describe only the baseline measures (recorded without the participants wearing prisms). In the baseline condition they found that when only visual information about the target was available (V:P), matching was less accurate (in terms of constant error) than when both visual and proprioceptive information were available (VP:P). Again, having both visual and proprioceptive information available about the target location facilitates performance on finger matching,

By using more targets and examining the patterns of end-point errors across the workspace more closely, Haggard et al., (2000) demonstrated how matching tasks may be used as a tool for mapping out the topography of spatial representations. Haggard et al.'s (2000) experimental set-up used nine equally spaced target locations spanning 560 mm across the body midline, 225 mm from body. 12 normal subjects without vision of the reaching hand, made pen-marks to indicate perceived target locations in V:P, VP:P and P:P conditions. Subjects indicated the position of the targets with both their left and right hands. In VP:P the target hand was moved to the target location actively whereas in the P:P condition the hand was placed passively. Their order of results was the same as that found previously (i.e. VP:P < V:P < P:P). A more detailed analysis of end-point errors found that, in the P:P condition, the perceived position of the target hand (whether the right or left hand) was displaced and rotated towards the shoulder of origin (clockwise for targets defined by the right hand and anti-clockwise for targets defined by the left hand). Because this hand bias was different to that produced when vision was available (a bias explained by a visual horopter effect), they argued that the displacement and rotation of the target location was largely representational (of the proprioceptive localization of the target). An explanation of the bias that was motor in origin was discounted largely because the motor component of the task was the same in all conditions and any motor bias should also have been observed in the other two conditions, but was not. The representation of space in the P:P condition, therefore, was different to that in the V:P condition when the target was defined visually (and end-point errors were not displaced or rotated in the same manner). The findings of this experiment supports the idea that there is no unified representation of proprioceptive space. Rather, there appears to be an egocentric space for each hand, based around the workspace of that hand and, as the origin for most hand movements is the shoulder, Haggard et al. (2000) suggested that the frame of reference for the hand is shifted towards its own shoulder.

van Beers and colleagues ran a comprehensive series of matching experiments in order to determine the nature and precision of proprioceptive localization of the hand in space. In van Beers et al. (1998), subjects pointed: a) with their unseen left hand (on the underside of a table top) to virtual visual targets which were presented on the upper surface of the table using a mirrored set-up (VL condition - equivalent to the V:P conditions described earlier); b) with their unseen right hand (masked by the mirror) above the table to the same virtual visual targets (VR condition); c) with their unseen left hand (under the table) to the felt position of the unseen right hand (above the table) (RL condition - equivalent to P:P). In this experiment the target hand was actively moved to the target by the subject. Subjects were allowed corrective movements after the index finger of the reaching hand had touched the table. The trunk was not restrained and head movements were also allowed.

In the two visual conditions (VL and VR) subjects generally overreached the targets. van Beers et al. (1998) also found that proprioceptive localization of the target hand was more accurate in terms of distance, with respect to the shoulder, than direction and that hand positions at a shorter distance from the shoulder are localized more precisely than more distant positions. In the RL condition they noticed that most subjects, pointing with the left hand, indicated too far to the right. This, they say, is in accordance with the "overlap effect" reported in similar experiments by Slinger and Horsley (1906) and Crowe et al. (1987). Crowe et al. (1987) tested 11 students and 24 children who made slow arm movements across a horizontal surface at shoulder-height to indicate the position of the index finger of the non-moving arm which was touching the underside of the horizontal surface. Both groups showed an 'overlap effect': movements with the right hand went too far to the left, while movements with the left hand went too far to the right.

An earlier van Beers' et al. experiment (van Beers et al., 1996) kept sensory information about the target constant (the target hand was always unseen and under the table), but varied the amount of information available about the target indicator. The target indicator could be either the finger tip of the right hand or a flexible pointer held in the right hand. The three experimental conditions were as follows: **P** - subject blindfolded so that only proprioceptive information about the indicator (the finger) was available; **V** - subject held a pointer and used the end of the pointer to indicate the target location. Because a flexible pointer was used, there was no proprioceptive feedback about the end of the pointer when it touched

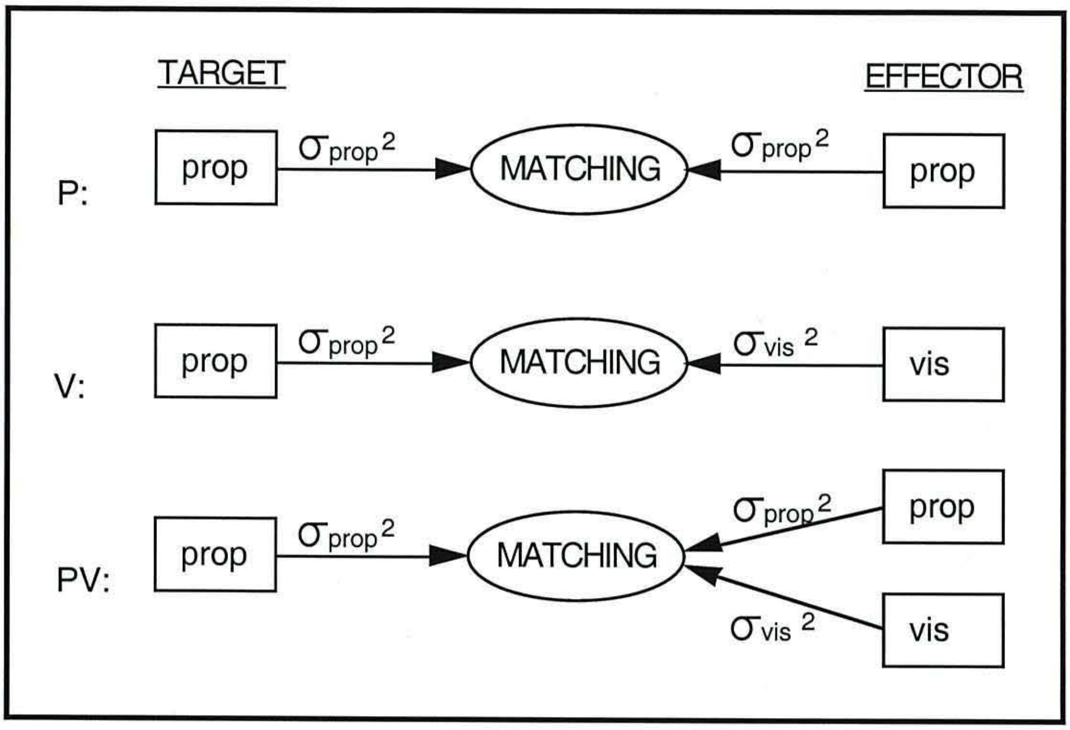

Figure 2.2: Schematic representation of the model that describes how proprioceptive and visual information are processed in performing the matching task. Position information about the target (rectangles on the left hand side) is combined with position information about the indicator (rectangles on the right hand side). The information about the target and the indicator can be considered to operate in series, which implies that the total variance if the matching process (the ellipses) equals the sum of the variance of the position information about the target and that of the indicator. In the model, s_{prop}^2 denotes the variance of position information arising from proprioception, whereas that arising from visual information is s_{vis}^2. In condition **P**, both target position and indicator position are derived from proprioception. In condition **V**, the target position is derived from proprioception, whereas the position of the indicator is derived from visual information. In condition **PV**, the target position is derived from proprioception, whereas the position of the indicator is derived from both proprioceptive and visual information. The two types of information can be considered to operate in parallel. Adapted from van Beers et al. (1996).

the table top, so in this condition only visual information about the indicator was available; **PV** - subjects indicated the target location with the tip of their finger, which could be seen (both proprioceptive and visual information about the indicator was available therefore). Note that the P condition here is the equivalent the P:P condition described earlier. The V and PV conditions are <u>not</u> the equivalent of V:P and VP:P respectively.).

The authors used this experiment to test a model (shown in Figure 2.2) in which they hypothesized that the total of the variance in the matching process (of target and indicator) would be equal to the sum of the variance of the position information about the target and that of the indicator. They found that the variance in the PV condition was in fact smaller than that predicted by the model. There are two oversights in this model, however. Firstly, the model does not take into account the extra proprioceptive component (tactile stimulation) in the PV condition as the indicator (the finger) touches the table top. There is no such proprioceptive component in the V condition, but this difference is not included in the model. Secondly, and more importantly, the boxes on the left hand side (Figure 2.2), denoting information regarding the target location, do not take into account any benefits in localising the target that might arise from having vision available (V and PV conditions). Although the target itself (the left index finger under the table) cannot be seen, the workspace in which it is located can. Given that visual and proprioceptive integration is known to take place (see above) and that spatially and temporally coincident stimuli in different modalities can produce "response enhancement" in multisensory neurons (responses to simultaneous stimulation in multiple modalities which are stronger than the sum of the responses to stimulation in each modality in isolation) (Graziano and Gross, 1998) it is not unreasonable to expect that there may be some enhancement in localising the unseen target hand when concomitant vision of the coincident workspace is available.

A similar omission in thinking was made in 1997 in a study by Desmurget and colleagues (1997b). This study was not designed to test the accuracy of the felt position of the target limb, but whether the advantage the authors had previously found for vision of the initial limb position was because the reaching limb and target could be seen simultaneously. Like van Beers et al. (1996) they failed to take into account the possible benefits to target localization of being able to see the area of workspace which obscured the unseen target limb.

In the current experiment we are not interested in the accuracy of proprioceptive position sense so much as the way in which different amounts, and different types, of sensory information might alter the way in which reaches are planned and executed. The experimental conditions employed in the current study will differ slightly from the V:P, VP:P and P:P conditions outlined in this introduction. Precise details will be given later, but briefly, in two of the conditions subjects will be required to point to targets under either entirely visual or proprioceptive guidance whilst in the third condition subjects will make a visually-guided pointing movement to a proprioceptively-defined target. In this chapter we will examine more aspects of proprioceptive matching than simply end-point errors. Spatial and temporal components of the reach itself, as well as final end-point errors, will be analysed. In this way we hope to demonstrate that when different sources of sensory information are available, reaches are planned within different frames of reference. To this end we will directly compare reaches made under the various sensory conditions in a series of planned comparisons.

2.2 Method

2.2.1 Subjects

5 normal healthy volunteers (3 males and 2 females) with an age range of 24-40 years (average age 27.5) participated in this study. None had a history of neurological disorder and none were assessed as having somatosensory deficits. All were right handers as assessed by a version of the Edinburgh Handedness Inventory (Oldfield, 1971) and all had normal or corrected to normal vision.

2.2.2 Data Analysis

Movements were recorded using a miniBIRD model 800 position and orientation measurement system (Ascension Technology Corporation, Vermont). Data collection was controlled by LabVIEW drivers developed at the University of Wales, Bangor. Prior to each experimental session the workspace and target locations were calibrated and several test recordings were made in order to ensure good recording conditions.

For experimental purposes movements were recorded at a sample rate of 50 Hz. X, Y and Z positional data was recorded from a single marker placed on the upper surface of the tip of the index finger on the right hand. Raw data were low-pass filtered off-line using a 4th order dual pass Butterworth filter with a low cut-off frequency of 10 Hz. Any electrical recording system will introduce noise into the raw data (a common source of noise is the 50 Hz electrical power supply). In motion analysis systems this noise can introduce displacement data which is not caused by human movement. Digital filtering is a common method used to remove such unwanted noise and the Butterworth filter is a commonly used filter in this type of research and yields satisfactory results for non-complex movements which do not occupy low- or high-frequency bands

(Ismail and Asfour, 1999). Butterworth filters are maximally flat in the pass band (i.e. no ripple) and allow frequencies within this band to pass almost unattenuated. This type of filter can introduce a phase shift, however, but this is eliminated by the second pass which introduces a phase shift equal in magnitude and in the opposite direction to the first pass. A 10 Hz low cut-off frequency will eliminate most sources of unwanted noise while allowing displacement data caused by human movement to pass through.

2.2.3 Accuracy and Reliability of MiniBIRD

The miniBIRD is a six degree-of-freedom measuring device that can measure the position and orientation of a small receiver (sensor/marker) with respect to a transmitter. In this respect the system needs no calibration as the centre of the transmitter (a cube measuring approx. 90 mm x 90 mm x 90 mm) is the origin of the reference frame and the x, y and z axes radiate orthogonally from it in the conventional manner. The system determines position and orientation by pulsing a DC magnetic field from the transmitter, the characteristics of which are then measured by the sensors. The miniBIRD Model 800 uses sensors measuring 8.1 mm x 8.1 mm x 18 mm, each of which is connected to an electronics unit via a 4 mm diameter 3 m long cable. The miniBIRD 800 claims a static position accuracy of 0.05 mm RMS and a static position resolution of 0.18 mm RMS. Due to the electromagnetic nature of the system it was necessary to ensure that the entire workspace in which the experiment took place was devoid of any materials which were good conductors of electricity. In order to test the accuracy and reliability of the miniBIRD system the following procedures, similar to those adopted by Haggard and Wing (1990), were carried out:

Two markers were placed on a rigid body 50 mm, 100 mm and 150 mm apart. The distance between the two markers was measured in lateral and radial orientations in 20 static locations covering the entire workspace in a 5x4 grid. The standard deviation of the distance between the two static markers was found to be less than 2 mm.

It was also thought necessary to test the system for accuracy and reliability when the markers were moving. To this end a similar procedure to that performed for static markers was adopted for dynamic markers. In this instance the rigid body holding the markers was moved across the grid pattern at a variety of velocities and at different orientations. It was found that 95% of the recorded data fell within +-2.56 mm of the mean marker separation. These recordings were made covering the full range of the miniBIRD transmitter (a 760 mm hemisphere from the centre of the transmitter). A second series of trials, using the same procedure, was performed covering only the workspace in which the experiment would take place (a rectangle measuring 800 mm wide by 450 mm deep. Within this area it was found that 95% of the recorded data fell within +-0.26 mm of the mean marker separation for static markers and +-1.23 mm for dynamic markers. In addition, to test the reliability of the system, 30 recordings were made with the markers in the middle of the workspace without moving the markers between recordings. 95% of the recorded data fell within +-0.12 mm of the mean marker separation. Finally, a test was carried out to compare miniBIRD against the optoelectronic MacReflex system (Qualisys Ltd.), the resolution of which is reported by the manufacturers to be 0.1 mm (see section 2.9, later in this chapter, for details of the MacReflex system). A single MacReflex optoelectronic marker was placed on top of a miniBIRD electromagnetic marker and a number of simultaneous recordings were made across the workspace. The positional accuracy of the miniBIRD system was fully corroborated by that of the MacReflex.

2.2.4 Procedure

Subjects were seated upright at a 100 cm high table upon which rested a matt black painted wooden board raised 15 cm above the table top. The thickness of this board was 8 mm. Eight 6 mm diameter drilled holes, laid out in the positions shown in Figure 2.3, served as the target locations in the three pointing conditions which were as follows:

1) Vision/Vision (**VV**). Before each trial the target location was defined visually by placing a small pine-coloured wooden dowel into the target hole on the upper side of the raised board. The dowel top did not protrude above the surface of the board. Subjects pointed with their eyes open and were allowed to move their head and eyes freely. The non-pointing hand was rested on the table top beneath the target board in a central position that did not correspond to any of the target locations.

2) Vision/Proprioception (**VP**). The target array was covered by a featureless board painted matt black so that there were no visual cues as to the target locations. Before each trial the target was defined proprioceptively by placing the tip of the index finger of the subject's unseen non-pointing, or target, hand onto a drilled hole on the underside of the raised board. Subjects pointed to the felt location of the index finger of their target hand with their eyes open so that visual information about the pointing limb was available throughout the trial. The index finger of the target hand remained on the target location throughout the reach, but could be rested, if necessary, between trials.

3) Proprioception/Proprioception (**PP**). The procedure and apparatus was identical to that used in the VP condition except that subjects were blindfolded so that they had no visual information about either the target

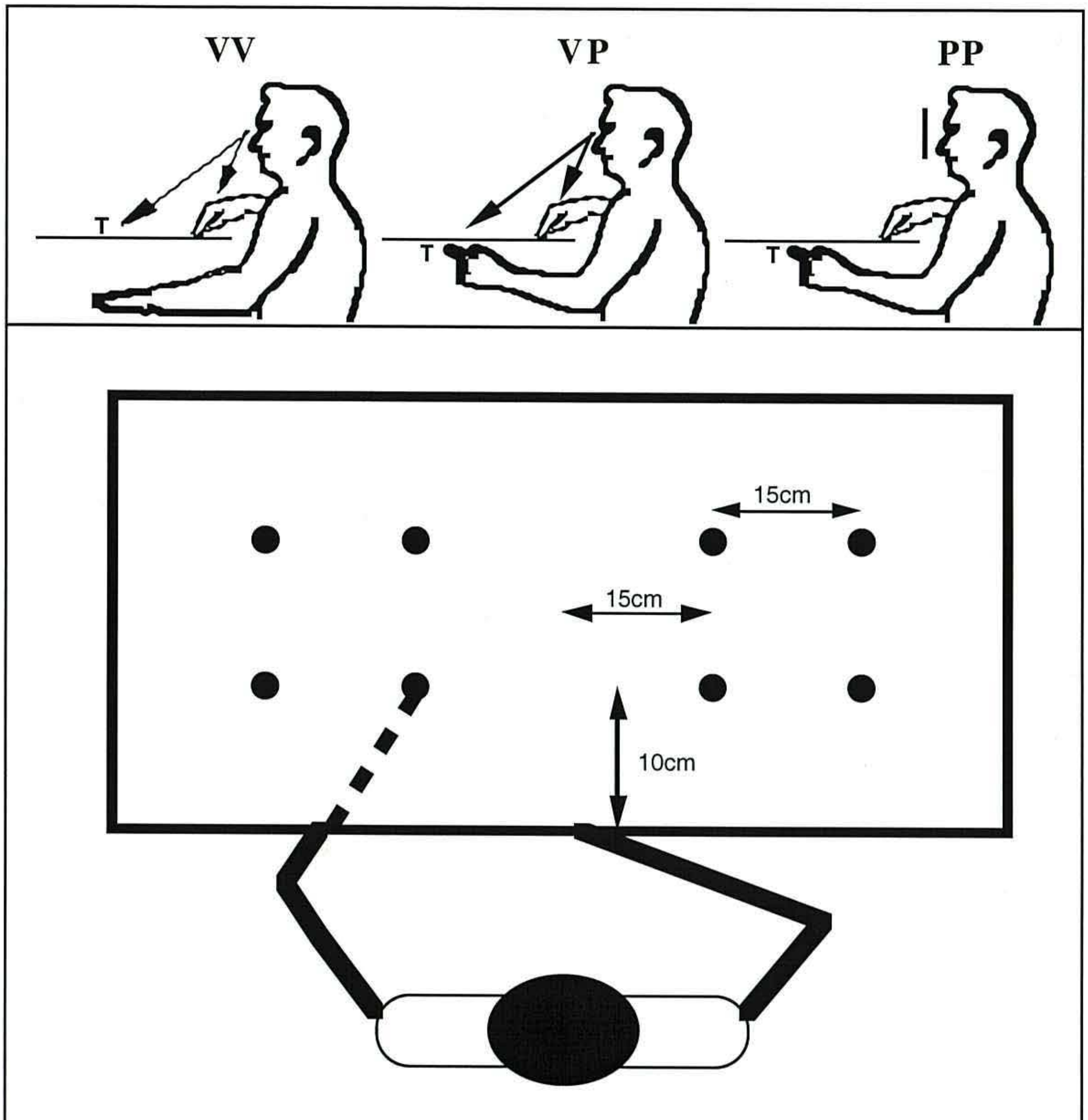

Figure 2.3: Top: The initial limb configuration in each of the three conditions. Bottom: The eight target locations. The subject's target (left) hand is positioned beneath the board whilst the pointing (right) hand rests on top of the board.

or the pointing hand.

The order of target presentation was randomized within each condition, the order of which were also randomized between subjects. Subjects made four pointing movements to each of the eight target location in each of the three conditions, making ninety-six reaches in all. In the VV condition the instructions to the subject were to, "Reach out and touch the target..." whereas in the VP and PP condition they were instructed to, "Reach out and touch the table top..." where they felt their other finger to be. Subjects pointed with the tip of their right index finger and were encouraged to be accurate and to effect their pointing movement in one smooth movement. They were not allowed to correct reaches which they perceived to be inaccurate after they had made tactile contact with the board surface. A tone signalled the start of each trial. As the proprioceptively perceived position of the limb tends to drift during prolonged (> 8 seconds) visual occlusion (Wann and Ibrahim, 1992) the go-signal tone was always given within 2 seconds of placement of the target finger in order to negate drift in the VP and PP conditions.

2.2.5 Dependent Measures

A total of eight temporal, spatial and kinematic measures were evaluated. The three measurements used to describe the temporal and kinematic characteristics of reaches were:

a) Movement time (**MT**), or the time taken to complete the reach, was calculated as the time to movement end-point minus the time to movement onset in milliseconds. Movement onset was defined as the first frame in which the finger marker exceeded a velocity of 2.5 cm/s. Movement end-point was defined as the first frame in which the velocity of the finger marker fell below 2.5 cm/s. The 'first frame' was determined as the first of five frames in which the mean value was above threshold and the mean value of the preceding five frames was below threshold;

b) Peak velocity (**PV**) was taken as the maximum three-dimensional velocity reached in the direction of movement;

c) Deceleration phase (**%DP**) was calculated as the time spent in the reach after the occurrence of peak velocity and was expressed as a percentage of movement time.

To aid spatial hand path analysis all hand paths were rotated, using the start point as the fulcrum, so that both the start- and end-points lay on the same axis (see Figure 2.4 for details). Two measurements were employed to describe the spatial characteristics of the pointing movement: a) An index of hand path curvature (**HPC**) was calculated by dividing the maximum lateral deviation (in mm) from a straight line path from start position to movement end-point by the straight line distance from start position to movement end-point. This index of curvature is independent of the movement amplitude and the direction (leftwards or rightwards) of the curvature; b) A signed index of hand path curvature (**HPC+-**) was calculated in exactly the same manner except that the sign of the lateral deviation was retained. A negative value indicated a leftward deviation from a straight-line path and a positive value a rightward deviation.

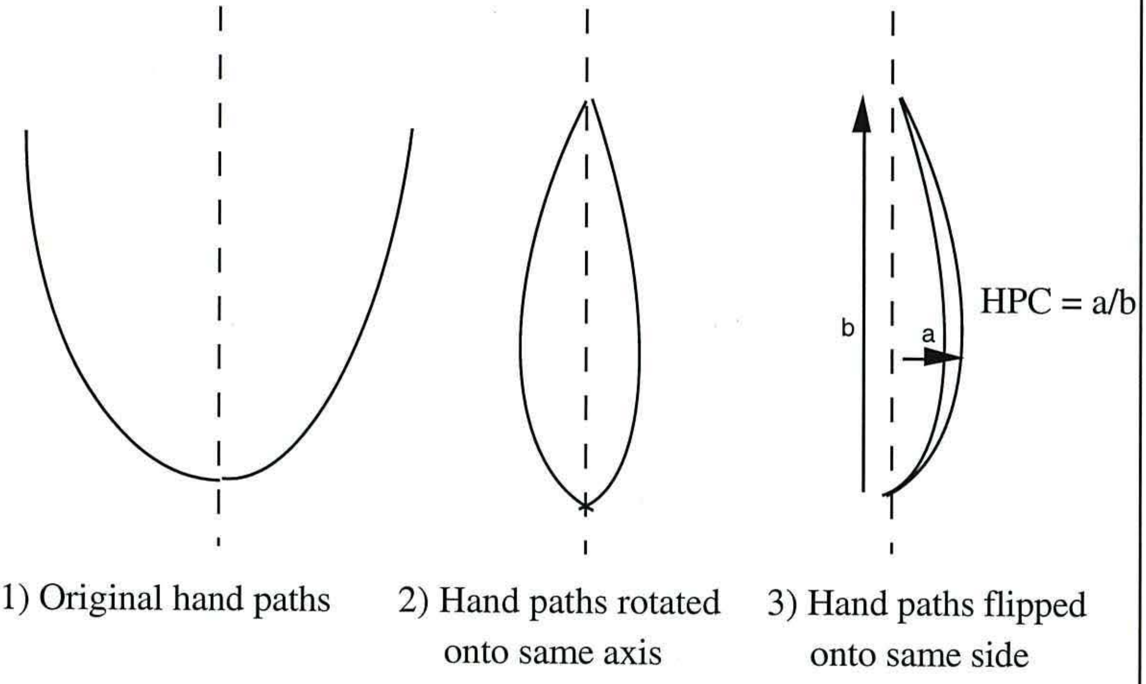

Figure 2.4: Procedure for calculating the HPC measure of hand path curvature. For HPC+-, the calculation is made prior to step 3 so that leftward curvatures retain a negative value.

In matching tasks analysis of variable end-point errors give information about the acuity of position sense whereas systematic, or constant, errors give information about the current status of proprioceptive position sense (i.e. where the limb is indicated to be relative to its actual location). For the purpose of this experiment we were interested in the latter only. For this reason, the following three measurements of end-point accuracy defined in relation to the direction of travel of the reach were used:

a) Direction errors (**DE**) were calculated as the angle (in degrees) formed between a straight line from start position to movement end-point and a straight line from the start position to the target location. A negative result indicates a leftward (or anti-clockwise) error and a positive result a rightward (or clockwise) error.

b) Amplitude errors (**AE**) were calculated as the straight-line distance (in mm) from the start position to movement end-point as compared to the straight-line distance from the start position to the target location. A positive value represents an over-reach of the distance to the target and a negative value, an under-reach.

c) Total error (**TE**) was calculated as the Euclidean distance between the movement end-point and the target location. The target locations for all end-point error measures were calibrated prior to each experimental session.

2.3 Results

For each of the dependent variables mean data for individual subjects were entered in a 2 factor analysis of variance (ANOVA) with the factors: CONDITION (VV vs. VP vs. PP) x SIDE OF REACH (contralateral vs. ipsilateral). As outlined in the introduction, a priori pairwise comparisons were performed on mean values for the following CONDITION pairs: VV vs. VP; VV vs. PP; VP vs. PP. Mean values for all conditions are given in Table 2.2 and probability values with F statistics for the a priori comparisons are given in Table 2.1. Note that 'contralateral' here refers to the area of space across the body midline from the shoulder of the reaching hand, not the target hand.

Movement Time

Statistical analysis revealed no main effect of CONDITION, but there was a main effect of SIDE OF REACH ($F_{[1,4]} = 39.3$, $p < 0.005$) with contralateral reaches taking longer to complete than ipsilateral reaches (means: contra = 869.6 ms [124.4]; ipsi = 780.0 ms [113.7]). A priori comparisons between the conditions revealed that movement times in the VV condition were significantly shorter than those in the PP condition (see Tables 2.1 and 2.2).

Peak Velocity

No main effect of CONDITION was found, but a main effect of SIDE OF REACH ($F_{[1,4]} = 43.2$, $p < 0.005$) showed that contralateral reaches achieved lower peak velocities than ipsilateral reaches (means: contra = 733.7 mm/s [54.6]; ipsi = 921.0 mm/s [80.4]). A priori planned comparisons revealed no significant differences between conditions.

Deceleration Phase

A main effect of CONDITION was found for the proportion of the reach spent decelerating ($F_{[2,8]} = 4.8$, $p < 0.05$). Further analysis revealed that subjects produced longer deceleration phases in the PP condition compared to either the VV or the VP conditions (see Tables 2.1 and 2.2).

Direction Errors

Analysis of direction errors revealed a main effect of CONDITION ($F_{[2,8]} = 14.7$, $p < 0.005$). Overall, end-point errors in the PP condition fell in a clockwise direction from the target location. Further analysis of condition means showed that end-point errors in the VV and VP conditions were more accurate than in the PP condition (see Tables 2.1 and 2.2).

Amplitude Errors

A main effect of CONDITION was found for amplitude errors ($F_{[2,8]} = 27.1$, $p < 0.0005$), as was a main effect of SIDE OF REACH ($F_{[1,4]} = 64.3$, $p < 0.005$). Movements made to ipsilateral targets overreached the target considerably more than movements to contralateral targets (means: contra = 7.774 mm [6.4]; ipsi = 23.038 mm [17.7]). Furthermore there was a CONDITION x SIDE OF REACH interaction ($F_{[2,8]} = 12.7$, $p < 0.05$) which indicated that the increase in amplitude error for ipsilateral compared to contralateral targets seen in the VP and PP conditions did not occur in the VV condition. Analysis of condition means revealed that reaches in the VV condition were more accurate than those in the VP and PP conditions (see Tables 2.1 and 2.2).

Total Error

A main effect of CONDITION was found ($F_{[2,8]} = 44.4$, $p = 0.0001$), as was a main effect of SIDE OF REACH ($F_{[1,4]} = 31.7$, $p < 0.005$). Furthermore there was a CONDITION x SIDE OF REACH interaction ($F_{[2,8]} = 12.2$, $p < 0.05$) which again indicated that the increase in end-point error for ipsilateral compared to contralateral targets seen in the VP and PP conditions did not occur in the VV condition. Further analysis showed that end-point errors in the VV condition were smaller than those in the VP ($F_{[1]} = 39.5$, $p < 0.001$) and PP ($F_{[1]} = 85.1$, $p = 0.0001$) conditions and that those in the VP condition were smaller yet than those in the PP condition ($F_{[1]} = 8.7$, $p < 0.05$).

HPC

Analysis revealed no significant main effects for overall hand path curvature. None of the a priori comparisons were significant either (closest comparison, or minimum: $F_{[1]} = 0.4$, $p = 0.4864$) indicating that the amount of absolute curvature under each of the conditions was equivalent (see Figure 2.5).

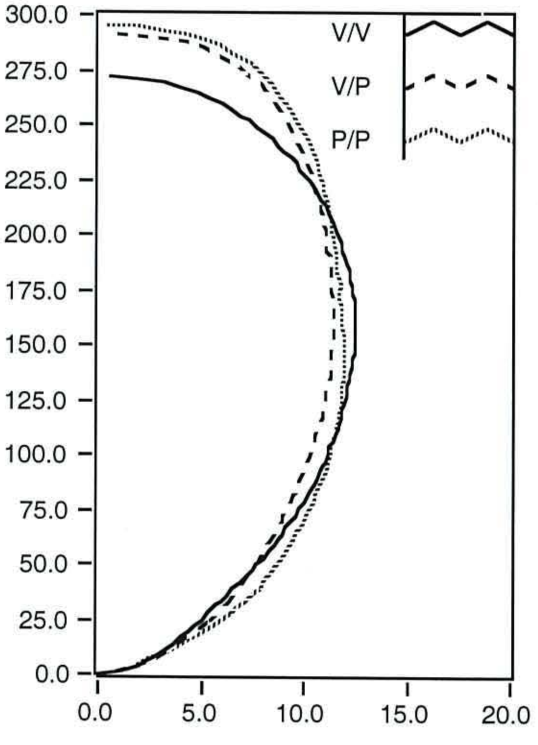

Figure 2.5: Mean hand paths for each of the three conditions. Hand paths have been rotated and transposed so that they all show a rightward curvature.

HPC+-

Analysis revealed no significant main effects for signed hand path curvature. There was, however, a significant interaction effect ($F_{[2,8]}$ = 32.4, p = 0.0001) which indicated that whereas reaches in the VV condition curved rightwards to ipsilateral targets and leftwards to contralateral targets, reaches in the PP condition showed the opposite pattern, curving rightwards to contralateral targets and leftwards to ipsilateral targets (see Figure 2.6). None of the a priori comparisons were significant (minimum: $F_{[1]}$ = 1.6, p = 0.231).

Table 2.1: F statistics and p values for all significant a priori pairwise comparisons for each dependent measure (NS = non-significant).

DEPENDENT MEASURE	COMPARISON		
	VV vs. VP	VV vs. PP	VP vs. PP
MT	**NS**	$F_{[1]} = 8.7$ $p < 0.05$	**NS**
PV	**NS**	**NS**	**NS**
%DP	**NS**	$F_{[1]} = 8.5$ $p < 0.05$	$F_{[1]} = 5.6$ $p < 0.05$
DE	**NS**	$F_{[1]} = 28.4$ $p < 0.05$	$F_{[1]} = 12.3$ $p < 0.05$
AE	$F_{[1]} = 35.4$ $p < 0.001$	$F_{[1]} = 45.5$ $p = 0.0001$	**NS**
TE	$F_{[1]} = 39.5$ $p < 0.001$	$F_{[1]} = 85.1$ $p = 0.0001$	$F_{[1]} = 8.7$ $p < 0.05$
HPC	**NS**	**NS**	**NS**
HPC+-	**NS**	**NS**	**NS**

Table 2.2: Mean values for contralateral and ipsilateral reaches in each condition for all dependent measures. Standard Deviations are given in square brackets.

DEPEND. MEASURE	V V		V P		P P	
	Contra	Ipsi	Contra	Ipsi	Contra	Ipsi
MT	812.750 [69.234]	718.000 [33.162]	842.317 [81.362]	797.357 [120.56]	953.600 [170.072]	824.517 [148.087]
PV	756.529 [57.522]	926.221 [31.335]	733.225 [65.696]	942.416 [86.785]	711.275 [39.313]	894.301 [112.407]
%DP	63.722 [4.639]	62.026 [4.595]	62.032 [5.529]	65.313 [6.779]	67.612 [6.217]	66.422 [4.251]
DE	0.315 [0.108]	-0.357 [0.232]	2.027 [0.961]	0.917 [2.952]	5.549 [2.568]	3.166 [3.287]
AE	1.483 [2.127]	1.472 [1.090]	10.799 [6.779]	31.319 [7.676]	11.041 [4.432]	36.324 [12.386]
TE	4.506 [0.868]	4.025 [1.162]	18.515 [5.308]	36.996 [5.443]	32.613 [9.864]	44.907 [12.465]
HPC	0.063 [0.017]	0.050 [0.014]	0.052 [0.019]	0.053 [0.013]	0.061 [0.025]	0.043 [0.012]
HPC+-	-0.016 [0.058]	0.028 [0.033]	0.025 [0.039]	0.010 [0.045]	0.041 [0.047]	-0.010 [0.031]

2.4 Discussion

Hand Path Curvature

The most interesting aspect of the hand path curvature analysis was that, although the overall curvature of hand paths did not vary significantly across the three conditions (Figure 2.5), the direction of curvature was found to vary according to the side of reach in each condition, most notably the difference between VV (in which the target was defined entirely visually) and PP (in which the target was defined entirely proprioceptively) conditions. Inspection of Figure 2.6 demonstrates that mean VV reaches curved leftwards to contralateral targets and rightwards to ipsilateral targets. This mirror-symmetry of hand paths is not uncommon in simple pointing studies (Boessenkool et al., 1998). Mean PP reaches, on the other hand, although still mirror-symmetric, displayed rightward curvature to contralateral targets and leftward curvature to ipsilateral targets. That is, VV reaches tended to bow away from the body midline, whereas PP reaches tended to bow towards the body midline. As both sets of reaches were performed from the same start position to identical target locations, moving through the same workspace, the difference in curvature revealed here cannot be explained by biomechanical factors. We suggest that these effects may reflect a change in the frame of reference used to plan the movements under distinct sensory conditions. Inward curvature might be expected if reaches into ipsilateral space were performed mainly by rotation about the elbow, with little or no upper limb movement, and reaches into contralateral space were performed mainly by rotation about the shoulder, with little or no forearm movement. It may be, therefore, that PP reaches are planned primarily within in an intrinsic motoric (joint- or muscle-based) coordinate system. VV reaches, which show a markedly different curvature, may be based within a more extrinsic coordinate system in which visual cues and perceptions play a much greater role in defining the frame of reference used. It is also noticeable that the curvature of the VP reaches appears to be somewhere in between that of the VV and PP reaches.

Although it is possible to complete the VP task simply by matching the proprioceptive positions of the finger, without reference to visual information, this clearly does not happen as the performance in the VP and PP conditions are markedly different. Some form of visuoproprioceptive integration occurs which seems to provide a performance which is somewhere between that on the purely visual and the purely proprioceptive tasks. It is tempting to suggest, perhaps, that movement planning involves a weighting of visual and proprioceptive information depending on the goodness of the source and that each of these sources have their own peculiarities which may influence the way a reach is planned. Heuer and Sangals (1998) analysed movements which corresponded to different types of visual stimuli and concluded that visuomotor transformations could be characterized as mixtures of different coordinate systems and that their respective weights in the mixtures were dependent on the task in hand. It is plausible that a similar arrangement exists for all types of sensorimotor transformations, not just visuomotor ones.

There is, however, an alternative possibility for the difference in curvature which will be outlined below. When reaches are made to punctate visual targets, it is necessary to effect the reach in such a way that no part of the reaching limb obscures the target - thus allowing optimal on-line visual control. When blindfolded, visual obscuration of the target is not an issue and the hand can follow a different, perhaps more efficient, path. An alternative hypothesis for different hand paths, therefore, might be that visually-guided and proprioceptively-guided reaches have different task requirements, rather than using alternative frames-of-reference. For this to have been the case, though, VV reaches into contralateral space should have bowed to the right, thus keeping the right hand away from the line-of-sight, rather than to the left, crossing the line-of-sight, as they did in this experiment.

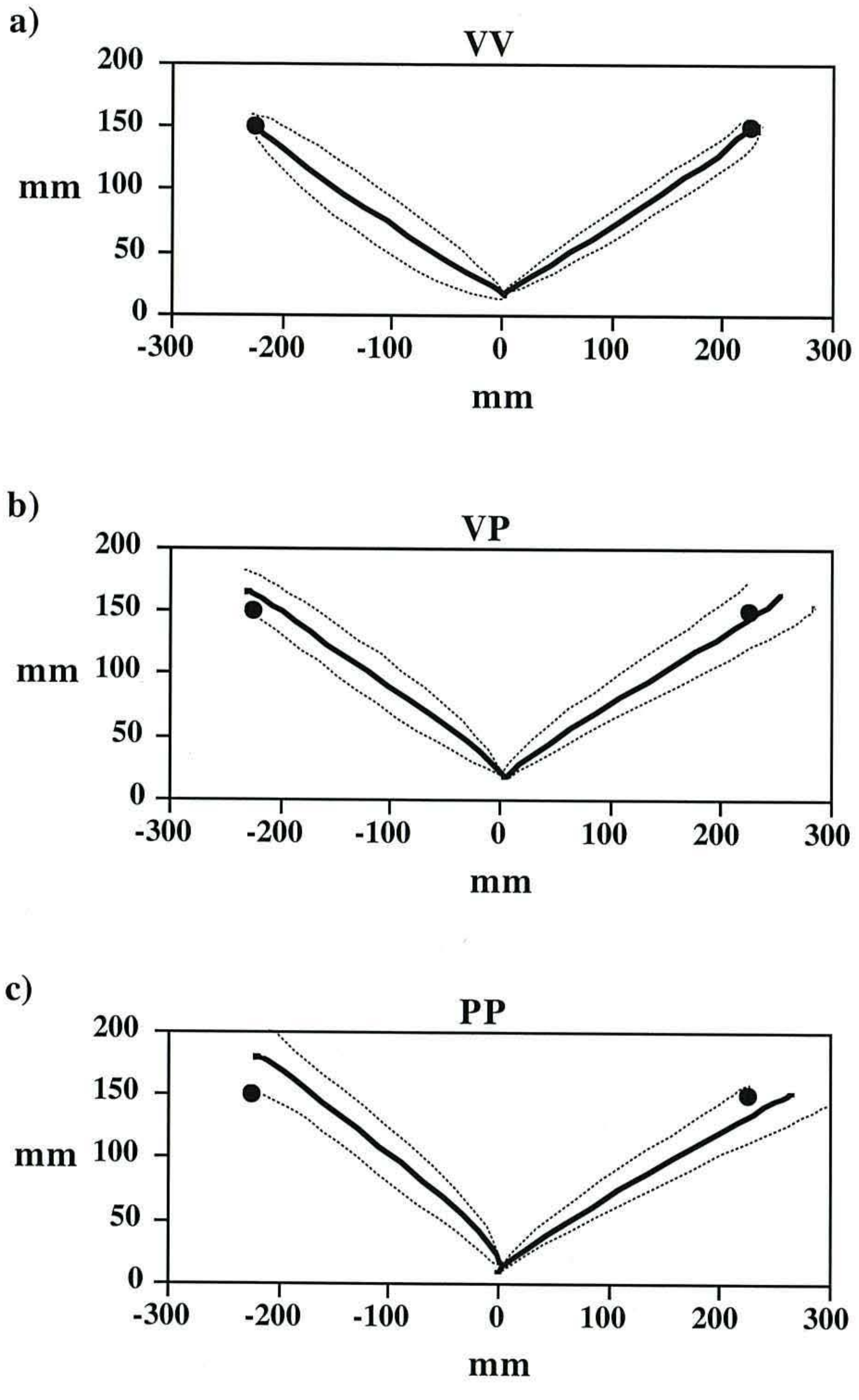

Figure 2.6: Mean hand paths and Standard Deviations for contralateral and ipsilateral reaches in the a) VV, b) VP and c) PP conditions. NB. hand paths have been normalized in space to account for the different target locations and rotated so that they are shown relative to the average target position.

Kinematic markers

There were few surprises to be found when the kinematics of SIDE OF REACH were analysed. Reaches into contralateral space achieved lower peak velocities and took longer to complete than equivalent reaches into ipsilateral space. The most likely explanation for this expected outcome is that it is a result of the inertial anisotropy of the reaching limb. Reaches into contralateral space require the whole of the upper limb to be moved about the shoulder whereas reaches into ipsilateral space often only require rotation of the forearm about the elbow. In contrast, the time spent decelerating for reaches into contralateral and ipsilateral space were extremely similar (means: contralateral = 64.5% [5.6]; ipsilateral = 64.6% [5.3]) suggesting that, despite the anisotropy of the limb, subjects found contralateral targets no more difficult than ipsilateral targets (the deceleration phase of a reach has often been associated with task difficulty with the hand slowing down, in order to achieve its goal, as task difficulty increases (Bootsma et al., 1994; Soechting, 1984; Jeannerod 1984; Jeannerod 1988)).

One thing that stands out from the data is that the deceleration phases of all movements represented quite a high proportion (60-70%) of the total movement time. It must be remembered, however, that in this experiment subjects were encouraged to be accurate and this probably accounts for the extended deceleration phases. In particular this may have been the case in the VP and PP conditions in which subjects were aware that they would not be allowed to correct their final finger positions once they had made contact with the table.

No significant difference was found between the VV and VP conditions on any of the temporal and kinematic dependent measures. If it is accepted that the human CNS attempts to execute movements with optimal efficiency, and that the optimal conditions for reaching (in this experiment) were met by the VV condition - in which both target and effector could be seen throughout - then VP reaches were executed as efficiently as VV reaches. This is in contrast to PP reaches in which both the overall time taken to complete reaches and the proportion of time spent in deceleration were the longest of all conditions. Again, biomechanical factors cannot be an explanatory factor because reaches were made from identical start positions to identical target locations. When the target cannot be seen, but the reaching hand and the area of workspace in which the target is located can, the execution of reaches seems to be unaffected by not being able to see the target itself. Whether the improved reach efficiency seen in the VP condition compared to the PP condition is due to vision of the hand or the target area is not clear from these results although it is most likely to be the former as occlusion of the reaching hand is known to affect indicators of reach efficiency such as movement time and deceleration time (Connolly and Goodale, 1999; Jeannerod 1988). On the other hand, as mentioned previously, it has been proposed that the deceleration phase of a reach, as well as increased movement time, can be taken as an index of task difficulty as the hand slows down in order to achieve its goal. Poor acuity of the proprioceptive system and difficulty in localising the unseen finger, without the aid of visual calibration, may have been reflected in the extended movement times and deceleration phases found in the PP condition. For this to have been the case, being able to see the area of workspace in which the unseen hand is located must have improved the acuity of the proprioceptive system and, in doing so, improved localization of the target - making the task easier to perform. Evidence that vision of the workspace in which the unseen target hand is located improves target localization may be drawn from the analysis of end-point errors in the current experiment.

End-point Errors

PP reaches were the least accurate of all conditions. VP reaches were significantly more accurate than PP reaches, but not as accurate as VV reaches. It was no surprise that the VV reaches were accurate as the task was not a very demanding one - simply placing the finger, which could be seen at all times, on a visual target, which could also be seen at all times. Furthermore the accuracy of reaches in the VV condition was maintained across the workspace, with contralateral reaches being as accurate as ipsilateral reaches (means: VV contra: 1.5 mm [2.1]; VV ipsi: 1.5 mm [1.1]) This was not the case for either the VP or PP conditions in which ipsilateral reaches were less accurate, in terms of total error, than contralateral reaches. 'Ipsilateral' here, remember, refers to reaches performed to targets in the same hemispace as the reaching limb. Ipsilateral reaches, therefore, were further from the target finger's shoulder of origin and some target locations - particularly the bottom right target in Figure 2.3 - would have rotated the shoulder of the target limb towards the extreme of its range. Proprioceptive perception of limb position is known to be poorest at the extreme ranges of limb orientation (Rossetti et al., 1994a) and this may have contributed to the reduced accuracy to ipsilateral proprioceptively-defined targets.

It should be noted that in the VP condition, as with the reach kinematics, vision of the area of workspace in which the target is located (as well as vision of the reaching hand) improved performance compared to the PP condition when it was not. Closer inspection of end-point errors, by breaking total error down into directional and amplitudinal components revealed further differences between the conditions. Both PP and VP reaches showed an amplitudinal overshoot, particularly to ipsilateral targets. As noted in the introduction, this so-called "over-lap effect" has been seen before in similar matching experiments in which vision of the reaching was occluded (e.g. Crowe et al., 1987; van Beers et al., 1998). In the current experiment the basis of the overshoot must be in the proprioceptively perceived position of the target limb, not the reaching limb, as overshooting also occurs in the VP condition when the reaching limb is visible. Clearly, the unseen target finger is perceived to be further away from the body than it really is. Again, ipsilateral reaches landed further from the target than contralateral reaches. It is unlikely that the reason for this is due to the inertial anisotropy of the reaching limb, as it is in the case when patients with dense fibre neuropathies overshoot ipsilateral targets when reaching without visual feedback (Ghez et al., 1990; Ghez et al, 1995) Firstly, our subjects had no recorded somatosensory deficits and secondly, vision of the reaching limb was available in the VP condition when targets were still overreached. It is more likely, as mentioned previously, that the greater distance from the shoulder of origin and the more extreme shoulder angles involved with ipsilateral targets resulted in poorer acuity which contributed to the greater ipsilateral over-lap.

Analysis of direction errors revealed that PP reaches were less accurate than both VV and VP reaches and, furthermore, direction errors appeared to be rotated clockwise about the target. It will not have escaped the astute reader that the rotation of end-point errors in the current experiment is in the opposite direction to that reported by Haggard et al. (2000) for targets defined by the left hand. This anomaly cannot be explained by the different limb configurations used between the two set-ups. Although the majority of the work reported by Haggard et al. (2000) involved the opposite limb configuration to that used here (target hand above the table; reaching hand beneath instead of vice versa) at least one condition (in Experiment 3 of the Haggard paper) used the same configuration and that experiment also revealed an clockwise rotation for targets defined by the left hand. One procedural difference between the current experiment and that reported by Haggard et al. (2000) involves the length of time the target finger remained at the target location. In the current experiment subjects performed a reach within two seconds of the finger being placed at the target location and the finger was moved to a new target for every trial. The procedure used by Haggard et al. (2000) allowed the target finger to remain in place for a total of three trials. Although it is not clear how long it took to perform three trials, it is possible that a certain degree of proprioceptive drift may have been introduced into the data.

A number of experiments (e.g. Soechting and Flanders, 1989; Soechting et al., 1990; Flanders et al., 1992; Gordon et al. 1994a) have indicated that end-point errors might be used to give an insight into the frame of reference being used for a particular task. It is not immediately clear from our results, however, whether the rotation of end-point errors is a rotation about the shoulder of the reaching hand or about the shoulder of the target hand, or even an amalgam of the two. There is a temptation to suggest that they are rotated about the target shoulder as to plan a reach in an intrinsic coordinate system based around the shoulder of origin of the target would make sense: it is the target limb which provides the information about the target location, just as visual information about visually-defined targets gives rise to reaches planned in a visually-based extrinsic frame of reference.

2.5 Overall Summary

The results of this initial experiment suggest that there may be a shift in the frame of reference used to plan reaches under the different visual and proprioceptive conditions. Particularly, there is a clear difference between VV and PP conditions: end-point errors appear to be rotated about the target shoulder and the shape of hand paths is radically altered when subjects are forced to rely solely upon proprioception. Furthermore, there is evidence to suggest that vision of the area in which a proprioceptively-defined target is located can serve to improve proprioceptive localization of that target despite the fact that it cannot actually be seen directly. Further experimentation is needed test both of these observations further. By introducing perturbations to either the visual or proprioceptive systems it may be possible to gain further insight into the way visual and proprioceptive information are used when performing this task and that is what later chapters will focus on. Before that, however, we will address an issue related to the visually-guided component in the VV and VP conditions in the current experiment.

2.6. Does proprioception of the seen limb significantly improve performance during visually-guided reaching?

2.7 Introduction

Throughout the previous experiment the VP condition was described as being a visually-guided movement towards a proprioceptively-defined target. Naturally, because none of our subjects suffered from any neurological or sensory impairments, the reaching hand could be felt as well as seen. In this sense the VP condition is truly a reach made with both visual and proprioceptive information available about the moving hand. The same case can also be made for VV reaches. It is well documented that having both vision and proprioception available about the target location improves reaching accuracy in proprioceptive matching tasks when the reaching hand cannot be seen (e.g. Wann, 1991; von Hofsten and Rosblad, 1988; Haggard et al., 2000). We wished to ascertain whether having both visual and proprioceptive information about the reaching limb available held any discernible advantage for normal subjects when pointing to an unseen proprioceptively-defined target. To this end we conducted a second experiment in which we compared indicating the target location with the index finger, as in the previous experiment, against indicating with the end of a hand-held stick-pointer. By doing this we hoped to detach the proprioceptive component of the seen and felt position of the pointing hand.

Although it was our intention to remove the proprioceptive component from the pointing hand in the VP condition it was not possible to do this completely. It is plausible that subjects may have been able to estimate the offset of the end of the stick from the end of the finger and use proprioceptive information about the end of the finger to control the estimated position of the end of the stick. To explore this possibility we also asked subjects to perform the PP condition (in which they were blindfolded). If subjects are able to accurately gauge the end of the stick using proprioceptive information alone then there should be no difference in the accuracy of reaches made when the subjects cannot see either the finger or the stick .

Pointing to proprioceptively-defined targets using an indicator, rather than the finger tip, was examined by van Beers et al. in 1996. This group used a flexible pointer so that little or no sensory information could be transmitted through feeling a rigid body touching the table surface. In their experiment, however, subjects were allowed to move the pointer after it had touched the table. In our experiment subjects were required to indicate the target location in one smooth movement. We found that flexible pointers tended to move as they hit the table surface making analysis of the initial landing point problematic. For this reason we used a rigid pointer and, in any case, it was necessary to use a rigid pointer so that subjects could feel the exact moment that the indicator touched the table surface in the blindfold condition.

To summarize, we hypothesized that if subjects were as accurate when pointing with a stick as with a finger in the VV and VP condition, but not as accurate when pointing with a stick as with a finger in the PP condition, then proprioception of the reaching limb did not play a significant role in guiding the movements of VV and VP reaches in our experimental set-up. To test this hypothesis we directly compared the accuracy of reaches made with the finger and with a stick in each condition in a set of planned comparisons.

2.8 Method

2.8.1 Subjects

5 healthy, right-handed, adult volunteers from the University of Wales, Bangor, were recruited for this study. Subjects were aged between 24 and 32 (mean age 26.3 years). None had a history of head injury or neurological disorder and all had normal or corrected to normal vision.

2.8.2 Data Analysis

Movements were recorded using a 4-camera MacReflex 3.2 optoelectronic motion recording system (Qualisys inc.) sampling at a rate of 50 Hz. MacReflex cameras flash infrared light which reflects off special infrared reflecting markers back to the camera. The cameras ignore all information in the visible part of the light spectrum and thus record only information about the infrared reflecting markers. When more than one camera is being used, to enable three-dimensional recording, the positions of the cameras must be calibrated so that their positions are known relative to each other. This is done by making recordings of a calibration frame, the markers of which are a known distance from each other. The calibration frame also sets the origin and reference frame for the x, y and z coordinates. The spatial resolution is given by the manufacturers as 1/30000 of the diagonal of the field of view. In This case the diagonal was approximately 3 m, giving a resolution of 0.1 mm. A procedure similar to that described in the previous experiment was followed to check the accuracy of the system. The standard deviation of the recorded distance separating two markers was less than 1 mm throughout the workspace.

Infrared reflective markers were attached to the distal portion of the right index finger or the end of the end of the stick as required by the condition. The 3D locations of the markers was reconstructed off-line and raw data were filtered using 4th order dual pass Butterworth filter.

2.8.3 Procedure

Subjects were seated at table, identical to that described in Chapter 2, upon which rested a matt black painted wooden board raised 15 cm above the table top. Four 6 mm diameter targets were drilled through the board at target locations as laid out in Figure 2.7. Subjects pointed to the targets with their right hand using either the tip of their index finger or the end of a short hand-held stick. The stick was in fact a 16 cm standard rubber-tipped Staedtler HB pencil. Subjects held the stick with finger and thumb so that 8 cm protruded from the end of the index finger. The stick was held in such a way that it remained in line with the index finger and as such functioned as an extension of the index finger. When pointing with the finger subjects began their reach from either start location A or start location B (8 cm closer to the body). When pointing with the stick, the end of the stick was similarly placed on either start location A or B. This slight alteration from the target configuration used in the previous experiment was brought about because it was found that the starting posture while holding the stick was too uncomfortable when the target hand was placed on the more extreme target locations used in Chapter 2. The order of target presentation and start point was pseudorandomized within each condition such that no start/target combination arose three times in succession. Three pointing conditions, for both finger and stick pointing, were employed:

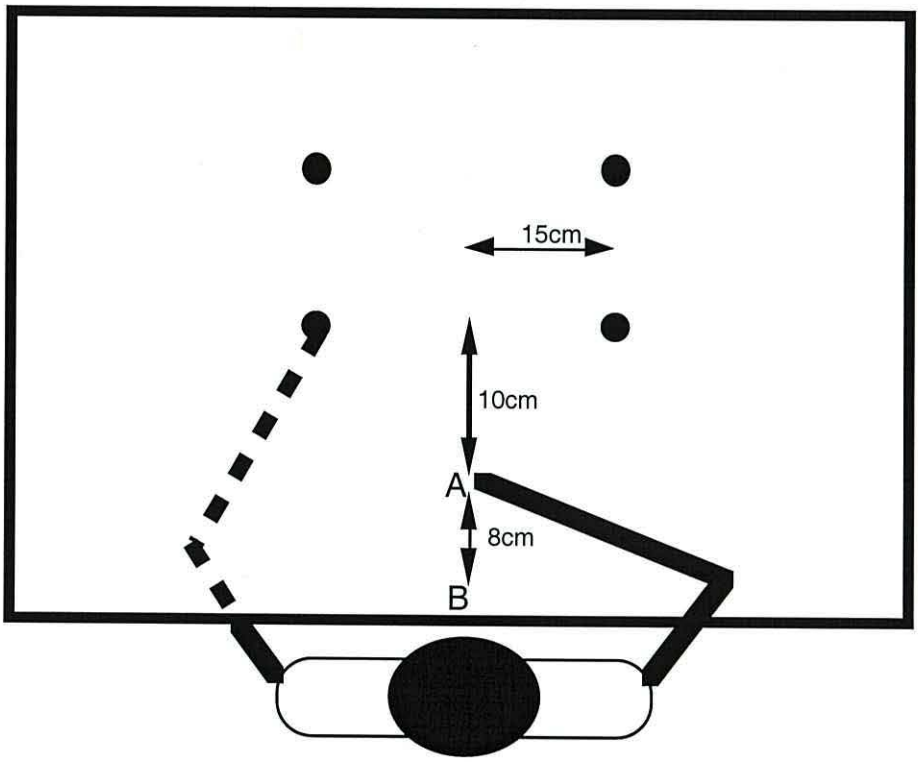

Figure 2.7: Depiction of the four target locations and two start locations A and B The right hand is above the board while the left hand is underneath.

1) Vision/Vision (**VV**) condition. Subjects pointed with their eyes open. The target location was visually-defined by the placing of a small wooden peg into the relevant drilled hole on the upper side of the raised board.

2) Vision/Proprioception (**VP**) condition. The target array was covered by a plain board so that there were no visual cues as to the target location. Each target was proprioceptively-defined by placing the index finger of subjects' unseen left hand onto the drilled hole on the underside of the raised board. In this condition subjects also had their eyes open so that visual information about the moving limb was available throughout.

3) Proprioception/Proprioception (**PP**) The target array was again covered by a plain board so that there were no visual cues as to the target location and each target was again proprioceptively-defined by placing the index finger of the subject's unseen left hand onto the drilled hole on the underside of the raised board. In this condition, however, the subject was blindfolded so that they were deprived of all visual information.

2.8.4 Dependent Measures

Direction errors (**DE**) were calculated as the angle (in degrees) formed between a straight line from start position to movement end-point and a straight line from the start position to the target location. A negative result indicates a leftward (or anti-clockwise) error and a positive result a rightward (or clockwise) error. Amplitude errors (**AE**) were calculated as the straight-line distance (in mm) from the start position to movement end-point as compared to the straight-line distance from the start position to the target location. A positive value represents an over-reach of the distance to the target and a negative value, an under-reach. Total errors (**TE**) were calculated as the Euclidean distance between the movement end-point of the effector and the target location. In all the above cases movement end-point was defined as the first frame in which the velocity of the finger (or stick) marker fell below 2.5 cm/s. The 'first frame' was determined as the first of five frames in which the mean value was below threshold and the mean value of the preceding five frames was above threshold.

As the sole purpose of this experiment was to gauge the accuracy of pointing movements no kinematic dependent measures were calculated.

2.9 Results

For each of the dependent variables mean data for individual subjects were entered in a 2 factor analysis of variance (ANOVA) with the factors: EFFECTOR (Finger vs. Stick) x CONDITION (VV vs. VP vs. PP). As outlined in the introduction, a priori pairwise comparisons were performed on mean values for the following CONDITION pairs: VV(finger) vs. VV(stick); VP(finger) vs. VP(stick); PP(finger) vs. PP(stick).

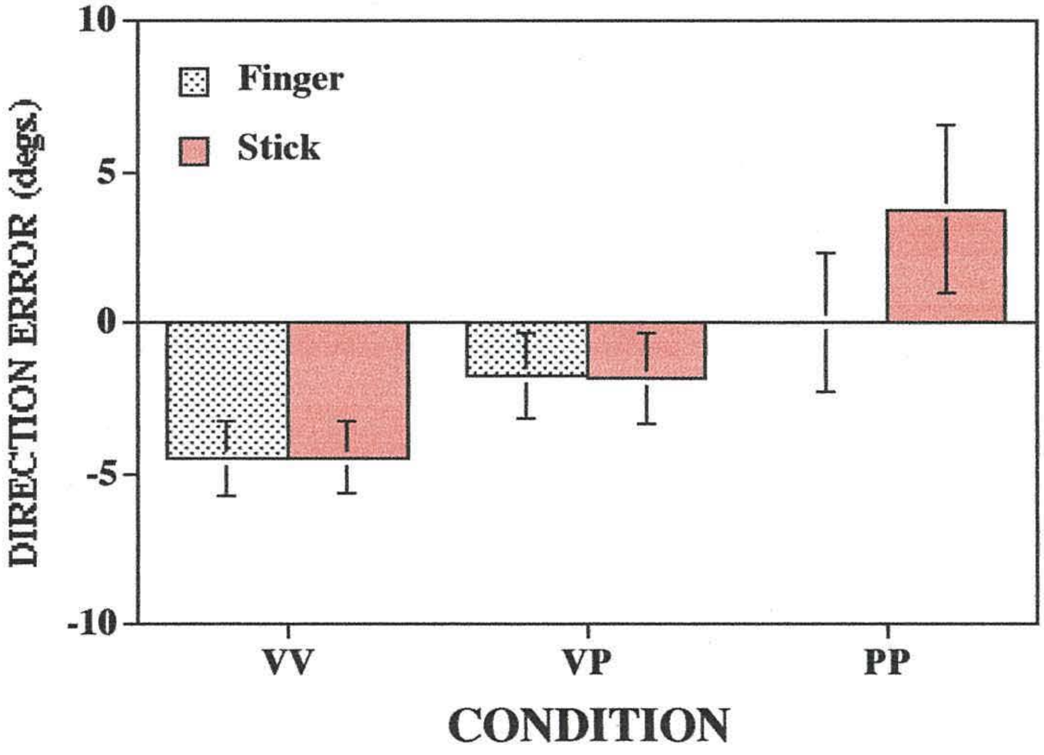

Figure 2.8: Graph plotting direction error in degrees for finger and stick pointing in each condition. Standard Error Mean bars are also shown.

Direction Error

There was a significant main effect of CONDITION ($F_{[2,10]} = 11.9$, $p < 0.05$), a significant main effect of EFFECTOR ($F_{[1,5]} = 7.3$, $p < 0.05$) as well as a significant CONDITION x EFFECTOR interaction ($F_{[2,10]} = 10.2$, $p < 0.05$). A priori analyses revealed that for direction error there were no significant differences between finger and stick pointing in either the VV or VP condition (VV(finger) vs. VV(stick): $F_{[1]} = 0.0002$, $p > 0.9$; VP(finger) vs. VP(stick): $F_{[1]} = 0.009$, $p > 0.9$). Reaches made with a stick were significantly less accurate than those made with the finger in the PP condition however ($F_{[1]} = 30.1$, $p < 0.0005$). Means for each condition are given in Figure 2.8.

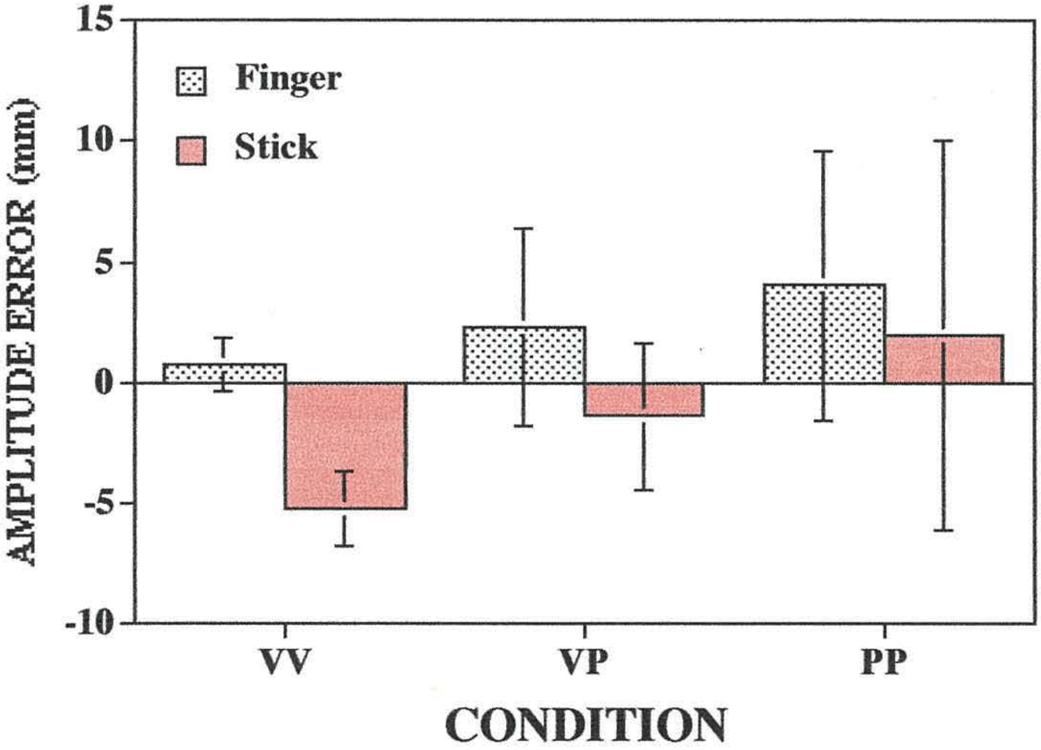

Figure 2.9: Graph plotting amplitude error in mm for finger and stick pointing in each condition.

Amplitude Error

There were no significant main effects or interactions for amplitude error. A priori comparisons revealed no significant differences for finger pointing compared to sick pointing in any of the conditions (minimum $F_{[1]} = 1.9$, $p = 1.959$. Means for each condition are given in Figure 2.9.

Total Error

For total error scores there was a significant main effect of CONDITION ($F_{[2,10]} = 16.6$, $p < 0.01$), a significant main effect of EFFECTOR ($F_{[1,5]} = 6.9$, $p < 0.05$) and a significant CONDITION x EFFECTOR interaction ($F_{[2,10]} = 20.0$, $p < 0.01$). As with direction error scores there were no significant differences found for total error between

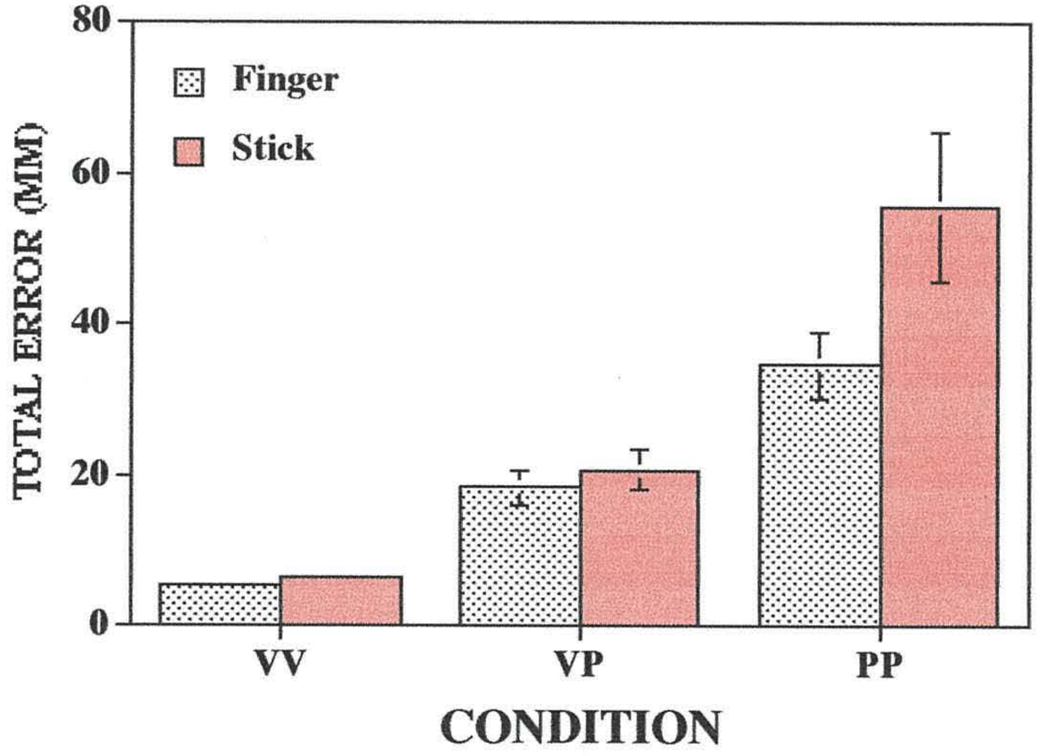

Figure 2.10: Graph plotting total error in mm for finger and stick pointing in each condition. Standard Error Mean bars are also shown.

finger and stick pointing in either the VV or VP condition (VV(finger) vs. VV(stick): $F_{[1]} = 0.1$, $p > 0.5$; VP(finger) vs. VP(stick): $F_{[1]} = 0.2$, $p > 0.5$). Reaches made with a stick were significantly less accurate than those made with the finger in the PP condition however ($F_{[1]} = 18.9$, $p < 0.05$). Means for each condition are given in Figure 2.10.

2.10 Discussion

The results of this experiment show that being able to feel, as well as see, the pointing hand does not significantly improve pointing accuracy when pointing to either a visually-defined or proprioceptively-defined target. This finding is not at all surprising given that deafferented humans and primates are well able to reach accurately towards visual targets (e.g. Polit and Bizzi 1979; Sanes 1985; Ghez 1990). We cannot say conclusively from this experiment whether subjects were able to estimate the length of the stick and subsequently guide it by using proprioceptive information about the limb holding the stick. It is likely that they were able to do something of the kind in order to perform reasonably well in the blindfolded (PP) condition in which they had no visual information or direct proprioceptive information regarding the point in space they were required to direct. If subjects were able to estimate the length of the stick and thus guide it by proprioception of the limb holding the stick, however, then this was not sufficient to have a bearing on our results. We are satisfied that our results effectively rule out the possibility that proprioception plays a significant role in the guidance of reaches in the VV and VP conditions and that as a consequence we are able to draw conclusions about the visually-guided aspect of our paradigm with confidence.

Chapter Three

3. The sensorimotor integration of visual and proprioceptive information in a group of patients with a disorder of visual space representation.

3.1 Introduction

In Chapter 2 we saw how the hand path curvature and end-point errors of healthy normal subjects provided evidence for a change in the frame of reference used in the planning of reaches aimed at visually-defined targets from those aimed at proprioceptively-defined targets. In this chapter these findings will be extended to a small group of individuals suffering from a disorder known as spatial neglect.

Patients with spatial neglect fail to respond appropriately to stimuli or events occurring within their contralesional hemispace. Eye and hand movements to objects or events occurring within ipsilesional space may also be restricted. Common bedside tests for spatial neglect include: line bisection (drawing a stroke mark through the centre of a line on a sheet of paper), cancellation (crossing out particular shapes or letters in an array containing a variety of shapes or letters), clock-drawing (drawing the face of an analogue clock, complete with numbers and hands) and copying (reproducing a drawn scene, usually consisting of largely symmetric objects (e.g. a house) with some asymmetric features (e.g. a chimney on one side)). Typical behaviour on these bedside tests includes: bisecting lines to the right of centre, omitting shapes or letters on the left hand side of a cancellation array, placing all the numbers of a clock face on the right hand side of the face and drawing only the right hand side of a scene, or the right hand side of each object within that scene (see Robertson and

Marshall, 1993, for comprehensive reviews). Such behaviours are generally thought to result from an impairment in the ability to construct an appropriate representation of extrapersonal space (Halligan and Marshall, 1991; Milner and Harvey, 1995), or as a consequence of an attentional bias which favours the processing of ipsilesional stimuli (Làdavas, 1990).

The attentional bias hypothesis was investigated by Làdavas (1990) who assessed the attentional performance of patients with visual extinction. With visual extinction only the ipsilesional stimulus is detected if visual stimuli are presented bilaterally and simultaneously, but both ipsilesional and contralesional stimuli are detected if they are presented on their own. Visual extinction is doubly dissociable from neglect, but the two syndromes frequently co-occur and extinction is commonly associated with neglect by many authors. Làdavas (1990) found that patients were faster to respond to right compared to left stimuli when instructed to attend to 3 spatial positions simultaneously located on the left, on the right and directly above the fixation stimulus. In a second experiment, in which patients focused attention on the right location, the speed and accuracy of responses to the right stimulus were the same as in the first experiment. Làdavas argued that the focus of attention in patients with visual extinction was on the rightmost stimulus and that the increased attention to the right is accompanied by a decreased attention to the left. Alternatively, Halligan and Marshall (1991) proposed that the distorted representation of space in neglect is compressed. They investigated a single patient (PP) with severe left neglect on a visuospatial localization task. An arrow could be presented either at the top or bottom of a monitor and always appeared at a location opposite an array of numbers. The task was to estimate visually the corresponding spatial position on the array of numbers to which the arrow was pointing by following 'in imagination' the direction of the arrowhead across 'empty' space. The patient showed systematic bias or 'deflections' in her judgement of target positions. Halligan and Marshall (1991) argued for a linear and uniform compression of visual space along the horizontal axis. Milner and Harvey (1995) also demonstrated what might be described as a compression of left visual space in three left neglect patients. Their task involved a relative size judgement for objects presented on the left and right side of a computer monitor. The horizontal dimension of left hand objects had to be substatially larger than the right hand object before it was perceived to be larger by the patients. Thus objects on the left appeared to have been compressed compared with those on the right.

Neglect patients may also suffer from an impairment in encoding the location of left-sided target and in computing the spatial and temporal aspects of a goal-directed movement towards those targets (Heilman, et al., 1985; Mattingley et al., 1992). Thus the neglect syndrome has variously been described as both a disorder of motor control and a disorder of the visual or attentional system and it has been difficult to dissociate between these two experimentally.

Attempts to dissociate the direction of hand movement from that of visual attention have included the use of pulley systems (Bisiach et al., 1990) or 90-degree mirrors (Tegnér and Levander, 1991; Bisiach et al., 1995). These studies have reported that some patients, particularly those with lesions extending into the frontal lobe, appear to have a direction-specific motor impairment. According to Mattingley and Driver (1997), however, there are serious problems with this interpretation, amongst which is the possibility that patients with frontal damage may be impaired on opposition tasks simply because they have general difficulties with incompatible tasks like moving their hand in the opposite direction to the target. The experimental set-up used in our proprioceptive pointing paradigm should allow for a dissociation between visual and motor factors because the motor component of the task is identical in all conditions.

Although spatial neglect can occur following damage to a variety of a brain regions, it is chiefly associated with damage to the inferior parietal lobule (IPL) and most frequently it involves the occipito-temporo-parietal junction of the right hemisphere (Vallar, 1993). The IPL is located in the posterior aspect of the parietal lobe adjacent to the occipital lobe and receives inputs from visual and somatosensory cortices. Lesions here do not affect the primary aspect of vision or somatosensation (i.e. they do not cause blindness or numbness), rather they produce deficits in complex cortical functions such as spatial perception and visuomotor integration (Andersen 1987). The posterior parietal cortex (PPC) is well placed to transform visuospatial input into a plan for motor output because it lies between the visual areas which encode spatial information and motor cortical areas (Snyder et al., 1997). Visually-guided reaching movements involve transforming visual information signalling the spatial position of the target, into a motor plan specifying the sequence of postural changes required to bring the hand to the target (Georgopoulos, 1995). Neurophysiological studies in the monkey suggest that the sensorimotor transformations associated with the planning and control of visually guided action are mediated by cortical circuits linking the occipital and posterior parietal cortices with motor regions of the frontal lobes (Snyder et al., 1997; Rushworth et al. 1997a). Rushworth et al. (1997a) trained monkeys to reach to visually-defined targets in the light and to targets defined by remembered limb position in the dark. Removal of areas 7a, 7ab and LIP caused reaching errors in the light, but not in the dark, while removal of areas 5, 7b and MIP had the opposite effect, suggesting that the two divisions of the parietal cortex organize limb movements in distinct spatial coordinate systems.

Patients with neglect have been found to produce abnormally curved hand paths when executing reaching movements. Such abnormalities may frequently persist long after the perceptual impairments associated with neglect are no longer evident (Goodale et al., 1990; Harvey et al., 1994; Chieffi et al., 1993). The existence of abnormally curved hand paths in patients with hemispatial neglect has been the source of some debate since 1990 when Goodale et al. first reported an initial rightward movement bias in patients who had previously shown, but no longer displayed, clinical signs of neglect. The remarkable pictures associated with this finding (Figure 3.1) inspired a new direction in kinematic studies and encouraged students of neglect to look beyond a hundred years of line bisection. The evidence for the initial rightward bias reported by Goodale et al. (1990) is initially striking, but in fact relatively thin. The observation appears to be based entirely on non-kinematic, non-statistical descriptions of selected reaches in selected patients. Although the abnormal curvature is undoubtedly real, the extent of this abnormality was exaggerated by presenting the data on XY plots with unequal axes: the X (across) scale is twice that of the Y (forward) scale and as neither scale is numbered, this has the effect of amplifying the apparent curvature of the reach.

A study by Harvey et al. (1994) which examined a group of right brain damaged (RBD) subjects found reaches with an increased rightward bias only when the reaching hand was not visible. Only two of the RBD patients in this study, however, had ever shown any signs of neglect and they had both recovered, clinically, by the time of testing. In 1993 Chieffi et al. assessed the curvature of hand paths during reach-to-grasp movements following neglect. Their patient, who also no longer displayed clinical signs of neglect, exhibited a rightward reaching bias when reaching for objects in the presence of an irrelevant ipsilateral distractor.

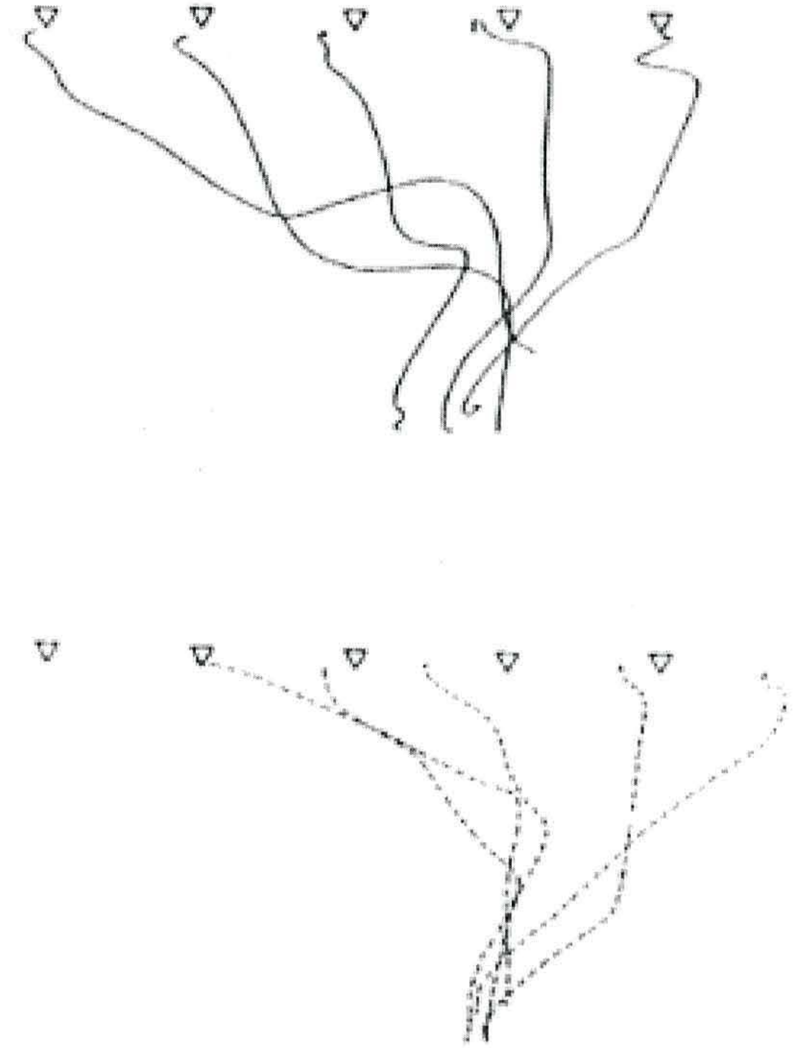

Figure 3.1: Reproduction of sample reaching data describing excessive rightward curvature of Patient D55 on single target pointing (top) and two-target bisection (bottom). From Goodale et al., 1990.

Goodale et al. (1990) suggested that the use of kinematic analysis in their task had revealed a persisting hemispatial neglect despite the patients' apparent recovery according to less subtle standard clinical examinations. More recently it has been argued, by Karnath et al. (1997), that as very few of the patients in these three studies actually had neglect at the time of

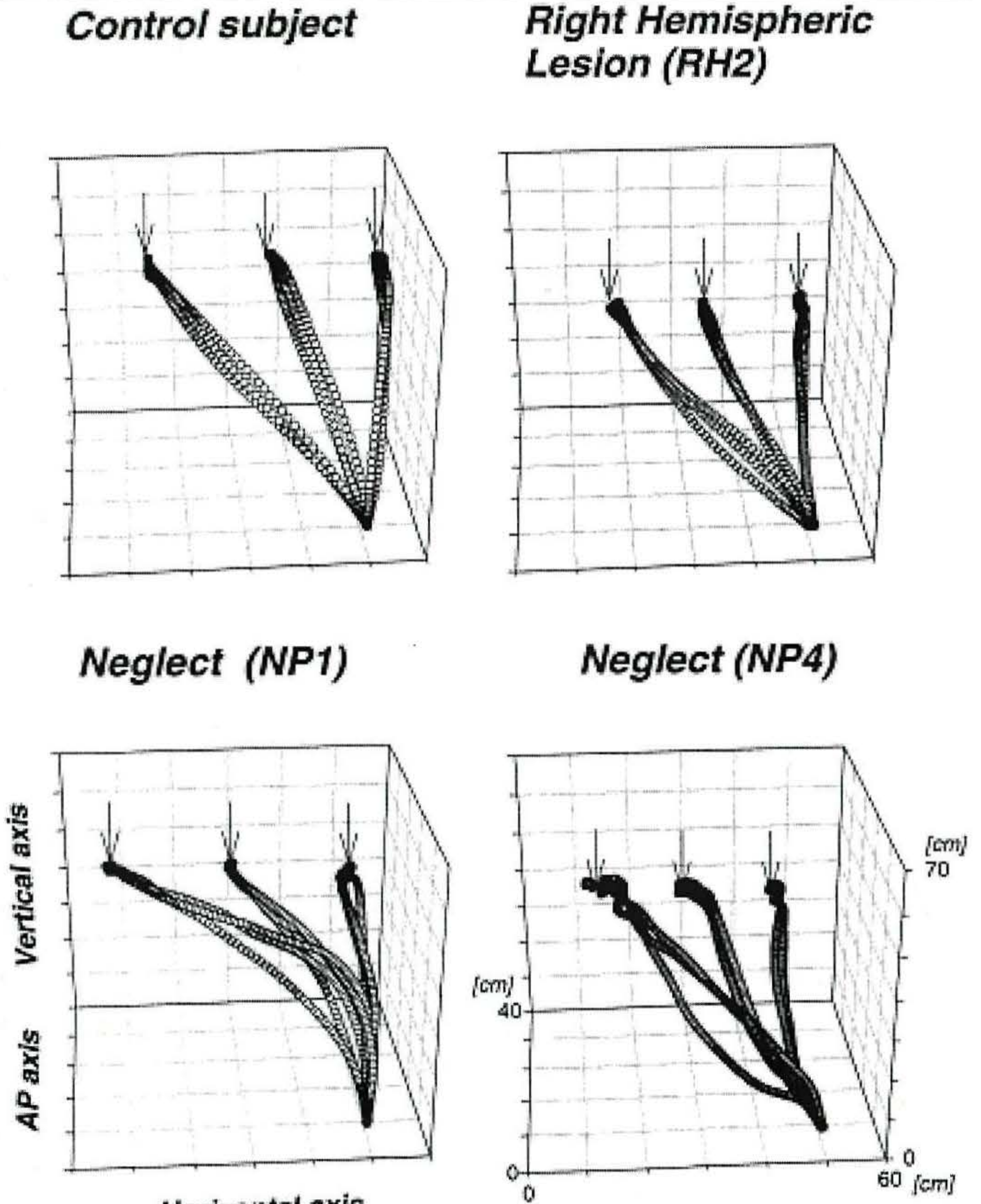

Figure 3.2: Exemplar hand paths from selected subjects from Karnath et al., 1997. Note that if the scales on each graph are the same then, although the start locations are all identical, the target locations (depicted by the arrows) are not. Particularly, note the width between the targets for NP1 and NP4 and the difference in the laterality of the right hand target between the control subect and NP4.

testing, the abnormal curvature reported may not have been a result of neglect at all. Rather the deviations reported by Goodale et al. (1990) may be indicative of a subtle, sub-clinical optic ataxia. To this end Karnath et al. conducted a pointing study in which the performance of 5 RBD patients with clinically manifest neglect was compared against the performance of two control groups: a healthy control group (n=6) and a RBD patient group without neglect as assessed by standard clinical testing (n=5). This study differed slightly from those reported previously. Pointing movements were performed either in the light or in total darkness to targets which were presented as free standing LED's in 3D space (i.e. they were not mounted on a table top or back board). The targets were not arranged equally across the workspace in respect of the initial position of the reaching hand; two targets to the left of the reaching hand and the other was more or less straight ahead. The exact placement of the targets is not given in the text of the paper, but close inspection of the graphs (see Figure 2) seems to indicate that target placement varied from subject to subject. The authors reported that all three groups performed their hand paths with the same straightness. It is clear from both Karnath et al.'s (1997) own descriptions and the graphs of their data (see Figure 3) that at least two of the five neglect patients performed the task in a substantially different manner to that of the other neglect patients, the non-neglect patients and the control subjects, all of whom performed stereotypically. The two patients in question appeared to raise the hand vertically to eye level before moving forward towards the target as well as deviating substantially in the horizontal plane. Both these patients displayed extraordinary hand path curvature in some, but by no means all, trials, particularly when reaching across the body midline into contralateral space. In one patient the curvature was ipsiversive, the other contraversive. The patients in question were the cases with the most severe neglect symptoms. It is a pity that these two patients were not studied further or that their data was not analyzed in more detail. The potentially interesting finding that the degree of abnormal curvature might be related to the severity of the neglect was lost in the group data. The reaching abnormalities of these patients was not restricted to the shape of their hand paths. The velocity profiles of reaches performed by the neglect patients were also abnormal insofar as peak velocity was achieved extremely early in the reach (see Konczak and Karnath, 1998).

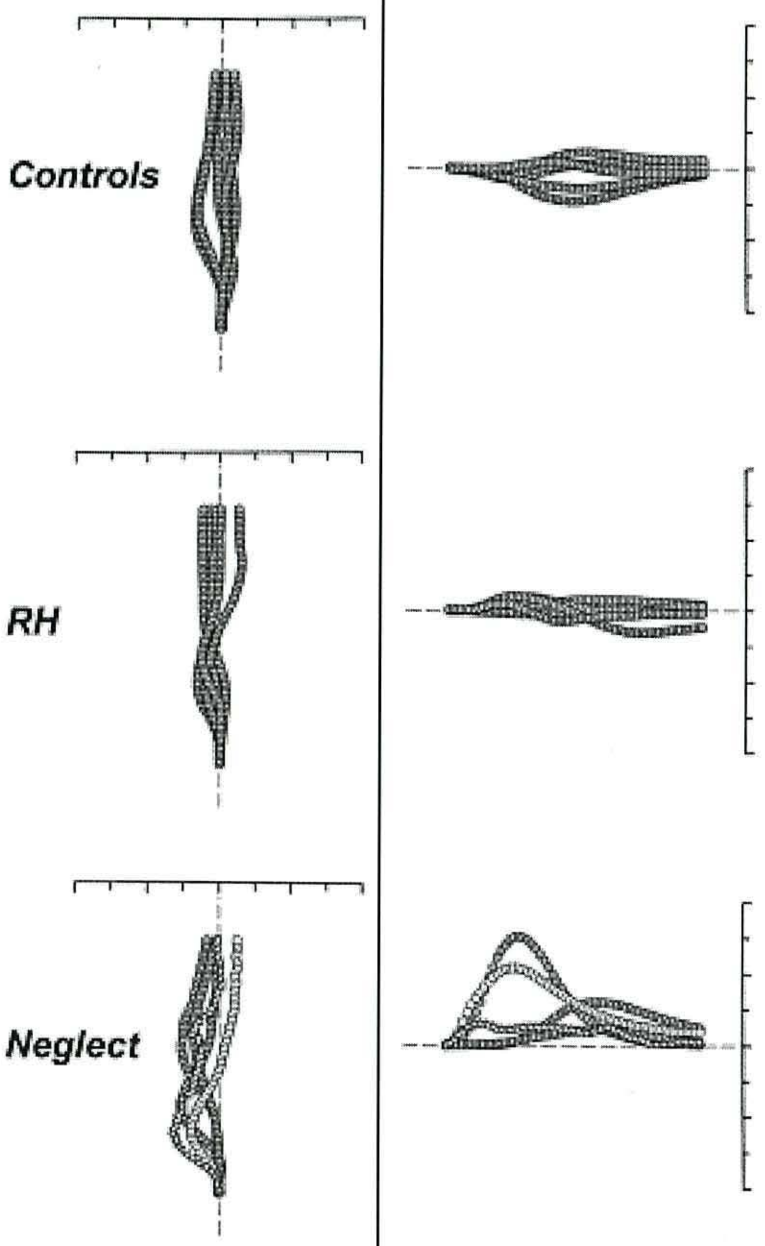

Figure 3.3: Averaged hand paths into left space from Karnath et al., 1997. Note the abnormal deviations in at least two of the neglect group for both horizontal (left hand column) and vertical (right hand column) displacement. Note how some hand paths by NP1 and NP4, depicted in Figure 3.2, also show abnormal deviations.

All of the above studies highlight the fact that neglect patients are heterogenous as a patient group and we can only conclude that some RBD patients exhibit abnormally curved reaches under certain conditions. That some of these patients have 'recovered' from neglect (according to standard clinical bed-side tests) and the fact that some patients, who have not recovered, do not show abnormal hand paths does not necessarily mean that abnormal hand path curvature is not a symptom of neglect. Neglect has traditionally been assessed by the use of a simple battery of pencil and paper tests such as line bisection, cancellation, copying, drawing etc. and for years this is all that technology has allowed us to use. It is a tautology, however, to use these standard assessments to 'define' neglect. Even within these traditional tests there are a wide range of dissociations. For example, patients may perform badly on line bisection, but not on cancellation, or vice versa, or even omitting to the right on one test and to the left on another (Halligan and Marshall, 1998), yet these patients are all still diagnosed as having neglect. Thus, it is unclear what behavioural measure should be used to define that a patient has, or does not have, neglect. The study reported by Goodale et al. 1990 is a good illustration of this point. All of the patients tested in Goodale's study, had been clinically diagnosed as having neglect, but this was no longer apparent when the behavioural (reaching) tests were carried out. The patients showed clear deviations in their limb trajectories during reaching, but was this due to a residual or sub-clinical visual neglect which could only be detected by the more sensitive reaching tasks as suggested by Goodale et al. (1990), or due to a previously undiagnosed and sub-clinical optic ataxia coexisting with the neglect as suggested by Karnath et al. (1997)?

It is not unreasonable that abnormal reaching behaviour may be a symptom of the broad classification of neglect which dissociates from some or all of the more standard clinical bed-side tests. However, to pursue the matter of whether abnormal hand path curvature exists as part of the 'neglect' syndrome is to miss a more fundamental point. It is of far greater theoretical importance to determine, in those patients in which abnormal reaching does occur, why it occurs and what the underlying processes and mechanisms may be.

Even in neurologically intact individuals, unconstrained reaching movements produce hand paths that are very gently curved. The degree of curvature can vary with movement direction (Miall and Haggard, 1995), task demands (Desmurget et al, 1997a) or as a consequence of non-target distractor objects or attended regions of space (Tipper et al., 1997; Howard and Tipper, 1997) The reason for the observed curvature in normals has been the subject of much debate. The various hypotheses that have been proposed can be boiled down to two basic ideas. The first is that hand paths are planned so that they optimize control variables related to the dynamics of the arm and that the kinematic and spatial invariances observed in human movement (e.g. Morrasso, 1981) are merely a side-effect. For example, Uno et al. (1989) proposed a model which minimizes the total squared changes of torque in producing the movement. Hand paths produced by the optimal minimum torque change are slightly curved and the degree of curvature changes with the direction of movement. The arm is proposed to follow accurately a path planned in intrinsic (joint or muscle) coordinates without reference to the path followed in extrinsic coordinates. Hollerbach and Atkeson (1987), inspired by robotics, also propose control of intrinsic variables by joint interpolation, rather than the spatial path of the hand movement. They suggest that the CNS derives the motion of the joints from the planned path of the limb end-point (inverse kinematics), computes the necessary joint torques (inverse dynamics), and then distributes the task of generating these torques amongst the muscles. This would require the

CNS to be able to estimate limb inertias, centre of mass and the moment arm of muscles accurately. This does not seem likely as a small feed-forward parameter error would lead to large motor instabilities. The alternative hypothesis, however, proposes that the path is actually planned in extrinsic coordinates, independent of the dynamic conditions, and the desired path is straight (Flash and Hogan 1985). The flagship of the extrinsic coordinates models is the equilibrium point hypothesis in which the CNS transforms the desired hand motion into a series of equilibrium positions (Bizzi et al., 1984; Feldman, 1986). The forces needed to track the equilibrium trajectory result from the elastic properties of the muscles. The elastic properties of the arm muscles allow the brain to deal with the inverse dynamics problem as it does not need to compute anything too complex. These elastic properties also provide instantaneous correcting forces when a limb is perturbed away from the intended trajectory. Once the brain can represent and control equilibrium postures it can control movements as temporal sequences of such postures. Thus the equilibrium point hypothesis can account for movement planning and on-line control without having to compute any of the complexities of limb dynamics, such as limb inertia. The initial acceleration of the limb varies systematically with the direction of movement: initial acceleration is lower for movements in directions of high limb inertia (Gordon et al., 1994b), which suggests that movements are generated by a shift in equilibrium position independent of direction and without reference to the inertia of the limb. Further support for the equilibrium-point hypothesis comes from work on the spinal cord of frogs by Bizzi et al. (1991). They found that stimulation of the spinal cord produces force vectors which move the leg to a certain position, regardless of the initial position of the leg. Stimulation of another point produces force vectors to move the leg to another position and stimulation of both points produces a summation of these force vectors.

If hand paths are planned in extrinsic coordinates, however, they should be straight. According to Flash and Hogan (1985), although hand paths are frequently observed to be slightly curved, the desired path is actually straight. One explanation for deviation from a straight line is that although the desired straight-line path may be defined by intermediate representations (e.g. a series of equilibrium positions), the limb dynamics and joint interactions lead to the actual trajectory being curved. Alternatively, the brain mechanism which control the reach may be inaccurate or incomplete and curvature is an unavoidable error in performance. Finally, there may be a visual misperception of a straight line: the hand follows what is perceived by the subject as a straight path, but is actually curved in real space (Wolpert et al., 1994). One or all of these could contribute to movement curvature. Good evidence that the latter (visual misperception) contributes to hand path curvature was provided by Miall and Haggard in 1995. They compared the hand path curvature of blind subjects with that of sighted, but blindfolded, subjects. The curvature of reaches by the blindfolded subjects was significantly higher, leading Miall and Haggard (1995) to suggest that this was as a result of their distorted visual experience. Spatial hand paths, therefore, may be influenced by sensory inputs (e.g. vision) and movement curvature is not the result of the dynamics of limb control alone.

Thus, hand path curvature has assumed theoretical importance as a means of differentiating between models of trajectory planning. Determining between these accounts has proven difficult: movements directed to different parts of space invariably involve different postural configurations which makes it difficult to rule out motor constraints of limb dynamics (or limb kinematics). Furthermore, experiments which use between-subjects designs (e.g. Miall and Haggard, 1995) may involve subjects who have different limb-segment lengths and, as a consequence, their limbs will have different biomechanical properties. Here, we avoid biomechanical explanations of hand path curvature by examining reaches which have identical start positions and target locations, within the same subjects, but which are executed under different sensory conditions.

The patients used in the current study, as is the case with many left-sided neglect patients, were unable to perform reaching tasks with their contralesional arm. For this reason the study will focus on reaches into ipsilesional and contralesional space made with the ipsilesional arm only. Reaches executed using the right arm into the left and right hemispace will differ biomechanically as they each involve different muscle groups and joint rotations. As we saw in Chapter 2, this will have implications for movement initiation time, movement execution time, and the path of the limb through space. Consequently, the main focus of the analyses will be to determine differences between the sensory conditions as a whole, rather than examine reaches across the workspace, in a series of planned comparisons. However, as outlined earlier, the averaging of reaches into opposite sides of space can serve to obscure abnormal reaching behaviour (see discussion of Karnath et al., 1997 earlier in this text). In addition, since Goodale et al. first published their graphs of errant hand paths in 1990 there has been a common assumption within motor control that the hand paths of neglect patients show a large ipsiversive bias, particularly when reaching into contralateral space. To address this issue directly, the direction of curvature will be examined separately in both left and right space.

3.2 Method

3.2.1 Patients

Patient LGC sustained a right-hemisphere cardio-vasculo-cerebral accident (CVA) in February 1996 at the age of 77. A subsequent computerized tomography (CT) scan revealed a lesion involving right

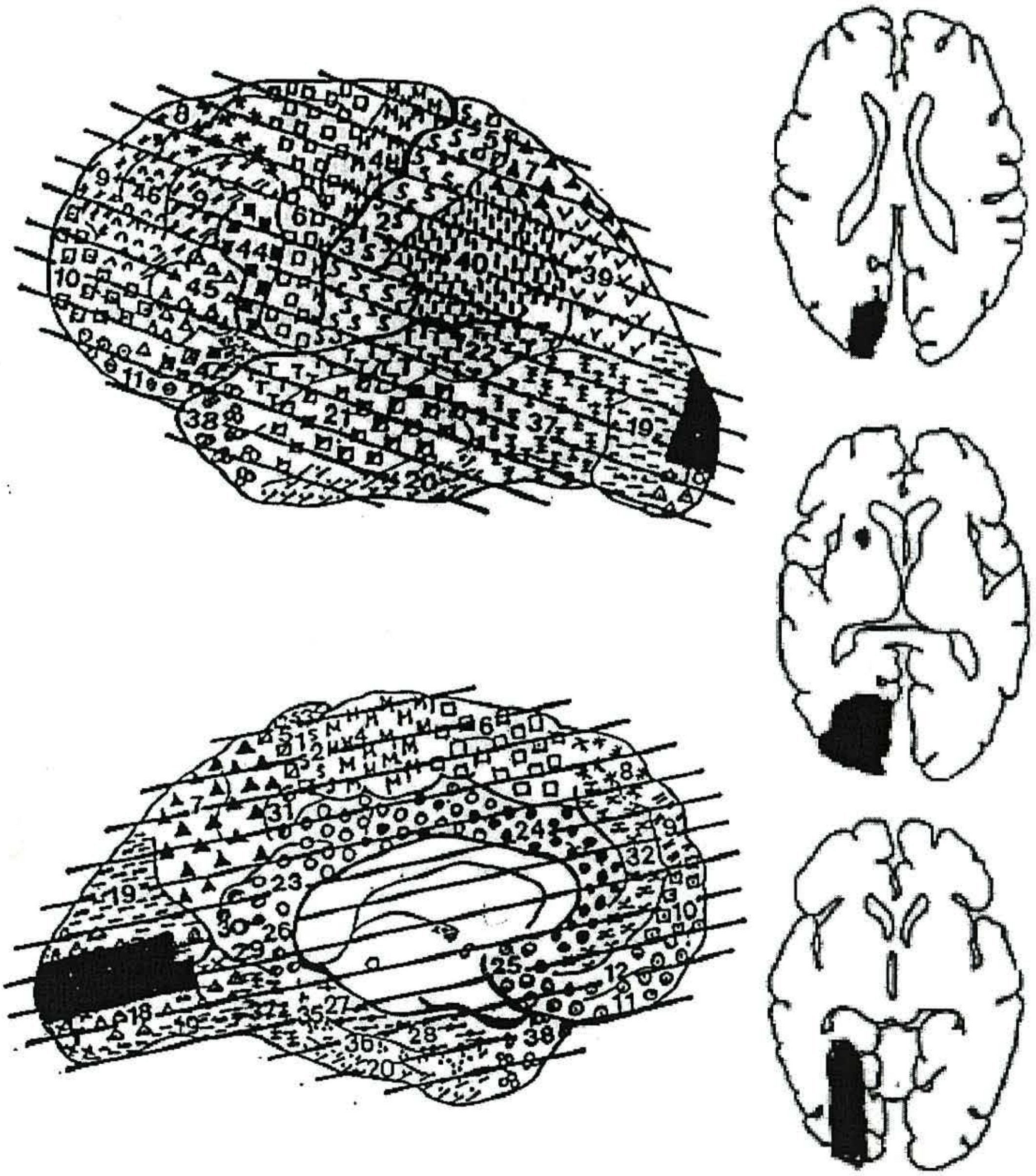

Figure 3.4: Lesion reconstructions for patient LGC drawn on standard templates (Damasio and Damasio, 1989). The right side of the brain is shown on the left and vice versa. See text for details of lesion.

occipital cortex which extended into the inferior temporal lobe, and a separate, deeper lesion involving the basal ganglia (see Figure 3.4). Behavioural assessment immediately prior to testing (May 1997) revealed a left hemiparesis, left hemianopia, and severe left spatial neglect. She was severely impaired on a range of cancellation tasks taken from the Behavioural Inattention Test (Vallar, 1993) scoring 18/36 on simple line cancellation, 6/40 on letter cancellation, and 8/54 on star cancellation, omitting items presented on the left in each case. She was also severely impaired on figure and shape copying and on a range of line bisection tasks she showed a consistent rightward bias (see Figure 3.5). In contrast, LGC showed a preserved ability to draw from memory and was unimpaired on a range of neuropsychological assessments of memory and verbal intelligence. Although she was unable to move her left arm by her own volition, it could be moved passively through the full range necessary for the experiment. She also had normal somatosensation in her left hand

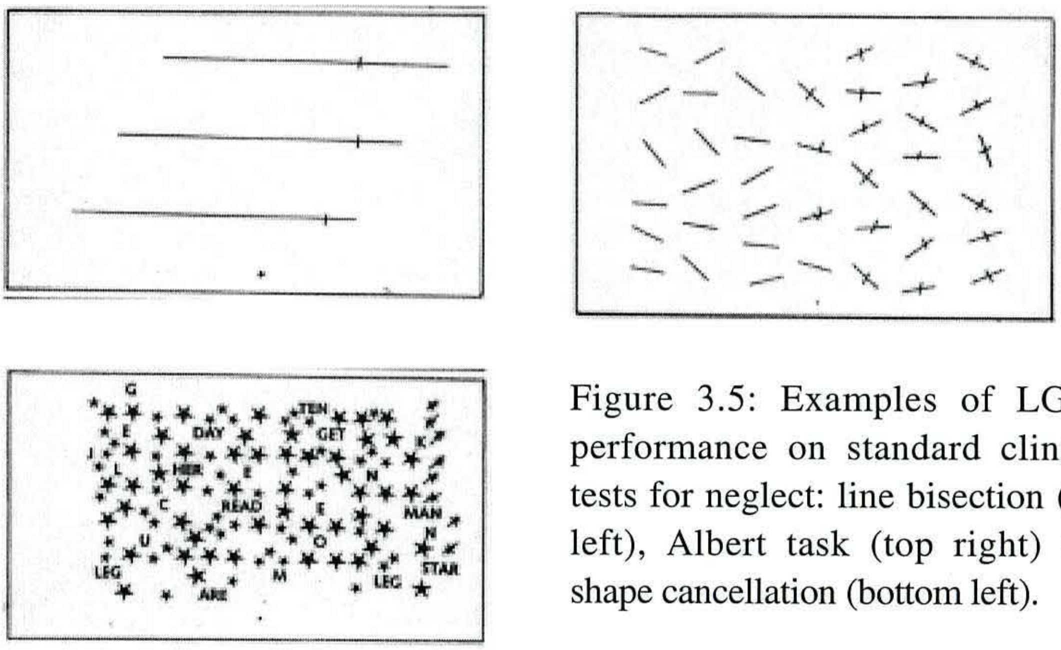

Figure 3.5: Examples of LGC's performance on standard clinical tests for neglect: line bisection (top left), Albert task (top right) and shape cancellation (bottom left).

as assessed by a range of tests including perception of cutaneous stimulation and joint rotation.

Patient RB sustained a right-hemisphere stroke in December 1997 aged 83. A CT scan revealed an extensive haemorrhage involving the right temporo-parietal cortex, together with a partial obliteration of the right lateral ventricle (shown in Figure 3.6). Behavioural assessment immediately prior to testing (May 1998) revealed a severe left spatial neglect. RB showed no evidence of hemianopia, but was severely impaired on a range of cancellation and line-bisection tasks as well as drawing from memory and picture copying (presented in Figure 3.7). As with LGC, RB's cancellation errors consisted of the omission of items presented on the left, and his line bisection performance showed a consistent rightward bias. RB also displayed symptoms of neglect dyslexia, either omitting or substituting letters at the beginnings of words (for example: reading apple for grapple and junction for dysfunction). RB was a highly distractible individual: he seemed compelled to stop and look out of every window on the right hand side of a corridor while completely ignoring those on the left. He would also attempt to show people a nasty and obviously painful cut, sustained after walking into the left hand side of a doorway, on his left wrist, but RB only ever looked for it on his right wrist. In early testing sessions RB was known to stop in mid reach to look out of a window to the right before orienting back to the target and completing the reach. RB was unimpaired on a range of neuropsychological assessments including both memory and verbal intelligence. Like LGC, RB had normal somatosensation in his left hand.

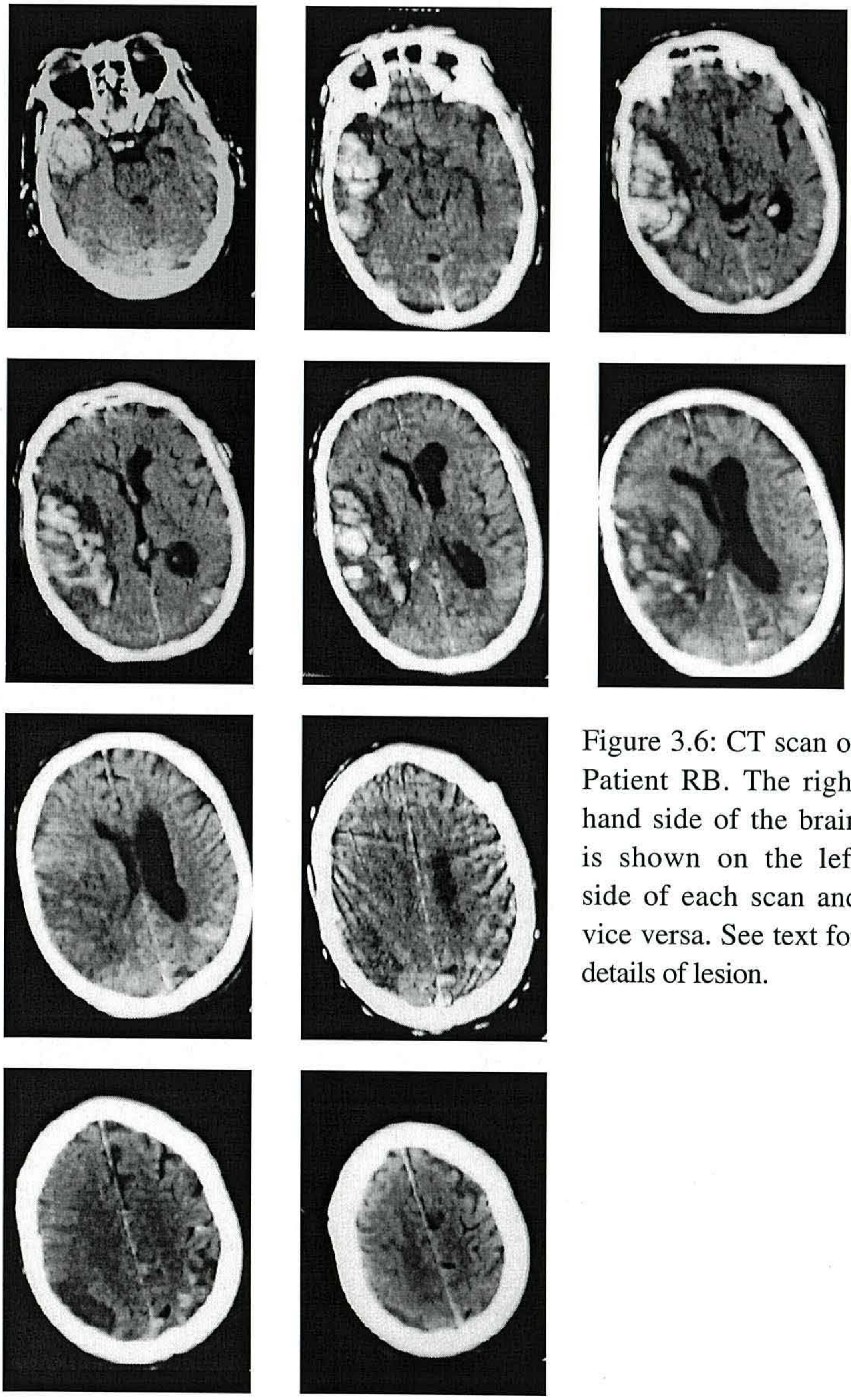

Figure 3.6: CT scan of Patient RB. The right hand side of the brain is shown on the left side of each scan and vice versa. See text for details of lesion.

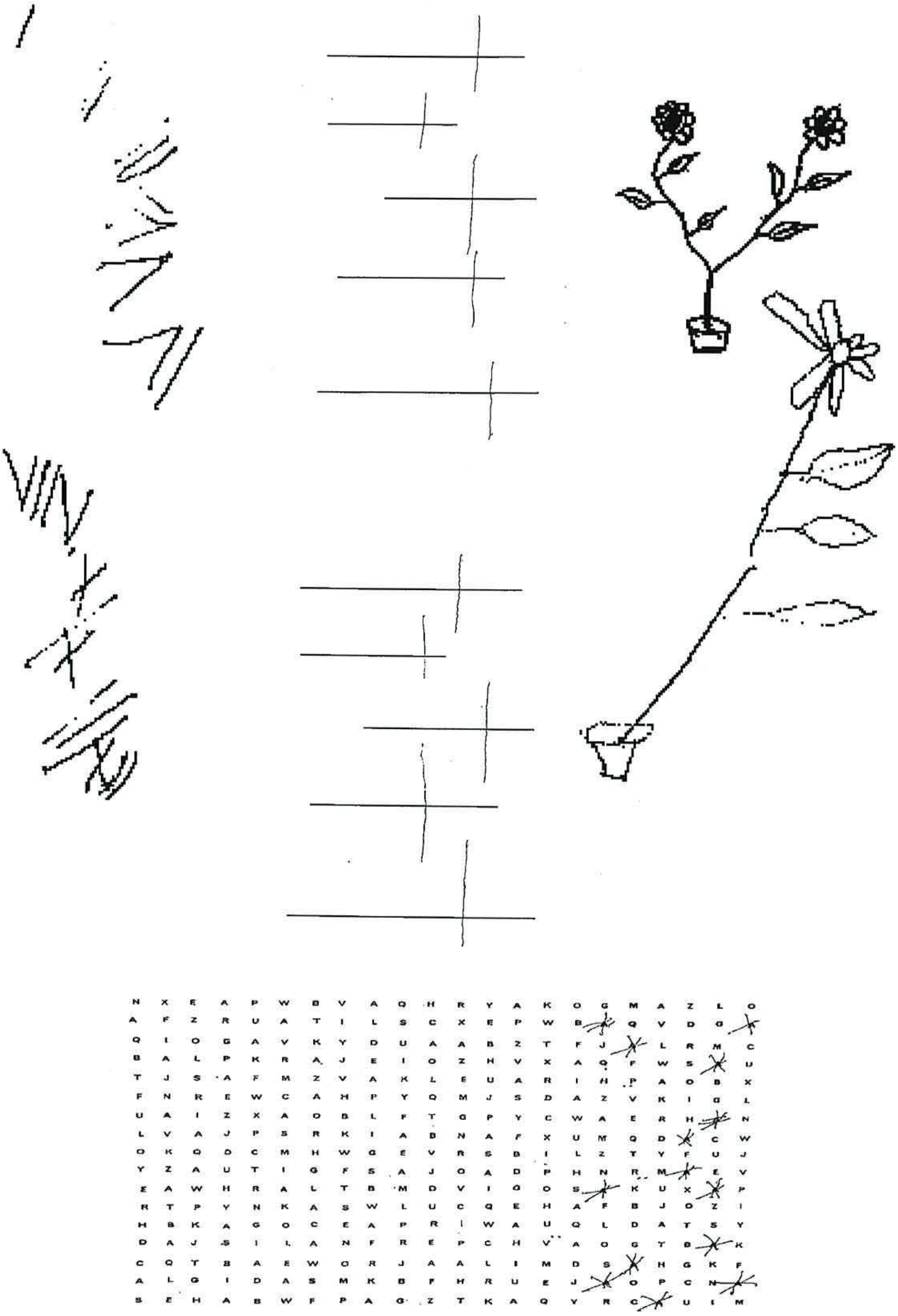

Figure 3.7: Examples of RB's performance on standard clinical tests for neglect: clock drawing (top left), line bisection (top centre), picture copying (top right) and letter cancellation (bottom).

Patient MJH, a 72 year old man, sustained a right-hemisphere infarct involving the territory of the right middle cerebral artery (Figure 3.6) in February 1997. Behavioural assessment immediately afterwards revealed a moderate-to-severe left neglect. However, behavioural assessment immediately prior to testing (in May 1997) revealed no evidence of any residual neglect: MJH completed all cancellation, line-bisection and other tasks used to assess neglect without error or rightward bias. Like both LGC and RB, MJH was also unimpaired on a range of neuropsychological assessments including both memory and verbal intelligence. MJH also had normal somatosensation in his left hand.

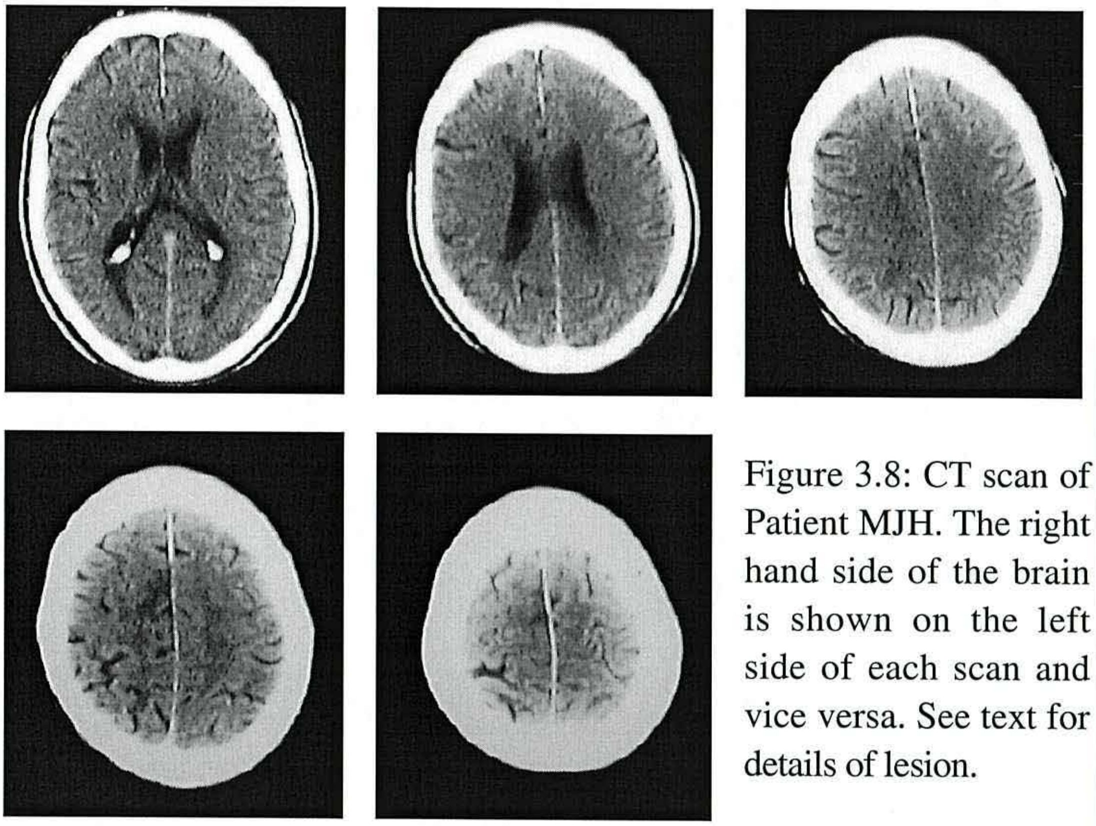
Figure 3.8: CT scan of Patient MJH. The right hand side of the brain is shown on the left side of each scan and vice versa. See text for details of lesion.

3.2.2 Data Analysis

For RB, movements were recorded using the same miniBIRD electromagnetic recording equipment as that described in Chapter 2 . Movements for LGC and MJH were recorded using a 4-camera MacReflex optoelectronic motion recording system (Qualisys inc.). This is the same equipment as used in Chapter 2 to confirm the accuracy of the miniBIRD system. All recordings were made at a sampling rate of 50 Hz and raw data were low-pass filtered using 4th order dual pass Butterworth filter with a cut-off frequency of 10 Hz.

3.2.3 Procedure

The procedure and apparatus was identical to that used in Chapter 2 with the exception that the three conditions were presented in an ABCCBA design with each condition split into two blocks consisting of two trials to each target location. To recap briefly, patients made pointing movements with the index finger of their right hand to eight target locations across the workspace. The targets were defined either visually, by a wooden dowel visible on the upper side of the pointing board (VV condition), or proprioceptively, by passively placing the index finger of the left hand, unseen, on the target location on the under side of the pointing board (VP and PP conditions). The pointing hand, on the upper side of the pointing board, could either be seen (VV and VP) or unseen due to the patient being blindfolded (PP).

3.2.4 Dependent Measures

To aid spatial hand path analysis all hand paths were rotated, using the start point as the fulcrum, so that both the start- and end-points lay on the same axis (see Figure 2.4, Chapter 2, for details). An index of hand path curvature (**HPC**) was calculated by dividing the maximum lateral deviation (in mm) from a straight line path from start position to movement end-point by the straight line distance from start position to movement end-point. This index of curvature is independent of the movement amplitude and the direction (leftwards or rightwards) of the curvature. A signed index of hand path curvature (**HPC+-**) was calculated in exactly the same manner except that the sign of the lateral deviation was retained. A negative value indicates a leftward deviation from a straight-line path and a positive value a rightward deviation. Note that both the HPC and HPC+- measurements are independent of movement amplitude.

Direction errors (**DE**) were calculated as the angle (in degrees) formed between a straight line from start position to movement end-point and a straight line from the start position to the target location. A negative result indicates a leftward (or anti-clockwise) error and a positive result a rightward (or clockwise) error. Amplitude errors (**AE**) were calculated as the straight-line distance (in mm) from the start position to movement end-point as compared to the straight-line distance from the start position to the target location. A positive value represents an over-reach of the distance to the target and a negative value, an under-reach.

Three temporal/kinematic indicators (movement time, peak velocity and deceleration phase) were also measured. Movement time (**MT**) was calculated as the time to movement end-point minus the time to movement onset in milliseconds. Movement onset was defined as the first frame in which the finger marker exceeded a velocity of 2.5 cm/s. Movement end-point was defined as the first frame in which the velocity of the finger marker fell below 2.5 cm/s. The 'first frame' was determined as the first of five frames in which the mean value was above threshold and the mean value of the preceding five frames was below threshold;

b) Peak velocity (**PV**) was taken as the maximum three-dimensional velocity reached in the direction of movement;

c) Deceleration phase (**%DP**) was calculated as the time spent in the reach after the occurrence of peak velocity and was expressed as a percentage of movement time.

3.3 Results

For each patient, individual scores were entered in a 2 factor repeated measures analysis of variance (ANOVA) with the factors: CONDITION (VV vs. VP vs. PP) x SIDE OF REACH (contralateral vs. ipsilateral). This procedure was repeated for AE, DE and HPC, MT, PV and %DP dependent variables. As outlined in the introduction, a priori pairwise comparisons were performed on mean values for the following CONDITION pairs: VV vs. VP; VV vs. PP; VP vs. PP. Additionally, in order to assess directly the effect of SIDE OF REACH on hand path curvature, the following a priori comparisons were performed on HPC+- data only: VV Contra vs. VV Ipsi; VP Contra vs. VP Ipsi; PP Contra vs. PP Ipsi. Note that 'contralateral' refers to the area of space across the body midline from the shoulder of the reaching hand, not the target hand.

Amplitude Error

Unlike the control subjects in Chapter 2, both the neglect patients, RB and LGC, undershot the distance to the target considerably in the PP condition. Means indicate that RB was much worse than LGC. RB was also worse in the VP condition, but LGC showed a substantial improvement, with her scores not being significantly different from those in the VV condition. MJH, the 'recovered' patient, performed equally accurately in all three conditions. Means are given in Figure 3.9.

Table 3.1: F statistics and probability values for the amplitude error planned comparisons for each patient.

AE	VV vs. VP	VV vs. PP	VP vs. PP
RB	$F_{[1]} = 28.1$ $p = 0.0001$	$F_{[1]} = 78.5$ $p = 0.0001$	$F_{[1]} = 12.7$ $p < 0.0005$
LGC	**NS**	$F_{[1]} = 21.5$ $p = 0.0001$	$F_{[1]} = 22.9$ $p = 0.0001$
MJH	**NS**	**NS**	**NS**

F statistics and probability values are given in Table 3.1.

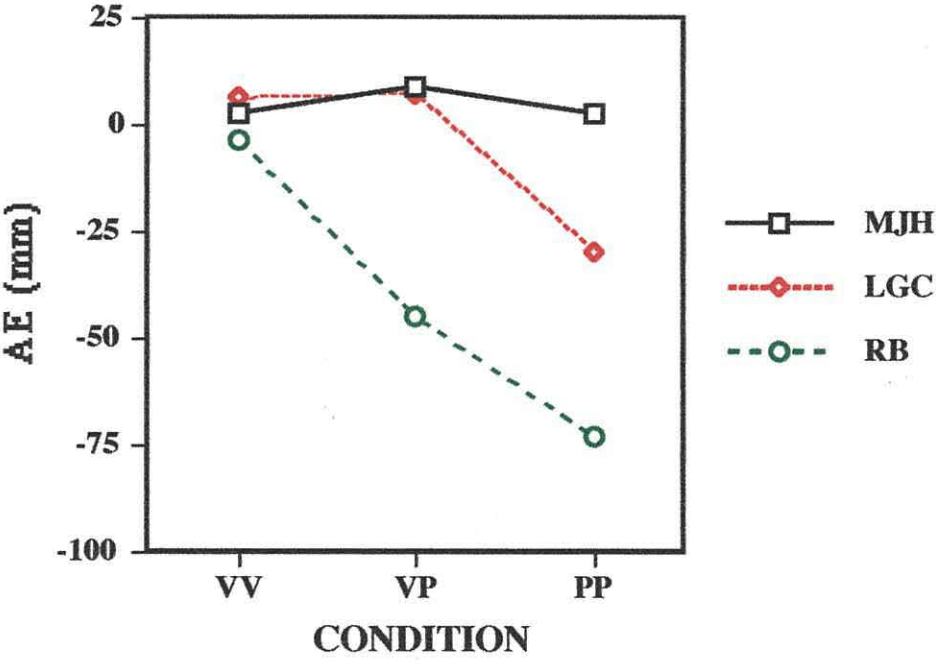

Figure 3.9: Mean amplitude error scores for each patient in each condition.

Direction Error

LGC and MJH were equally as accurate, in terms of direction error, in all conditions. RB, the case with the worst neglect, on the other hand was significantly less accurate, veering anti-clockwise in the PP condition.

Means are given in Figure 3.10. F statistics and probability values are given in Table 3.2.

Table 3.2: F statistics and probability values for the direction error planned comparisons for each patient.

DE	**VV vs. VP**	**VV vs. PP**	**VP vs. PP**
RB	**NS**	$F_{[1]} = 26.6$ $p = 0.0001$	$F_{[1]} = 33.5$ $p = 0.0001$
LGC	**NS**	**NS**	**NS**
MJH	**NS**	**NS**	**NS**

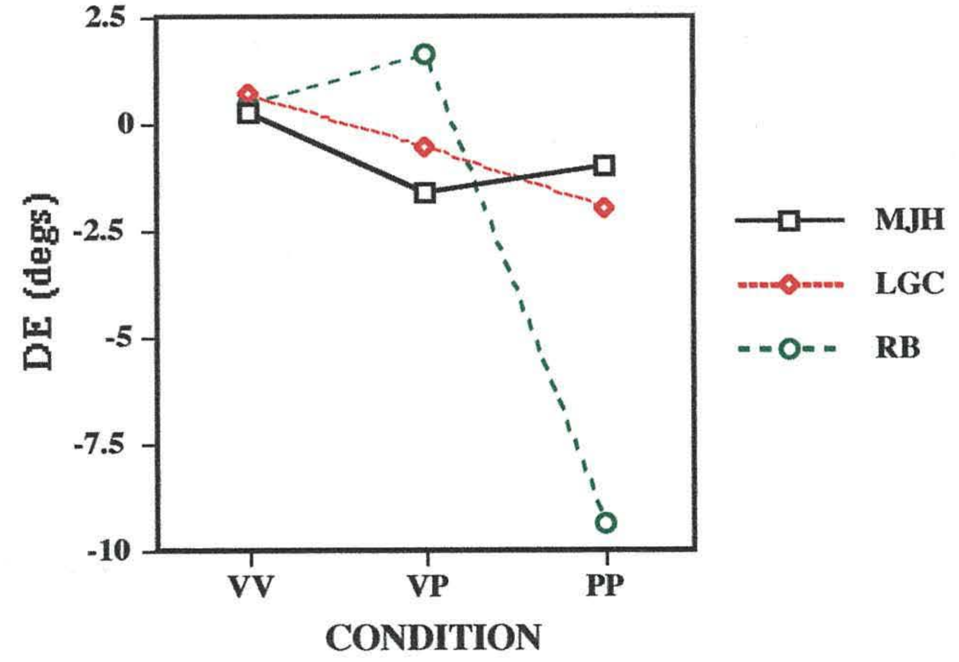

Figure 3.10: Mean direction error scores for each patient in each condition.

HPC

Reaches were more curved in the VV condition than either VP or PP conditions in all patients. For patient LGC alone VP reaches were also more curved than PP reaches and although the statistics for the other patients did not reach significance, both of their results were in the same

Table 3.3: F statistics and probability values for the HPC planned comparisons for each patient.

HPC	VV vs. VP	VV vs. PP	VP vs. PP
RB	$F_{[1]} = 4.5$ $p < 0.05$	$F_{[1]} = 14.2$ $p < 0.005$	**NS**
LGC	$F_{[1]} = 21.9$ $p = 0.0001$	$F_{[1]} = 94.1$ $p = 0.0001$	$F_{[1]} = 25.2$ $p = 0.0001$
MJH	$F_{[1]} = 6.6$ $p < 0.05$	$F_{[1]} = 20.2$ $p = 0.0001$	**NS**

direction as LGC's. Means are given in Figure 3.11. F statistics and probability values are given in Table 3.3.

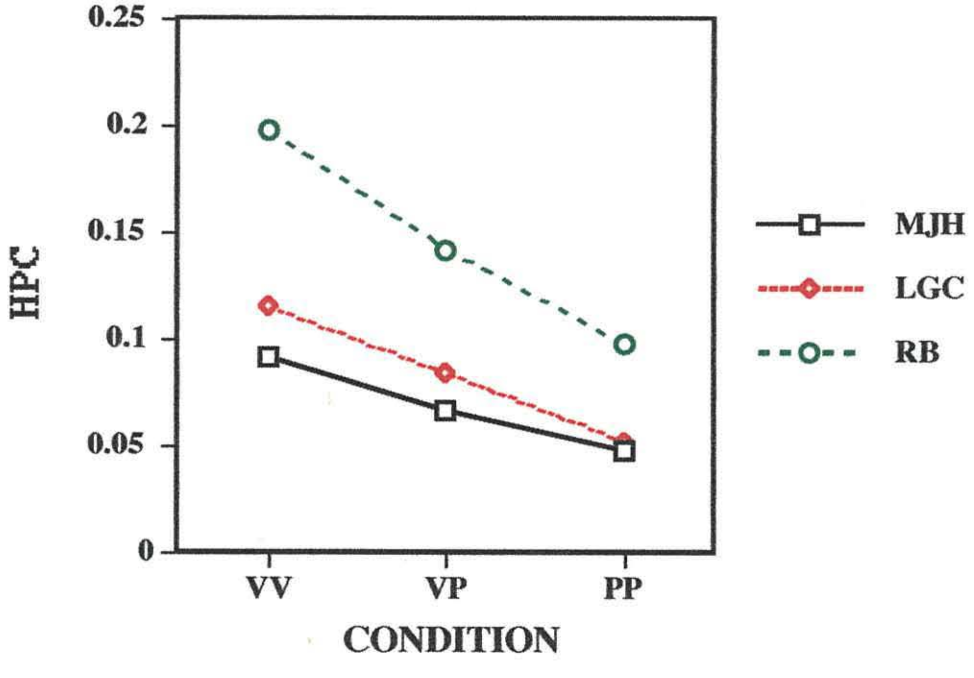

Figure 3.11: Mean HPC scores for each patient in each condition.

HPC+-

LGC and MJH showed almost symmetric directional curvature with contralateral reaches bowing leftwards and ipsilateral reaches bowing rightwards, with the amount of curvature increasing as the amount of

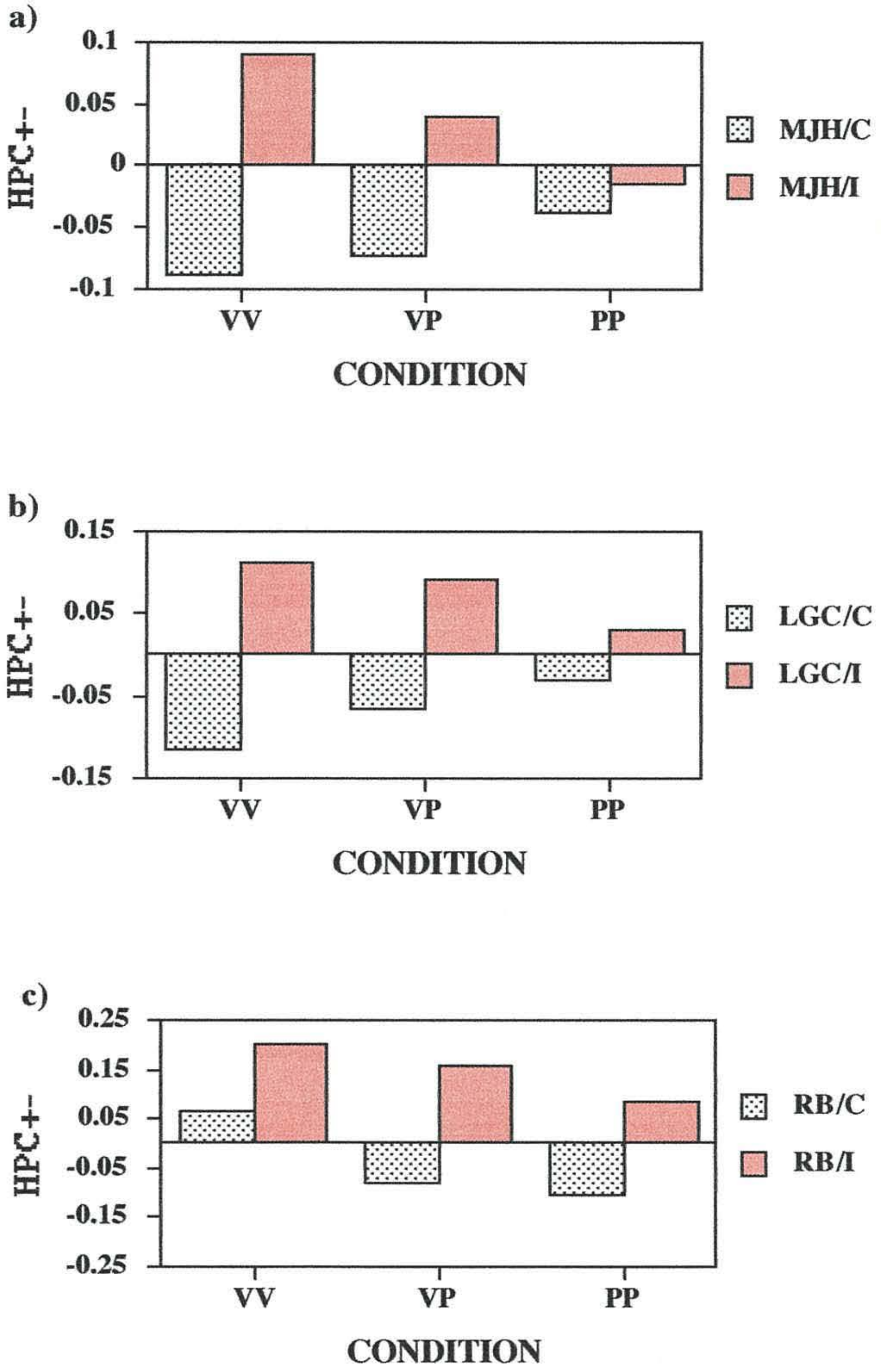

Figure 3.12: Mean HPC+- scores for contralateral and ipsilateral reaches in each condition for patients: a) MJH, b) LGC and c) RB.

visual information available increased. RB's reaches were not mirror symmetric: both contralateral and ipsilateral VV reaches bowed rightwards. In none of the cases did visually-guided reaches into contralateral space curve more than visually-guided reaches into ipsilateral space. Note also that for two of the patients, LGC and MJH, contralateral reaches curved leftwards, into contralateral space and not away from it. Mean hand paths are given in Figure 3.12. F statistics and probability values are given in Table 3.4.

Table 3.4: F statistics and probability values for the HPC+- planned comparisons for each patient.

HPC +-	**VV/C vs. VV/I**	**VP/C vs. VP/I**	**PP/C vs. PP/I**
RB	$F_{[1]} = 5.8$ $p < 0.05$	$F_{[1]} = 17.7$ $p < 0.01$	$F_{[1]} = 10.8$ $p < 0.01$
LGC	$F_{[1]} = 372.6$ $p = 0.0001$	$F_{[1]} = 184.0$ $p = 0.0001$	$F_{[1]} = 27.5$ $p = 0.0001$
MJH	$F_{[1]} = 112.1$ $p = 0.0001$	$F_{[1]} = 44.4$ $p = 0.0001$	**NS**

Movement Time

For patient LGC, movement times for reaches made to targets defined by proprioception (VP and PP) were greater than those made to visually-defined targets whereas MJH displayed increased movement times for PP reaches alone. RB, on the other hand, showed an altogether different pattern of behaviour. His VP reaches took longer to complete

Table 3.5: F statistics and probability values for the movement time planned comparisons for each patient.

MT	**VV vs. VP**	**VV vs. PP**	**VP vs. PP**
RB	$F_{[1]} = 12.3$ $p < 0.005$	$F_{[1]} = 35.3$ $p = 0.0001$	$F_{[1]} = 5.9$ $p < 0.05$
LGC	$F_{[1]} = 4.9$ $p < 0.05$	$F_{[1]} = 10.3$ $p < 0.005$	**NS**
MJH	**NS**	$F_{[1]} = 25.7$ $p < 0.0005$	$F_{[1]} = 42.8$ $p = 0.0001$

than his PP reaches and his VV reaches took longer still. Means are given in Figure 3.13. F statistics and probability values are given in Table 3.5.

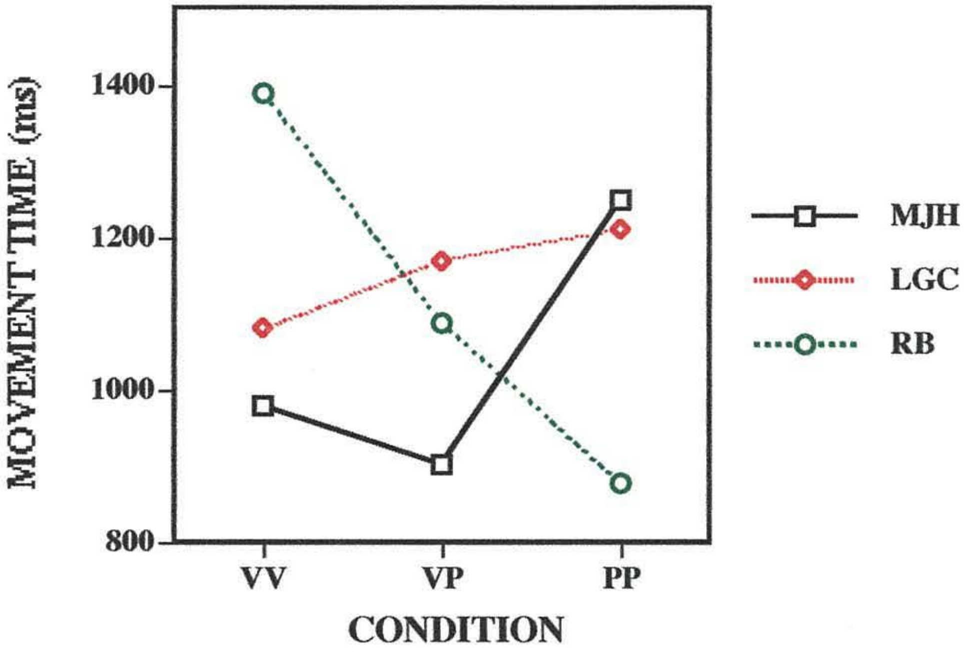

Figure 3.13: Mean movement time scores for each patient in each condition.

Peak Velocity

All three patients showed similar peak velocity outcomes, generally, with peak velocities for VV reaches being significantly higher than for VP reaches and peak velocities for VP reaches in turn being significantly

Table 3.6: F statistics and probability values for the peak velocity planned comparisons for each patient.

PV	**VV vs. VP**	**VV vs. PP**	**VP vs. PP**
RB	$F_{[1]} = 13.4$ $p < 0.005$	$F_{[1]} = 38.1$ $p = 0.0001$	$F_{[1]} = 6.3$ $p < 0.05$
LGC	$F_{[1]} = 30.0$ $p = 0.0001$	$F_{[1]} = 112.4$ $p = 0.0001$	$F_{[1]} = 26.2$ $p = 0.0001$
MJH	**NS**	$F_{[1]} = 35.6$ $p = 0.0001$	$F_{[1]} = 50.6$ $p = 0.0001$

higher than for PP reaches. Only MJH displayed peak velocities for VV reaches that were not greater than those for VP reaches, although both of these were greater than for PP reaches. Means are given in Figure 3.14. F statistics and probability values are given in Table 3.6.

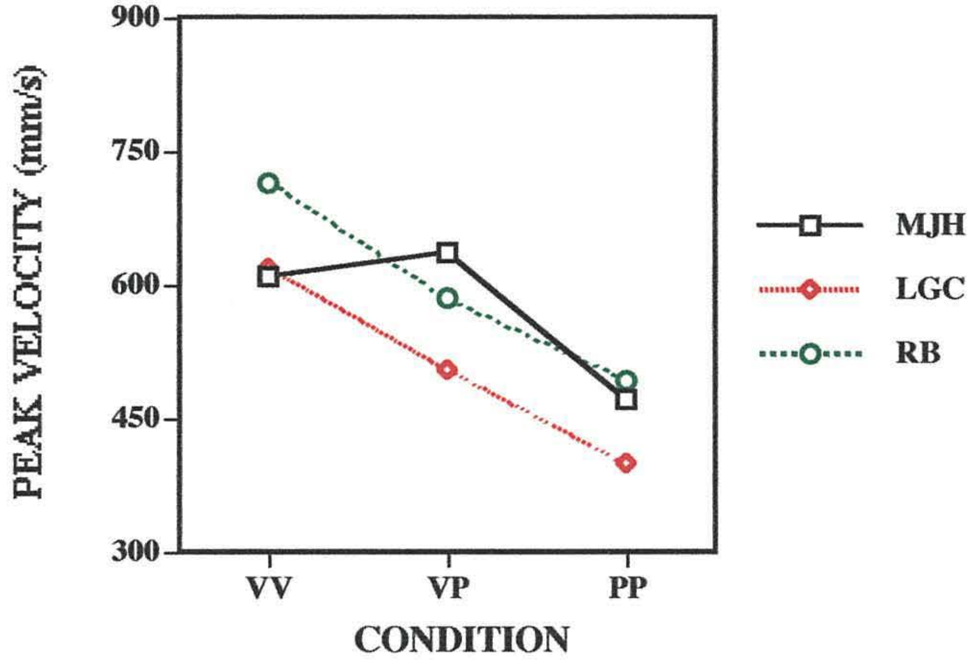

Figure 3.14: Mean peak velocity scores for each patient in each condition.

Deceleration Phase

MJH and LGC spent a similar percentage of movement time decelerating in each condition and they both showed the longest deceleration phase in the PP condition. Again, RB displayed a different pattern; spending the least time decelerating in the PP condition. Means are given in Figure 3.15. F statistics and probability values are given in Table 3.7.

Table 3.7: F statistics and probability values for the deceleration phase planned comparisons for each patient.

%DP	**VV vs. VP**	**VV vs. PP**	**VP vs. PP**
RB	**NS**	$F_{[1]} = 10.5$ $p < 0.005$	**NS**
LGC	**NS**	**NS**	$F_{[1]} = 4.6$ $p < 0.05$
MJH	**NS**	$F_{[1]} = 6.6$ $p < 0.05$	$F_{[1]} = 15.5$ $p < 0.0005$

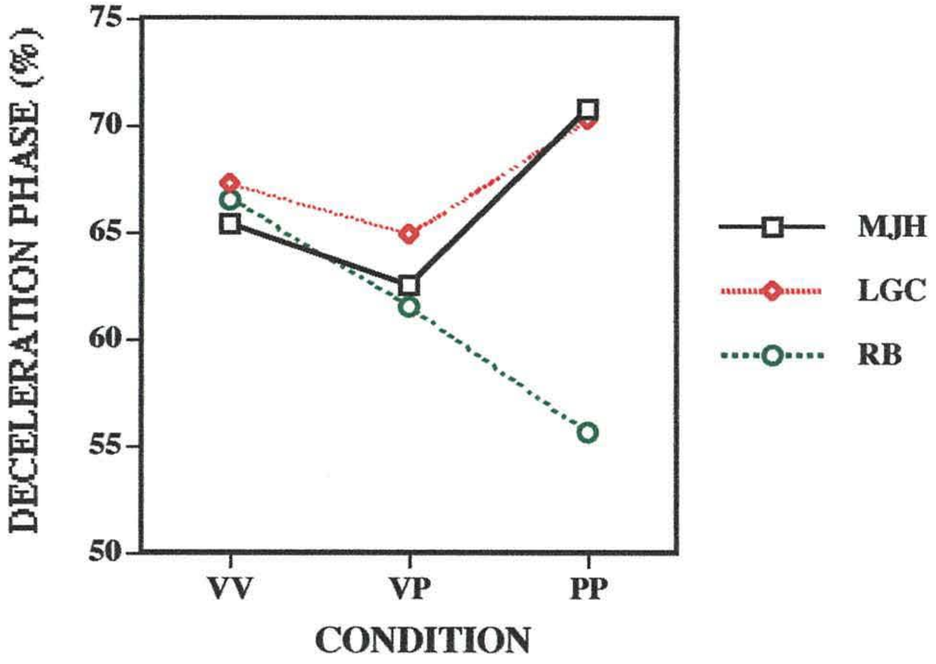

Figure 3.15: Mean % deceleration phase scores for each patient in each condition.

3.4 Discussion

The hand path curvature of all three patients clearly demonstrated an increase in curvature for reaches made towards visually-defined targets (Figure 3.11). The variation in curvature between conditions is in stark contrast to the performance of the healthy subjects, whose data was presented in Chapter 2 (Figure 3.16a), for whom the overall curvature of

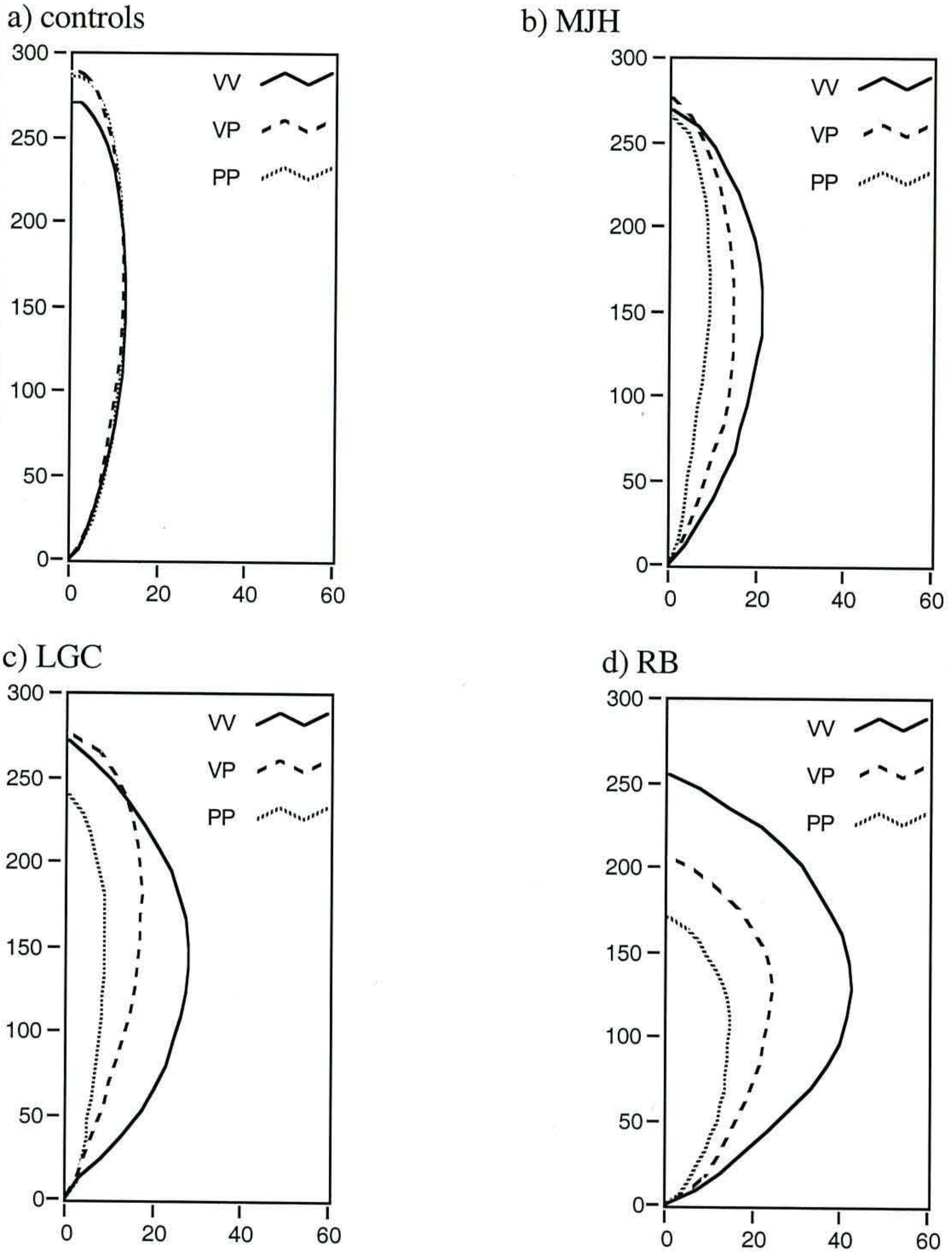

Figure 3.16: Mean rotated hand paths of a) healthy normal subjects (from Chapter 2), b) patient MJH, c) patient LGC and d) patient RB. NB. All hand paths have been rotated and flipped using the procedure outlined for calculating HPC.

reaches, regardless of the direction of curvature, was remarkably similar in all conditions. All three patients showed the same pattern: visually-guided reaches to visually-defined targets curved the most, whereas the straightest reaches were those made when blindfolded, with only proprioceptive information about the target and the reaching limb available. Furthermore, the curvature of VP reaches (when vision was available, but the target was defined by proprioception) appeared to lie between that of VV and PP reaches. Thus, the more visual information that was available to the patients for planning and controlling reaches, the more curvature was introduced into the reach.

Why should the availability of visual information cause neglect patients to misreach in this manner and what are the implications for motor control? As discussed in the introduction, the spatial hand paths of visually-guided reaching and pointing movements in normal subjects have frequently been described as being slightly curved in nature and the reason for this curvature has been the subject of much debate. Two general models of trajectory planning maintain that hand paths are curved either due to the motor constraints of limb dynamics (e.g. Uno et al., 1989) or that hand paths are curved because the topography of visual space is curved (e.g. Miall and Haggard, 1995; Wolpert et al., 1994; Haggard and Richardson, 1996).

Our results further demonstrate that movement curvature can result from visual distortion rather than limb dynamics. Firstly, as the reaches in this experiment were all made from identical start positions, with identical body postures, to identical target locations, hand paths planned with respect to limb dynamics in an intrinsic joint- or muscle- based coordinate system should have been the same in each condition. This was clearly not the case. Furthermore, if the hand paths of normal subjects are influenced by distortions of the visual representation of space then it follows that a patient group with a severe distortion of visual space will display severely distorted hand path curvature under visual reaching conditions and this is precisely what happened. Furthermore, by comparing reaching movements directed to visually-defined target locations against reaching movements directed to proprioceptively-defined targets we have been able to distinguish between visual and motor components of reaching in neglect. The observed differences in hand path curvature demonstrates that the underlying cause of our patients' abnormal curvature cannot be an impairment of motor control but rather it is a spatial distortion in the visual representation of space used to plan movements.

Additional hand path (Tipper et al., 1997; Howard and Tipper, 1997) and eye path (Sheliga et al., 1995) curvature can also be induced in normals, however, by the presence of attended to distractor objects or regions of space. If the path of the reaching hand can be modified by selective visual attention in normal individuals then might patients who suffer from abnormal spatial attention be expected to show more pronounced effects? Our findings demonstrate an analogous (but more marked) change in hand path curvature occurring in neglect which may persist long after clinical and perceptual evidence of neglect are no longer apparent. It is interesting to note here that the severity of the curvature seen in our neglect patients appears to be related to the severity of their neglect: the worse the clinical neglect, the greater the curvature of VV reaches (i.e. RB > LGC > MJH > Controls).

The observed curvature of our patients, however, does not readily fit into existing 'spatial distortion' models of neglect, such as compression (Halligan and Marshall, 1991) or egocentric rotation (Karnath et al., 1993), or 'attentional' models of neglect based on increased attention to the right, accompanied by a decreased attention to the left (e.g. Làdavas, 1990). The results do not fit such models because, like our healthy subjects, the VV reaches of LGC and MJH show an almost mirror symmetric directional curvature with contralateral reaches bowing leftwards and ipsilateral reaches bowing rightwards. Contralateral and ipsilateral reaches should not be symmetric if one side of space is compressed or rotated and neither do reaches seem to consistently bend away from, or towards, an attended to region of space. Rather, for our patients, the amount of curvature increases as the amount of visual information available increases. What the hand paths may do, in effect, is trace out the topography of a distorted representation of visual space in these patients.

It is worth repeating here that, contrary to popular opinion, in none of the cases reported here do visually-guided reaches into contralateral space curve more than ipsilateral reaches, or vice versa, and neither do they consist of an initial rightward movement bias followed by a leftward correction. Our results show that this clearly does not happen in all cases. Two of our patients clearly show leftward contralateral reaches which mirror rightward ipsilateral reaches.

Although all reaches started from identical start positions and were aimed at identical target locations, those target locations were not always reached: some patients showed a marked hypometria. This hypometria almost certainly accounts for RB's slightly unusual reach kinematics. Despite reaching a lower peak velocity. RB's PP reaches were completed far more quickly than either his VP or VV reaches. The most likely explanation is that, overall, his reaches were a lot shorter, in terms of length, in this condition. Shorter reaches normally display lower peak velocities and, sometimes, shorter movement times. Could the observed hypometria, though, account for the observed differences in curvature? Whereas neurologically intact subjects were <u>hyper</u>metric when reaching to proprioceptively-defined targets, patients tended to be <u>hypo</u>metric. RB, the patient with clinically the worst neglect, was the most hypometric, undershooting in both the VP and PP conditions. LGC, with a milder diagnosis only displayed hypometria in the PP condition and MJH showed no hypometria at all. The two most plausible explanations for this hypometria are that it is either a symptom of the neglect syndrome which isn't tapped by standard clinical tests, or that it is a sub-clinical somatosensory deficit . Given that it is the introduction of vision that brings about the substantial amelioration of amplitude error seen between the PP and VP conditions, and that there is no evidence of hypometria in the VV condition, it seems unlikely that this hypometria is a result of spatial neglect and is more likely to be a sub-clinical somatosensory deficit.

It will be seen from Figure 3.16 that some of the straighter mean reaches also appeared to be of shorter amplitude. While this may have been the case for RB, it is not the case that all straighter reaches were shorter reaches. In particular, the reaches of MJH are clearly different in their curvature, but very similar in their amplitude. Similarly, that is also the case for LGC's VV and VP reaches. The HPC measure, being a ratio measure, was designed to be independent of movement amplitude. It is not one of the more commonly used measurements and as such should be compared against other, more widely accepted, measurements in order to assess its validity as a measure of hand path curvature. To do this we compared LGC's HPC measure to three other measures of hand path curvature: the area under the curve of the hand path (the area between the curve of the hand path and a straight line drawn from start- to end-point), the maximum deviation from a straight-line path (the maximum deviation perpendicular to the straight line path from start- to end-point) and the PL/DIS measure (the path length divided by the straight line distance) used by Karnath and colleagues (1997). As can be seen from the results, shown in Figure 3.17, the HPC measure compares favourably with

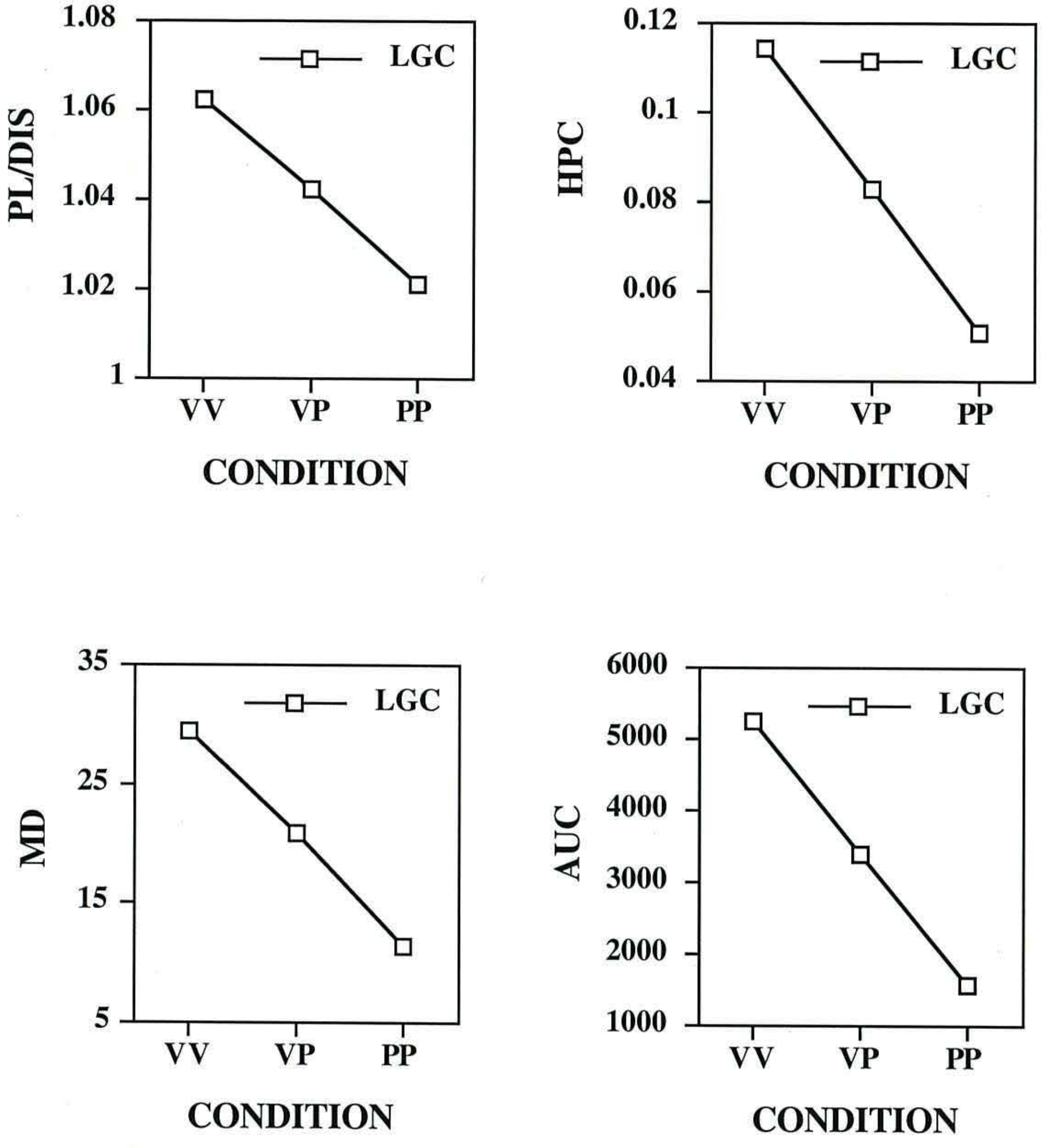

Figure 3.17: Graphs depicting the mean scores of LGC on various measurements of hand path curvature: a) HPC, b) maximum deviation in mm perpendicular to the straight line path from start- to end-point, c) PL/DIS (the path length divided by the straight line distance (see Karnath et al., 1997) and d) area under the curve (mm^2) - the area between the curve of the hand path and a straight line drawn from start- to end-point.

other assessments of hand path curvature. Each of the measures depicted in Figure 3.17 provided significant results in a 1 x 3 repeated measure ANOVA to an alpha level of 0.0001.

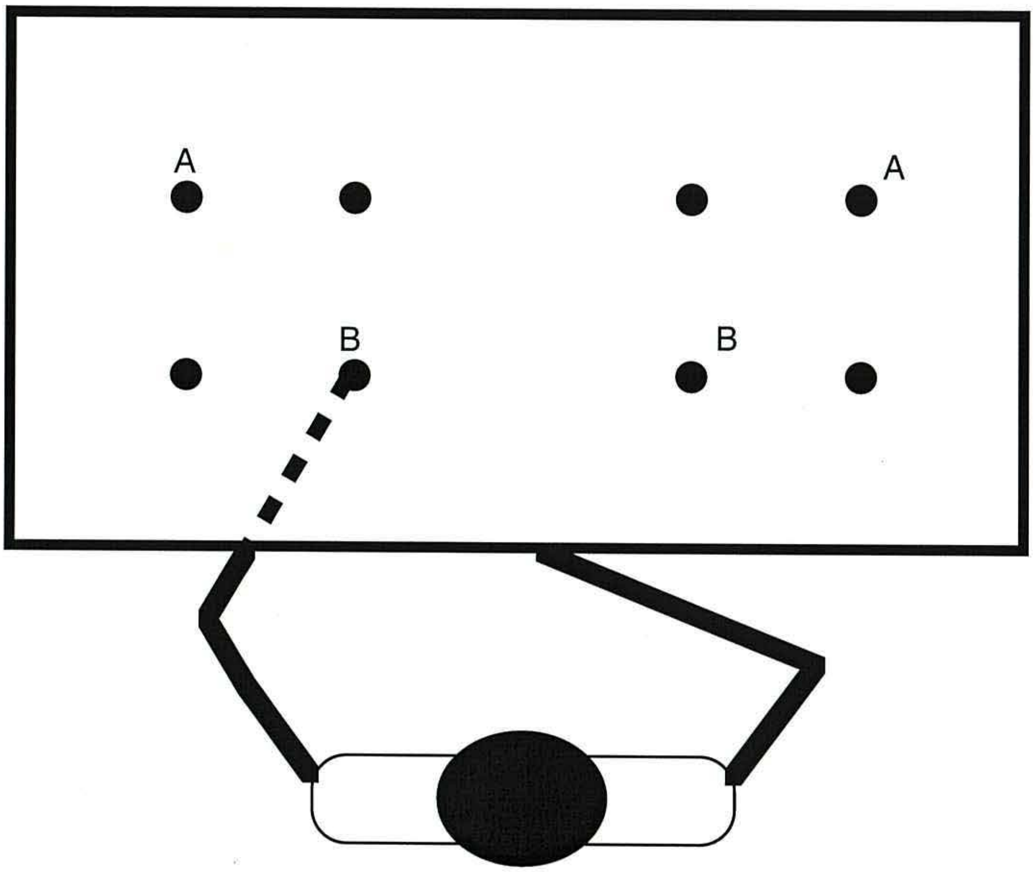

Figure 3.18: Depicting targets **A** and **B** used for re-analysis of healthy normal subjects' data. Note that targets **A** lie in the same directions as targets **B**, but are twice as far from the start point.

This does not mean, however, that shorter reaches may not in fact be straighter and there is no escaping the fact that the undershoot in LGC's PP reaches, for example, is as striking as is her additional curvature in the VV condition. In respect to this we decided to re-analyse some of the data from the healthy subjects in chapter 2 in the following manner: The targets marked **A** and **B** in Figure 3.18 lie in the same direction from the start point, but the distance to **A** is twice that to **B**. HPC data from these target locations were entered in a 2 x 3 two factor repeated measures ANOVA with the factors CONDITION (VV vs. VP vs. PP) and TARGET DISTANCE (Far vs. Near). In order to directly compare the effects of target distance on hand path curvature the following planned comparisons were performed: VV(Far) vs. VV(Near); VP(Far) vs. VP(Near); PP(Far) vs. PP(Near). All three comparisons revealed that longer reaches produced movements which were in fact straighter than shorter reaches (means and statistics are given in Figure 3.19 and Table 3.8). This rules out the possibility that the patients' PP reaches were straighter overall than VV reaches simply because some of them were shorter.

Table 3.8: F statistics and probability values for the HPC+- planned comparisons for each patient.

VV/F vs. VV/N	**VP/F vs. VP/N**	**PP/F vs. PP/N**
$F_{[1]} = 14.509$ $p < 0.01$	$F_{[1]} = 12.204$ $p < 0.01$	$F_{[1]} = 18.430$ $p < 0.01$

The additional curvature observed in the VV condition does not seem to be as a result of the difficulty of the movement. In the main the kinematic data suggests what we would expect, that visually-guided reaches to visually-defined targets (VV condition) were performed more efficiently (greater peak velocities, shorter movement times and shorter deceleration phases) than reaches directed to proprioceptively-defined targets without vision. Only RB, whose kinematic data has already been discussed, did not show this pattern.

Another possible explanation for the differences in curvature between conditions might be related to the speed of movement in each of those conditions. It was observed that, in general, the peak velocity of patients' reaches were lowest in the PP condition and highest in the VV condition (see Figure 3.14) , whereas peak velocity differences in healthy subjects (see Chapter 2) were not so readily apparent. Is it possible that the greater speed of reach in the VV condition caused the greater curvature observed in the patients? All existing evidence is to the contrary. Although the majority of this evidence is derived from drawing studies, several authors have observed that movements are consistent with a power law in which movements that are more curved are also slower (Laquaniti et al., 1983; Gribble and Ostry, 1996; Wann et al., 1988). It is unlikely in our case, therefore, that faster reaches produced more curved reaches.

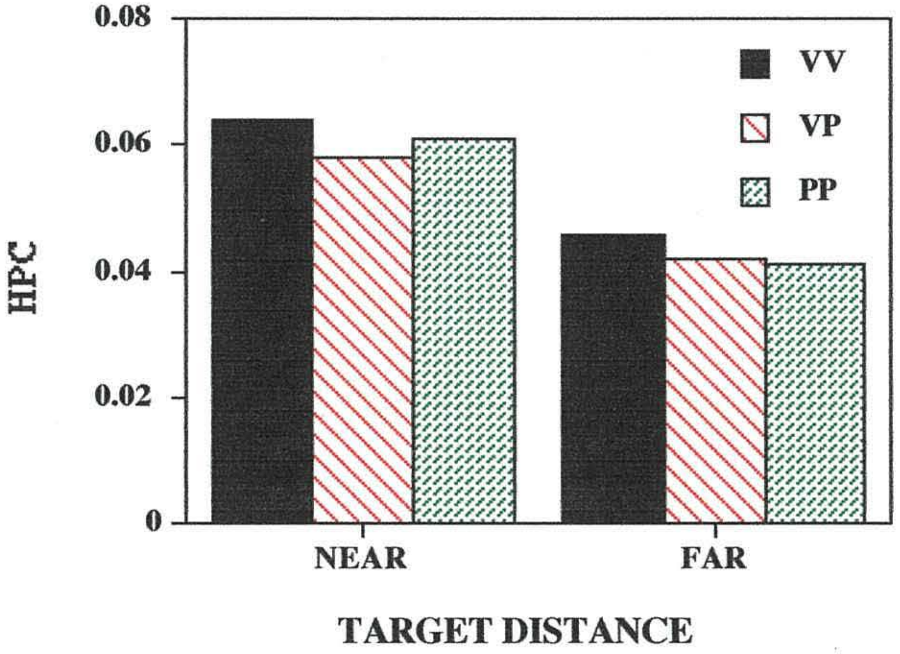

Figure 3.19: Mean HPC scores for neurologically intact subjects (see Chapter 2) for reaches to near and far targets in each condition.

3.5 Summary

In this chapter we have shown that reaches to and from identical positions executed by three patients recovering from neglect are significantly more curved to visually-defined targets compared to when the same targets are defined proprioceptively. These findings indicate that abnormal hand paths in neglect result from an impairment in the visual representation of space used to guide reaches. Despite the fact that the patients do not exhibit the same rotation of end-point errors as healthy subjects we suggest that the hand path curvature data indicates that reaches made to proprioceptively-defined and visually-defined targets are planned within different frames of reference. Recent studies in the monkey suggest the existence of several distinct spatial coordinate systems within the parietal cortex which mediate the sensorimotor transformations related to the control of hand movements (Rizzolatti et al., 1997; Rushworth et al, 1997a; Rushworth et al, 1997b) and different frames of reference may be utilized when reaching to proprioceptively-defined target locations as when reaching to visually-defined target locations. According to Krakauer et al., 1999) psychophysical studies of reaching suggest that hand kinematics are learned from errors in direction and extent (in an extrinsic coordinate system) whereas dynamics are learned from proprioceptive errors in an (intrinsic coordinate system) and that these two forms of learning are independent. Our findings provide further neurological evidence that hand paths are primarily planned in spatial (extrinsic) coordinates during visually-guided reaches and that reaches planned in extrinsic (visual) and intrinsic (joint or muscle) coordinates are most likely mediated by separate cortical circuits.

In the next two chapters we will induce a visual distortion in normal healthy individuals by the use of displacing prisms. Chapter 4 will discuss the underlying mechanisms of prism adaptation in relation to our proprioceptive pointing task and in Chapter 5 we will discuss changes in hand path curvature induced by prism displacement in relation to the findings in this chapter.

Chapter Four

4. The effects of prism adaptation on proprioceptive pointing.

4.1 Introduction

In Chapter One we discussed at length the optimal requirements for accurate reaching movements. Accurate reaching requires that sensory information about the location of the target and the hand in space be translated into the body-centred coordinates used to specify the movement in terms of joint rotations and muscle lengths. The optimal conditions for accurate reaching include having both visual and proprioceptive information about the position of the hand, as well as visual information regarding the target location, available both immediately prior to, and during, the execution of the movement (Prablanc et al., 1979; Jeannerod, 1988; Ghez et al., 1990; Rossetti et al., 1994b, 1995; Desmurget et al., 1995, 1997b). The visual and proprioceptive systems are independent of each other and must cooperate in order for accurate and efficient reaching to take place. Degradation, perturbation or removal of either system results in a loss of reaching accuracy and efficiency (see Jeannerod, 1988, for review). As the data in Chapter Three clearly demonstrated, pathological disturbance of the visual representation of space can lead to abnormal patterns of reaching behaviour which affect the spatial planning of visually-guided reaches without affecting final end-point accuracy. In the next two chapters we hope to extend these findings by examining the effects of inducing a distortion of visual input in healthy normal subjects, through the use of laterally displacing prisms, while leaving proprioceptive input unaffected. In this chapter we use a modified version of the proprioceptive pointing task used in earlier chapters to demonstrate the mechanisms of prism adaptation and discuss how these findings can help us to understand more about sensorimotor transformations.

Exposure to prisms which laterally displace the visual field leads, initially, to inaccurate reaching movements. Subjects wearing rightward displacing prisms, who are asked to point to a visually-defined target, will generally misreach to the right of the target (i.e. in the direction of the visual displacement). A short period of practice, however, is usually sufficient to allow correction of this misreaching and pointing becomes accurate once more. This effect is known as prism adaptation. If the prisms are subsequently removed, the subject will initially misreach in the direction opposite to that of the visual field displacement. This is known as the prism aftereffect or negative aftereffect (see Harris, 1965; Kornheiser, 1976; Welch, 1986 for reviews).

It is generally accepted that, theoretically, there are three possible components involved in prism adaptation (e.g. Welch et al., 1974; Welch, 1986): visual shift, proprioceptive shift and changes in the visuomotor translation. Kitazawa et al. (1997) attributed these three components to three separate transformations which could take place between visual input and motor output mediating reaching to a target: the mapping of retinal images of the target into body-centred coordinates; the use of somatosensory signals from the arm, with efference copy, to estimate the position of the reaching hand in body-centred coordinates; and the translation of the representation of the target location in body-centred coordinates into relevant motor commands.

Visual remapping of the target location involves the translation of the displaced retinal image location of the target into body-centred coordinates which accurately reflect the target's true location with respect to the body (see Figure 4.1). In contrast, proprioceptive shift remaps the felt position of the adapted limb so that it is in alignment with the displacement of the visual field (see Figure 4.2). Alternatively, it may be that neither the visual location of the target, nor the felt location of the hand are remapped, but rather it is the visuomotor transformation which encodes the direction and distance between the two which is remapped (see Figure 4.3).

According to Kitazawa et al. (1995) movements in each trial during prism adaptation are influenced by updated visuomotor transformations from the previous trial. After every trial a small amount of error correction, in proportion to the error in that trial, is added to the visuomotor transformation. Jakobson and Goodale (1989) proposed that the visuomotor recalibration seen during prism adaptation is automatic and can take place without feedback from terminal errors (i.e. it happens during the movement) and without recourse to conscious strategies.

Several studies have demonstrated that prism adaptation does not transfer to actions which share few movement characteristics with the action performed during adaptation. For example, adaptation to prisms during overarm throwing does not transfer to underarm throwing (Martin et al., 1996); adaptation of pointing movements in the horizontal plane transfers only incompletely to movements in the sagittal plane (Freedman et al., 1965); adaptation acquired during slow, horizontal, oscillatory arm movements with decreasing amplitudes around the shoulder joint does not fully transfer to fast, straight movements (Baily, 1972); and adaptation does not generalize across widely varying velocities of movement (Kitazawa et al., 1997). More importantly, from the point of view of this study, is that when the adaptation procedure involves concurrent exposure to the prism-displaced limb prism adaptation does not transfer to the non-adapted limb (i.e. the one not used during the adaptation phase) provided it is not viewed during the exposure period. (Harris, 1963, 1965;

Mikaelian, 1963; Hamilton, 1964; Cohen, 1966; Kennedy, 1966). "Concurrent" exposure means that the hand can be seen continuously during the adaptation phase, as opposed to "terminal" exposure in which the hand is only seen at the end of a goal-directed reaching movement.

By examining the effects of the blindfold condition of our proprioceptive pointing paradigm, it should be possible to disentangle the contributions of the three postulated components of prism adaptation: visual shift, proprioceptive shift and changes in visuomotor transformation:

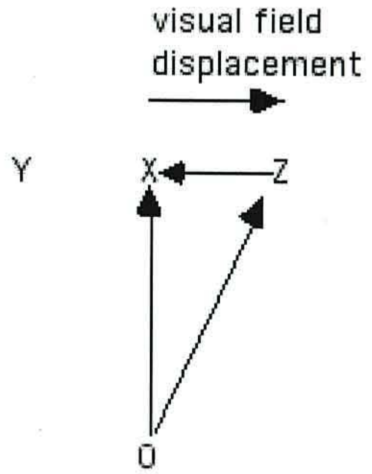

Figure 4.1: Visual Remapping. Target X, due to the visual displacement of the prisms, appears to be at Z and initially produces the inaccurate movement vector OZ. During adaptation, target X, which appears to be at Z, is remapped to location X in body-centred coordinates by the visual system. This permits the production of the correct movement vector OX. In the same way, a target which appeared to be at X would be translated to Y, giving the movement vector 0Y.

If a visual shift is purely retinal in origin then there should be no evidence of adaptation effects when subjects, following a period of normal adaptation, subsequently close their eyes and point to a proprioceptive target defined by their passively located non-adapted hand. That is, if the unseen non-adapted limb is placed at target location X , in Figure 4.1, the resultant reach from O, without information from the adapted retinal image (because the eyes are closed), should be accurately directed to X.

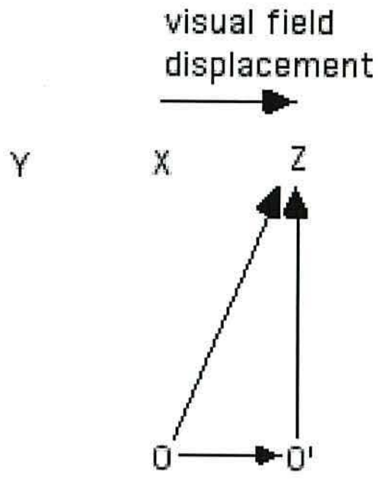

Figure 4.2: Proprioceptive shift. Target X is perceived to be at Z, due to the effect of the prisms, by the visual system while the reaching hand is felt, by the somatosensory system, to be at O. Thus, the resultant movement vector OZ is inaccurate to the right of X. During prism adaptation the spatial representation of the proprioceptive localization of the movement vector origin, the hand, is realigned to O'. The movement vector O'Z, which is the equivalent distance and direction of OZ, is now the accurate movement vector because the actual origin of the vector is still position O. Similarly, a visual target at Y would be perceived to be at X and would produce an accurate movement vector, O'X, with O as the true movement origin.

If prism adaptation is based on a proprioceptive shift, specifically the recalibration of the felt position of the hand (Figure 4.2), then a reach from the adapted hand to the felt location of the non-adapted hand, with the eyes closed, should reveal the following effects: The non-adapted limb (the target) is perceived to be in its veridical position, X (Figure 4.2), and the adapted limb is perceived to be displaced in the direction of the prisms, at position O', resulting in the planned movement vector O'X. Because the real origin of the movement is position O, the subsequent movement produced will actually be OY, resulting in an inaccurate reach to Y - a bias in the direction opposite to the visual field displacement. In the reverse condition, with the non-adapted limb reaching to the felt location of the unseen adapted limb we should see the opposite effect: If the adapted hand is at target X, but, due to the proprioceptive realignment, is perceived to be at Z, and the non-adapted hand is perceived to be in its veridical location, O, then the resultant movement vector, OZ, will elicit an inaccurate reach biased in the same direction as the visual field displacement.

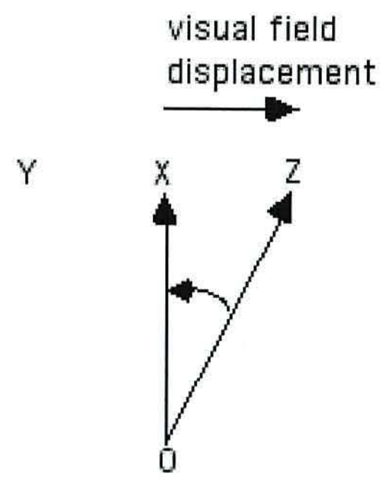

Figure 4.3: Changes in visuomotor transformation. The target is located at X, but, due to the rightward visual field displacement of the prisms, is perceived to be at Z. Initially, this produces an inaccurate movement vector, OZ. During repeated trials, this error in the visuomotor transformation is gradually corrected until vector OX is produced. Similarly, after adaptation, target Y, perceived at X, would produce vector OY.

An alternative to a proprioceptive shift involving recalibration of the felt position of the hand is one involving recalibration of the felt position of the eye. Ocular position signals could play an important role in prism adaptation as the eyes, as well as, or instead of, the adapted limb, may be subject to proprioceptive recalibration. For example, subjects asked to indicate their mid-saggital plane will, under conditions of rightward prismatic displacement, indicate a point to the right of their midline. Asked where a light on their objective midline (i.e. directly in front of their nose) is located, subjects will report that it lies slightly to their left and will perceive their eyes to be facing straight ahead when they are in fact deviated to the right. Ebenholtz and colleagues (e.g. Ebenholtz, 1974; Paap and Ebenholtz, 1976) argued that these effects are the result of eye muscle potentiation due to having eyes displaced to the right for a prolonged period, rather than perceptual recalibration. Assuming that the blindfolded eyes provide null information about the location of the target, then adaptation to prisms based purely on a change in the proprioceptively calibrated position of the eyes should mean that the two hands will point accurately to each other in the blindfold condition.

Table 4.1: Expected outcomes for reaches made without vision to the felt location of the contralateral limb according to three theories of prism adaptation.

	Adapted hand reaching to felt position of non-adapted target hand	Non-adapted hand reaching to felt position of adapted target hand
Visual Shift	Accurate	Accurate
Proprioceptive Shift (Hand)	Bias away from prism displacement	Bias towards prism displacement
(Eyes)	Accurate	Accurate
Change in visuomotor transformation	Bias away from prism displacement	Accurate

How will the visual and proprioceptive shift predictions be distinguishable from those resulting from a postulated visuomotor transformation change? Pointing with the eyes closed (after prism adaptation), with the adapted hand to the non-adapted hand, should produce the same results as a proprioceptive hand shift: With the non-adapted hand placed at (and perceived to be at) Z (see Figure 4.3), the altered movement vector OX will produce a reach biased away from the direction of prism displacement, the same result as for a proprioceptive hand shift. There is a crucial difference, however, when the non-adapted limb reaches to the felt location of the adapted limb. If the changed visuomotor transformations are specific to the adapted limb, then a reach with the non-adapted limb should be accurate. If the new transformations are more global- which, if there is no transfer to the non-adapted limb, they shouldn't be - a proprioceptive target at X will produce a reach to Y (see Figure 4.3). Either way, the results will be different to those found following a proprioceptive or visual shift. The predicted outcomes for each of the postulated components of prism adaptation for reaches without vision to the felt location of the contralateral hand are summarized in Table 4.1.

In the previous chapters we reported data from a proprioceptive pointing tasks in which patients and healthy normal individuals were required to match the felt position of their unseen static left hand by pointing to it with their right hand either with, or without, vision of the pointing limb. We suggested that vision and the various body parts involved in the task each had separate representations of space, or reference frames, associated with them. We also suggested that different weights may be applied to each of these various spatial maps when they are integrated to form a single coordinate system in which to plan a reach.

In 1998 Plooy et al., performed an experiment which demonstrated a situation in which such a weighting system might operate. A target finger, either the participant's or the experimenter's was inserted through a hole in a specially constructed viewing box which allowed vision of the target finger, but not of the matching hand (Figure 2.1). The task was to position the finger of the unseen matching hand, on the outside of the viewing box, such that it was at the same distance as the perceived location of the target finger. Subjects viewed the target finger through 8-dioptre prisms, to create an illusion of greater visual depth, and performed four conditions: pointing to their own or the experimenter's finger respectively in normal lighting conditions or pointing in the dark to their own or the experimenter's finger to which was attached a light emitting diode. They concluded from their results that when both visual and proprioceptive cues were present, only the visual cues appeared to determine performance with limb proprioception being virtually ignored. That is, if the percept of the target distance included a major contribution from retinal cues, then the visual component dominated the proprioceptive component. If the visual component was largely determined by vergence information, limb proprioception made a significant contribution and actually dominated when the vergence effort signal was weak.

In 1997 Mon-Williams et al. used prisms to place visual and proprioceptive maps in opposition by asking subjects to place the unseen finger of one hand (under a thin table) in the same position as the other hand seen (above the table) through displacing prisms. With full vision of the displaced hand available, subjects reported their limbs aligned even when they were misaligned by as much as 10 cm with the unseen finger positioned away from the actual location of the seen finger in the direction of visual displacement. Under reduced viewing conditions (in darkness with only an LED taped to the visually displaced hand visible) subjects positioned their limbs so that they were more closely aligned and reported that the LED seemed to become detached from their finger tip. Mon-Williams et al. (1997) concluded from this that "we believe in what we see, rather than in what we feel, when the visual background is rich, and in what we feel when the visual background is sparse." We suggest that it is not so much a case of "believing what we see" or "what we feel" rather than the CNS applying different weight to proprioceptive and visual information depending upon the goodness of the input. In this chapter we hope to show that the availability and quality of different sources of sensory input changes the weight with which each of these sensory inputs is used in the programming of a movement.

A secondary outcome of the current study is that it will allow us to demonstrate a previously unreported adaptation transference. The adaptation that will take place in this experiment will be in response to a displacement of visually-defined targets in visual space. Our paradigm will allow us to show whether prism adaptation to visually-defined targets transfers to reaches in which the specified amplitude and direction to the target is identical, but the target is defined proprioceptively.

4.2 Method

4.2.1 Subjects

Thirty healthy adults participated in this study as part of a student credit scheme at the University of Wales, Bangor. All participants were right handed and had normal or corrected to normal vision. The 24 females and 6 males had an average age of 21.2. Twenty three of the subjects were right-eye dominant.

4.2.2 Data Analysis

Pointing movements were recorded from a single marker attached to the distal portion of the nail of the index finger of the pointing hand. Recordings were sampled at 86.1 Hz using the miniBIRD electromagnetic tracking system (Ascension Technologies Corp.). This slightly unusual sampling rate was chosen so as to minimize electrical noise interference.

Raw data were filtered off-line using a 4th order zero-lag Butterworth filter.

4.2.3 Procedure

Subjects were seated in front of a horizontal, matt black, 90 cm x 90 cm wooden board, raised 15 cm above the table top. Six 6 mm cylindrical pegs were pushed into holes in board. These served as target locations and were laid out as in Figure 4.4a. Sagittal head movements

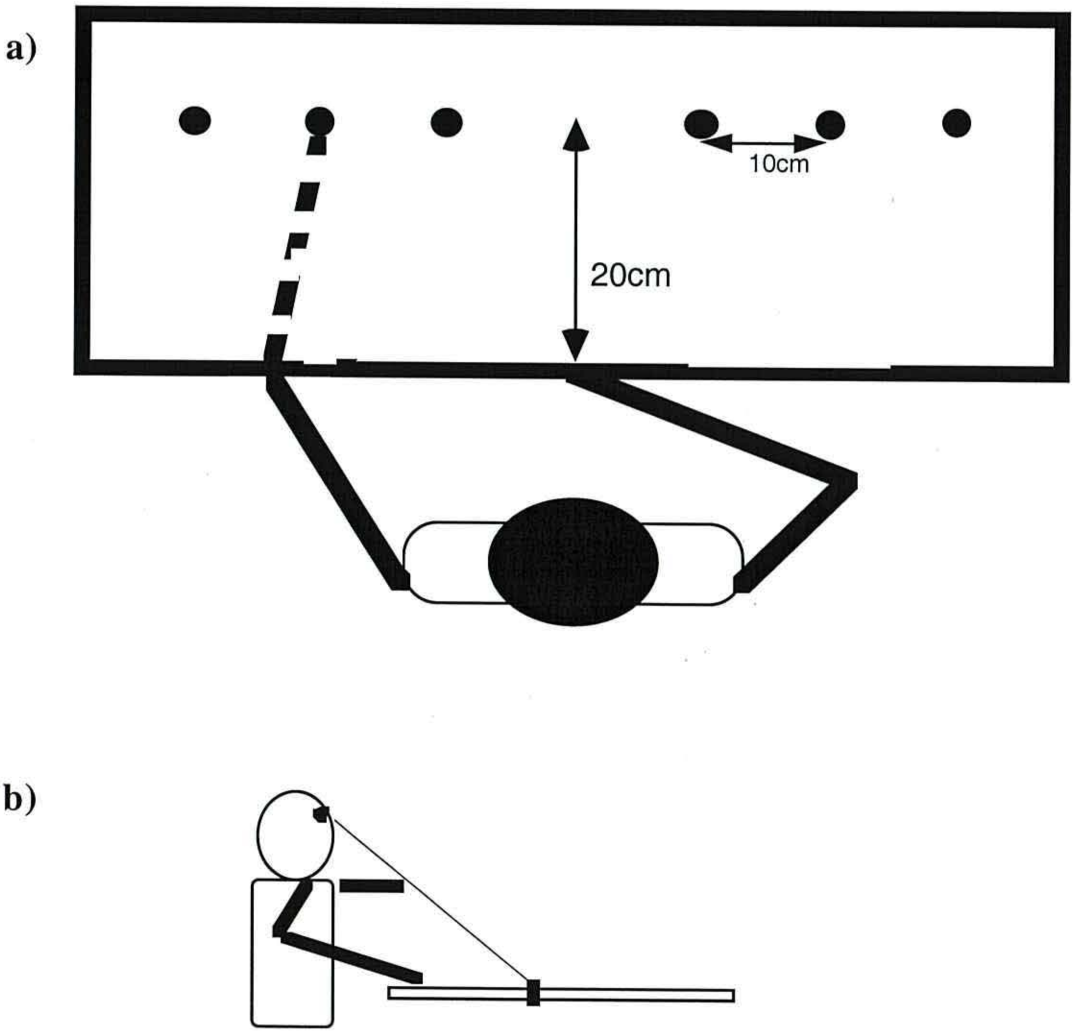

Figure 4.4: The arrangement of a) the six target locations and b) the screen positioned to restrict vision of the hand.

were restricted with a chin rest and subjects wore a pair of goggles to which 25 dioptre displacing prisms were attached. The dioptre is used to describe the power of a refractive lens (or ocular refraction) and when the term is used in relation to prisms it is known as a prism dioptre. 1 prism dioptre causes a displacement of 1 cm at a distance of 1 m and is the angle whose tangent is approximately 0.0101. 25 prism dioptres thus cause a displacement of 25 cm at 1 m (an angle of 14.48 degrees). At 30 cm , the approximate distance of the eyes to the targets in this experiment, the lateral displacement for 25 dioptre prisms is 7.75 cm.

All subjects underwent a period of prism adaptation prior to the experimental condition. Prism adaptation consisted of performing a total of sixty radial pointing movements (ten to each target location) and sixty lateral point-to point movements whilst wearing the prism goggles and with full vision of both the target and pointing hand. The non-pointing hand was kept stationary and out of sight under the board throughout the adaptation period which lasted for approximately ten minutes. The hand used during the adaptation phase was always the right hand. Subjects were randomly allocated to one of six groups with five subjects in each group in a between-subjects design. The six group conditions were as follows:

1) Vision/Vision (Adapted Hand) - **VV(AH)**

After prism adaptation subjects continued to wear the prisms. A matt black screen was placed across the workspace at shoulder height between the subject's head and hand so that the target locations were visible, but vision of the pointing board and the reaching hand up to that point was occluded (see Figure 4.4b). They pointed to each of the six targets ten times in a pseudorandomized order (such that no target appeared more than twice in succession) with their right hand, which was their adapted hand. The non-adapted (left) hand was placed out of sight under the pointing board throughout the session.

2) Vision/Vision (Non-Adapted Hand) - **VV(NAH)**

Conditions were identical to those in the Vision/Vision (Adapted Hand) condition, except that subjects pointed with their left hand, which was their non-adapted hand, and their adapted hand was placed out of sight under the pointing board.

3) Vision/Proprioception (Adapted Hand) - **VP(AH)**

After prism adaptation subjects continued to wear the prisms. A matt black screen was placed across the workspace at shoulder height between the subject's head and hand so that they were unable to see the starting position of the hand, or the moving hand during the early portion of the reach. The pointing board surface was closely covered with a matt black featureless board so that the targets could not be seen, but subjects were still able to see the area of the workspace in which the targets were located. The target locations were defined by passively placing the index finger of the subject's non-reaching, non-adapted, left hand on the target peg on the underside of the pointing board. They pointed to the felt location of each of the six targets ten times in a pseudorandomized order with their right, adapted hand. The board which covered the targets prevented the location of the target dowels being felt by the pointing hand.

4) Vision/Proprioception (Non-Adapted Hand) - **VP(NAH)**

Conditions were identical to those in the Vision/Proprioception (Adapted Hand) condition, except that subjects pointed with their left hand, which was their non-adapted hand, and their adapted hand was the target hand.

5) Proprioception/Proprioception (Adapted Hand) - **PP(AH)**

After prism adaptation subjects kept their eyes closed while the prisms were removed and a blindfold was applied. The targets were covered with a board so that they could not be felt by the pointing hand. The target locations were defined by passively placing the index finger of the subject's non-reaching, non-adapted left hand on the target peg on the underside of the pointing board. They pointed to the felt location of each of the six targets ten times in a pseudorandomized order with their adapted, right hand.

6) Proprioception/Proprioception (Non-Adapted Hand) - **PP(NAH)**

Conditions were identical to those in the Proprioception /Proprioception (Adapted Hand) condition, except that subjects pointed with their left hand, which was their non-adapted hand, and their adapted hand was the target hand.

4.2.4 Dependent Measures

Pointing accuracy was assessed by measuring direction errors (**DE**) which were calculated as the angle (in degrees) formed between a straight line from start position to movement end-point and a straight line from the start position to the target location. A negative result indicates a leftward error (away from the direction of visual field displacement) and a positive result a rightward error (in the direction of the visual field displacement). The kinematically determined movement end-point was calculated as the first frame in which the velocity in the direction of movement of the index finger fell below 2.5 cm/s. The 'first frame' was determined as the first of five frames in which the mean value was below threshold and the mean value of the preceding five frames was above threshold. The placement of the board which occluded vision of the reaching limb during the early stages of the movement signalled, to a certain extent, the distance to the targets. As a consequence of this measurements of amplitude error are rendered meaningless and will not be reported here.

4.3 Results

Data for each subject were segmented into ten bins with each bin containing six trials. Subject means for each bin were entered in separate independent measures ANOVAs, so that each ANOVA consisted of five mean subject scores in each of 6 conditions: VV(AH), VV(NAH), VP(AH), VP(NAH), PP(AH) and PP(NAH). All ten ANOVAs revealed strongly significant main effects of CONDITION (minimum: bin 10: $F_{[1]} = 11.6$, $p = 0.0001$). All significant results were further examined by Student Newman-Keuls post hoc comparisons with an alpha level of 0.05. The results of these are shown in Table 4.2. The means for each group and the post hoc comparisons are presented graphically in Figure 4.5.

Table 4.2: Results of the Student Newman-Keuls post hoc comparisons for each pair of conditions in each bin. Significant results (alpha = 0.05) are indicated by an asterisk.

					BIN					
COMPARISON	1	2	3	4	5	6	7	8	9	10
VV AH - VV NAH										
VV AH - VP AH	*	*	*	*	*	*	*	*	*	*
VV AH - VP NAH	*	*	*	*	*	*	*	*	*	*
VV AH - PP AH	*	*	*	*	*					
VV AH - PP NAH	*	*	*			*		*	*	
VV NAH - VP AH	*	*	*	*	*	*	*	*	*	*
VV NAH - VP NAH	*	*	*	*	*	*	*	*	*	*
VV NAH - PP AH	*	*	*	*	*					
VV NAH - PP NAH	*	*	*	*	*	*	*	*	*	*
VP AH - VP NAH	*					*			*	
VP AH - PP AH		*	*	*	*	*	*	*	*	*
VP AH - PP NAH	*	*	*	*	*	*	*	*	*	*
VP NAH - PP AH							*	*		
VP NAH - PP NAH	*	*	*	*	*	*	*	*	*	*
PP AH - PP NAH	*	*	*	*	*	*	*	*	*	*

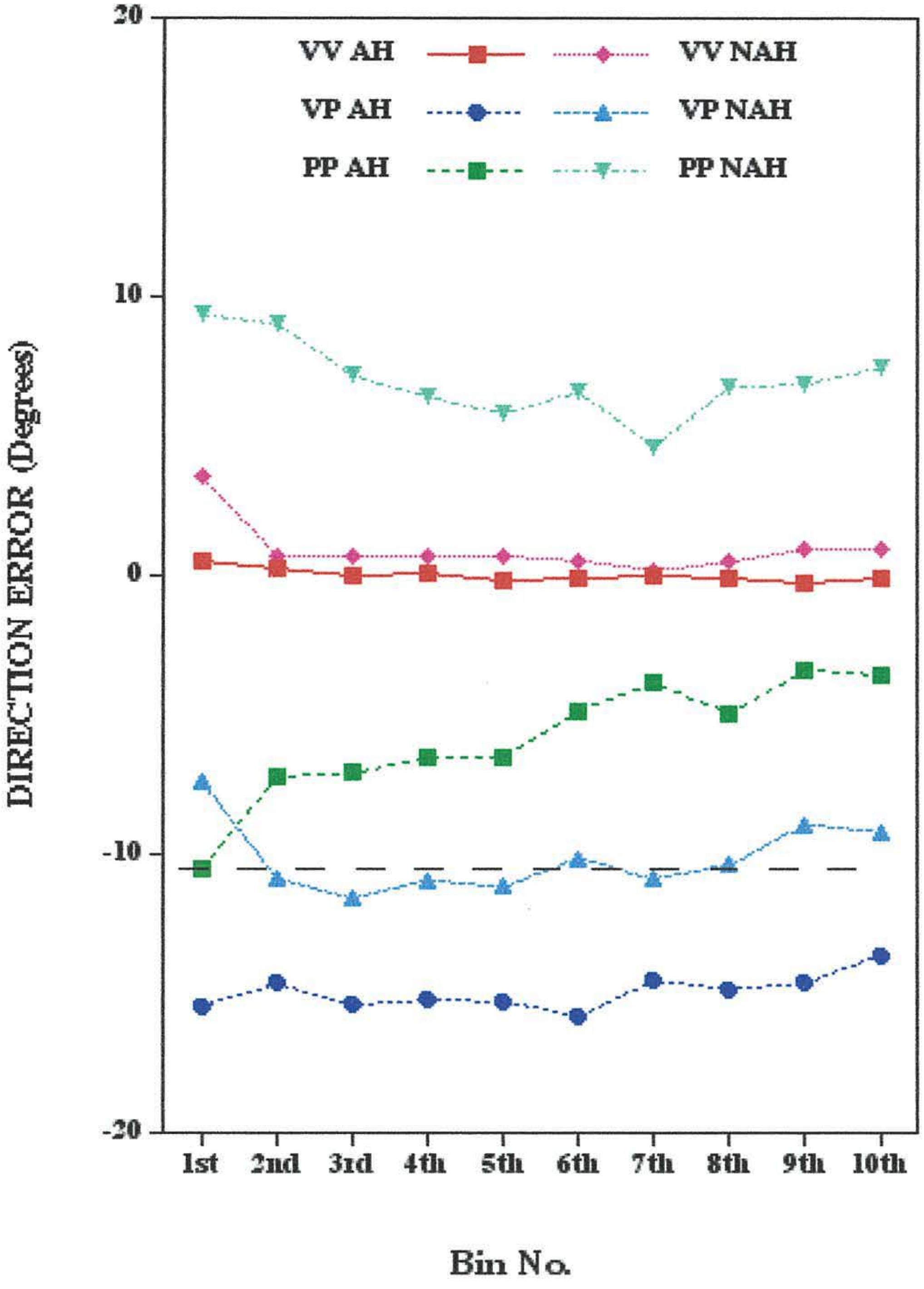

Figure 4.5: Direction error for each 6 trial bin in each condition. Negative values represent a leftward error (i.e. in the direction opposite to the prism displacement). The dotted line represents zero for the VP conditions following adjustment for the calculated subjective midline shift (see discussion text for details).

4.4 Discussion

The two purely visual conditions (VV(AH) and VV(NAH)) clearly demonstrated the known effects of prism adaptation. Reaches with the adapted hand to visually-defined targets were accurate from the outset whereas reaches with the non-adapted hand showed a mean deviation in the direction of the prism displacement in the first bin, but were accurate by the second bin. It is not known whether the difference between the mean scores in the first two bins for VV(NAH) reaches was significant. We do know that the difference in end-point errors between the two visual conditions (VV(AH) and VV(NAH)) in the first bin did not reach the level of significance, the most likely explanation for which is that the bins include the first six reaches by each subject. In the VV(NAH) condition most subjects, after initial inaccuracies, were reaching accurately within as few as three reaches. The rapid improvement during the first bin has created a slightly larger standard deviation in the mean for the VV(NAH) condition and hence the difference between VV(AH) and VV(NAH) did not reach significance.

Blindfolded subjects pointing with their adapted hand to the felt, unseen, position of their non-adapted hand (PP(AH) condition) exhibited a significant bias, approximately 10^{o}, in the direction opposite to the visual field displacement. This leftward shift is analogous to a prism aftereffect after wearing rightward displacing prisms. The results cannot be explained in terms of a visual shift (as shown in Figure 4.1) as subjects were blindfolded, but they could be consistent with either a rightward proprioceptive shift of the perceived initial position of the reaching (adapted) limb (Figure 4.2) or a leftward alteration in the sensorimotor transformation of the target position (Figure 4.3). This is not so for the reverse condition (PP(NAH)) in which the non-adapted hand reached to the felt, unseen, location of the adapted hand. Direction errors here fell in the other direction, that is, 10° in the same direction as the direction of visual field displacement. As outlined in Table 4.1 and Figure 4.3, a change in the sensorimotor transformation would not have produced a movement vector in this direction and could only have been the result of a remapping of the frame of reference associated with the proprioceptively encoded position of the adapted hand (i.e. a proprioceptive shift as described in Figure 4.2). That this happens is further evidence that there is no unified representation of egocentric proprioceptive space, rather that the spatial representations for each limb are separate.

It is interesting to note that, under purely proprioceptive conditions, both the adapted and non-adapted hands showed a steady improvement in directional accuracy over the time course of the experiment. Although the non-adapted hand showed only a slight improvement, the adapted hand showed a steady and significant improvement when compared to the VV(AH) and VV (NAH) conditions. The gradual improvement in accuracy may have been the result of proprioceptive feedback regarding the mismatch in the felt locations of each finger at the end of each reach (when both fingertips are in contact with the table and in close proximity to each other). The problem with this view is that, although there is an objective spatial error between the hands, there is no subjective error because the felt position of the adapted hand has been shifted and is perceived to be in the location indicated by the non-adapted hand. An alternative explanation is that the prism effect in the adapted hand, without reinforcement from the visual system, spontaneously decays. Both the effects of prism adaptation and the negative aftereffects have been observed to decay in the dark by a number of authors (e.g. Fishkin, 1969; Hamilton and Bossom, 1964). The decay of the prism effect is slower than its acquisition (Dewar, 1971) but, the decay is more rapid if the exposure procedure in the adaptation phase was concurrent, as in the current experiment, rather than terminal (Dewar, 1970). The reason that the decay in the PP(AH) condition was faster than that in the PP(NAH) might have been that throughout the PP(AH) condition the adapted hand made large active movements, whereas in the PP(NAH) condition the adapted hand made only small, passive, movements from target to target. Active motion is known to help refresh proprioceptive information (Paillard and Brouchon, 1968) and may have contributed to the rapid decay of the prism adaptation. The presence of an adaptation affect and its subsequent decay in the blindfold condition demonstrates that adaptation to a displaced visual target remains even when vision is subsequently removed - in effect transferring from visually-defined to proprioceptively-defined targets.

Although proprioceptive shift gives a parsimonious account of the results observed in the two PP conditions there may be more to prism adaptation than mere proprioceptive shift (see Welch, 1986 for review) as the introduction of vision in the two VP conditions demonstrates. Reaching errors in the VP(AH) condition were the same as those found in the PP(AH) condition (i.e. a 10^{o} bias away from the direction of prismatic displacement) and it is tempting to explain the result in the same way: as an error resulting from a proprioceptive shift in the felt position of the adapted hand. The same argument does not work, however, for the VP(NAH) condition in which direction errors fell more than 10^{o} away from the direction of prism displacement - representing a massive 20^{o} shift from the errors observed in the PP(NAH) condition. Thus the end-point errors in this condition fall in the direction opposite to that predicted by a model based purely on a shift in the felt position of the adapted hand.

Neither the initial position of the reaching limb, nor the targets themselves could be seen in the VP(NAH) condition: although the eyes were open, visual information was limited to vision of the featureless

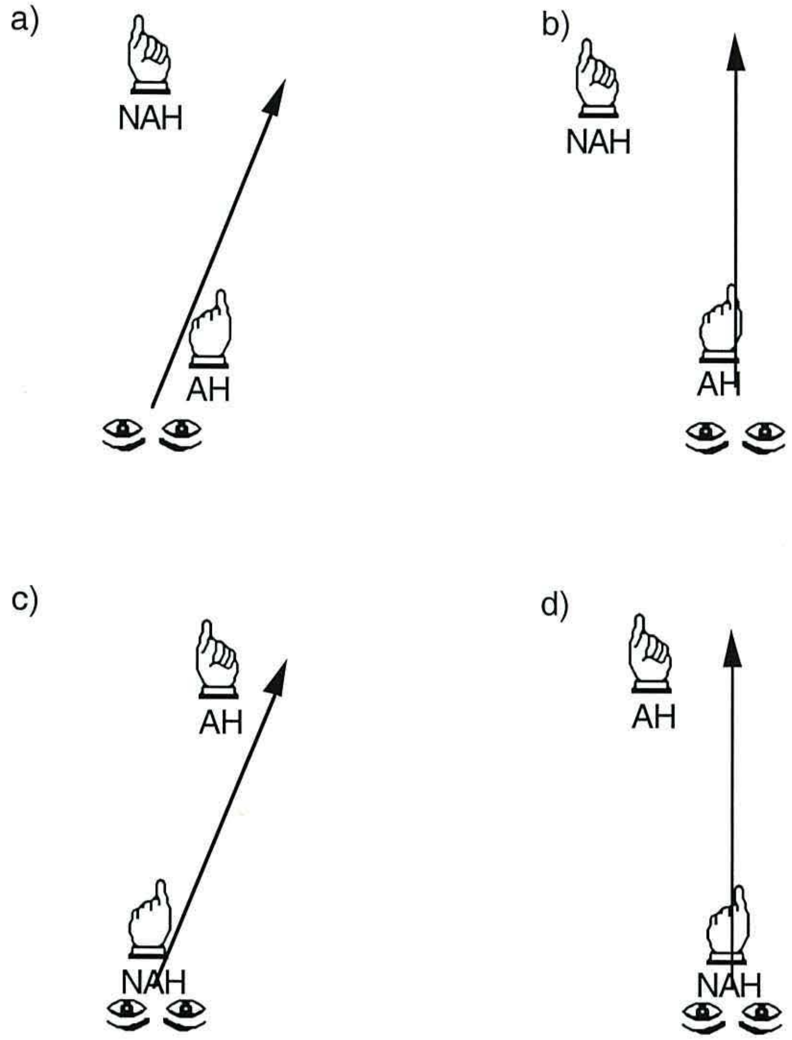

Figure 4.6: Possible sensorimotor transformations which may account for the results in the VP condition: a) the arrow depicts the direction of eye displacement following exposure to rightward displacing prisms. The non-adapted target hand is placed on the objective midline while the adapted hand, although also on the midline, is felt to be slightly to the right of this; b) following translation of the felt hand positions into an eye-centred frame of reference, the resultant movement from AH to NAH is leftward of the actual target position; c) the same as a) except that the adapted hand is now the target and the non-adapted hand is the effector; d) relationship of the hands following translation into eye-centred reference frame.

general workspace and the final position of the reaching hand. A scarcity of retinal information, however, does not prohibit the use of gaze angle information. As outlined in the introduction, ocular position signals may play an important role in prism adaptation. Subjects asked to indicate their mid-saggital plane will, under conditions of rightward prismatic displacement, indicate a point to the right of their midline and when asked where a light on their objective midline (i.e. directly in front of their nose) is located, subjects will report that it lies slightly to their left. Most importantly, they will perceive their eyes to be facing straight ahead when they are in fact deviated slightly to the right. This effect can be termed as a shift in the subjective midline.

According to Ebenholtz (1974) the eyes deviate to the right as a result of eye-muscle potentiation: that is, the muscles controlling the eyes are deviated from their natural resting state for so long that the new deviated position, in effect, becomes the natural resting state which the neural system perceives as straight ahead. If the target hand, placed on the body mid-sagittal axis, is translated into a head/eye-centred coordinate system, in which straight ahead is perceived to be slightly to the right, the target hand is now to the left of straight ahead resulting in the leftward reaching errors observed here. Put more simply, the effect of this subjective shift in the perceived midline could be characterised in the following manner: my hand is aligned with my head; my eyes are facing to the right of my head; my eyes are facing straight ahead; therefore my head and hand are to the left of straight ahead. A more detailed description is given in Figure 4.6.

Note that for this account to work in both the adapted hand and non-adapted hand pointing conditions the amount of the perceived displacement of the adapted hand must be less than the eye displacement/subjective midline shift. The magnitude of proprioceptive shift is generally found to be smaller than the lateral displacement of the prisms (e.g. Redding, 1973; Redding, 1975; Paap and Ebenholtz, 1976). We can see the same effect in the current experiment: the proprioceptive shift, as indexed by the pointing error measured in the PP/AH condition (around 10^{o}) is less than the visual displacement of the prisms (14.48^{o}). It is also worth noting that the sum of the absolute amount of proprioceptive shift, as indexed by the PP/AH direction error in the first bin (10.53^{o}), and the amount of visual shift, as indexed by the VV/NAH aftereffect first bin direction error (3.53^{o}), reveals a total shift of 14.06^{o} - very close to the putative total possible shift (14.48^{o}). (See Harris (1963) and Redding (1978) for examples of this type of calculation).

If we replot the VP data around the hypothesised subjective midline shift (by shifting the data by approx. 10.5 degrees (see dotted line on Figure 4.6)) the VP data begins to make more sense. In bin 1 the VP/NAH and VP/AH end-point errors show the same biases towards and away from the direction of prism displacement as in the equivalent PP conditions - the two main differences being the magnitude of errors (with VP errors being smaller than PP errors which can be explained fully by our weighting hypothesis) and the disappearance of errors after bin 1 in the VP/NAH condition. This disappearance of end-point errors can be explained by on-line visual correction mechanisms. Using Figure 4.2 to illustrate the point: the adapted target hand is at X, but felt to be at Z; the unadapted hand is at O, and felt to be at O; the resultant reach $\underline{OZ}$ is the same as that in the PP/NAH condition. Importantly, however, in the VP/NAH condition the eyes are open and can see the featureless workspace. The eyes may be looking towards Z, but because prisms are being worn and everything is shifted to the right, the actual portion of table surface being fixated is at X. Thus, the reaching hand feels as though it is being directed to the felt location of the target hand (Z), but when the reaching hand becomes visible at the end of the reach it looks as though it is in the wrong place (i.e. not at X). This visual error wins over proprioception and is corrected in subsequent trials.

What happens in the reverse (VP/AH) condition? The unadapted target hand is at X, and felt to be at X; the reaching hand is at O, but felt to be at O'. The resultant reach, O'X has its true origin at O and therefore becomes the reach OY - inaccurate in the direction opposite to the prism displacement (as in PP/AH). The eyes are looking towards X, but, because of the prisms, are actually looking at Y. The finger appears at Y, where it is expected to be, and so no visual error is detected and the inaccurate reaches persist on subsequent trials, except that the proprioceptive shift gradually spontaneously decays in the same manner as for PP/AH reaches.

The above account is highly speculative, but nevertheless, the fact remains that no single reference frame or component of prism adaptation can fully account for the data. It must be the case, therefore, that different mechanisms are at work under different conditions. In short, the results of this experiment add weight to the idea that there are a number of autonomous spatial maps associated with different body parts and that they can be linked together in various ways depending on task demands. Evidence that such a set-up is possible comes from cell recording in the monkey. Extensive recording on the macaque, reviewed by Boussaoud and Bremmer (1999), indicates that eye position signals reach not only the inferior parietal lobule (the region of the brain most commonly associated with playing a major role in coordinate transformations) but also V1, V3A, MT, MST, the parieto-occipital region, the supplementary eye field, the prefrontal cortex and the premotor cortex. They argue that as sensory input signals are distributed across the visuomotor continuum they could potentially allow for multiple task-dependent reference frames. Redding and Wallace (1992) described such a system as a hand-to-eye coordinative linkage between the spatial subsystems of the hands and the eyes, the hierarchy of which may differ according to the amount of feedback available.

We suggest that a purely proprioceptively-based coordinate system, based around the hand or shoulder of either limb, is being used for the conditions in which the subjects are blindfolded. During the VP conditions the frame of reference is shifted to one which makes use of whatever visual information is available - in this case gaze angle. Proprioceptive information is not discarded in this case, but the weight given to it is reduced. In the VV conditions, when more visual information is available, the weighting given to proprioception is reduced still further.

Taken on its own, the evidence provided for this hypothesis by the current experiment is not particularly strong and, as stated earlier, is highly speculative. Taken in conjunction with the previous chapters, however, there is a growing indication that the postulated changes in reference frame must be taking place. In the next chapter we will further investigate the processes of prism adaptation in this task. We will also seek to tie this and the previous chapter together by inducing, in normal subjects, the type of curvature found in our neglect patients by the use of prism adaptation.

Chapter Five

5. The selective effects of prism adaptation on reaching to visually- and proprioceptively-defined targets.

5.1 Introduction

In Chapter 4 we saw how the reaching performance of normal subjects, as indexed by end-point error scores, was altered by a brief period of exposure to rightward displacing prisms. This change in end-point errors, we argued, was largely dependent upon the weighting given to visual, ocular and proprioceptive cues. In Chapter 3 we saw that the pattern of reaching behaviour in neglect patients was also altered depending upon the visual and proprioceptive information available with reaches being abnormally curved when reaching to either visually-defined targets or to proprioceptively-defined targets when vision was available. The aim of this chapter is to investigate the effects of prism adaptation and the adaptation aftereffect on the curvature of reaching movements in normal subjects. The results will be discussed in relation to the neglect patient results reported Chapter 3 and we will examine the possibility that prism adaptation and the neglect syndrome may, to some extent, involve the same neural mechanisms.

Although neglect can occur following damage to a variety of brain regions, one of the lesion sites most commonly associated with neglect is the inferior parietal lobe in the right hemisphere. Damage to the parietal lobe is frequently accompanied by an impairment in the coordinate transformations necessary for the representation of extrapersonal space resulting in abnormal exploration of, or interaction with, extrapersonal space (Andersen, 1987).

Exposure to a visual distortion, such as that produced by prism exposure, initially produces a disorganization of visuomotor behaviour (e.g. miss-pointing) which is quickly corrected through a process of visuomotor adaptation (Redding and Wallace, 1996). The neural structures involved in prism adaptation, however, were traditionally thought not to involve the parietal areas, but instead were thought to involve the cerebellar region of the brain (reviewed in Jeannerod and Rossetti, 1993). A recent PET study, however, has revealed that the posterior parietal cortex contralateral to the acting hand is activated during adaptation to a prismatically induced shift of the visual field (Clower et al., 1996). Both of these regions could be involved, though, as successful prism adaptation involves both sensory realignment and strategic behavioural changes and the cerebellar and parietal regions may control different aspects of these. The intraparietal areas are known to be involved in sensorimotor transformations (Sakata and Taira, 1994) and early sensorimotor transformations could provide the basis for higher-level spatial representations, including the sensorimotor interface required for movement planning (Mattingley et al., 1998).

One mechanisms thought to be involved in the adaptation to short-term prism exposure is a shift in the representations of the perceived position of body parts (i.e. proprioception). The realignment of the visual and proprioceptive maps can be demonstrated by asking subjects to point straight ahead in the dark after a short period of adaptation (Redding and Wallace, 1996). Under these circumstances normal subjects indicate their subjective midline to be deviated in the direction opposite to the optical deviation. A pathological shift in the perception of the subjective body midline is also one of the classic features of neglect. When asked to indicate straight ahead, many patients with left neglect will indicate a direction to the right of their real midline (Perenin, 1997). If neglect patients show a pathological misperception of the midline and a similar misperception can be induced in normals, through prism adaptation, then prism adaptation and neglect may share common brain mechanisms. Exposure to, and subsequent adaptation to, visual distortions must activate the neural structures responsible for the transformation of sensorimotor coordinates and demonstrates the plasticity of the coordinate transformations involved in multisensory and sensorimotor integration (Rossetti et al., 1993; Sugita, 1996).

In 1998 Rossetti et al., conducted a study to investigate the effects of prism adaptation on various classic aspects of the neglect syndrome including the manual demonstration of the subjective midline. They tested 16 right brain damaged patients with long-standing symptoms of left neglect. Prior to adaptation the patients indicated their midline by pointing to their subjective straight-ahead. The patients' mean straight ahead was found to be deviated to the right of their objective midline. Following adaptation the patients demonstrated straight-ahead shifts to the left, as did control subjects. The patients' pathological deviation was therefore greatly improved, demonstrating that neglect patients can easily adapt to a lateral shift of the visual field to the right, and that prism adaptation, acting against the rightward bias of straight-ahead, allows these patients to show a post-test performance which is close to that of normal pre-test performance (see Figure 5.1).

In a second experiment Rossetti et al. (1998) investigated whether prism adaptation could also improve other manifestations of neglect. In this case 12 neglect patients were randomly assigned to a prism group, who underwent a period of adaptation to 10-degree rightward displacing prisms, and a control group, who followed the same adaptation procedures, but wore plain spectacles. Both groups performed a pre- and post test battery of classic clinical neglect tests (line bisection, line cancellation, copying a five item drawing, drawing from memory and reading a simple text). All patients in the prism group exhibited a clear improvement following prism exposure on tasks such as copying (see Figures 5.2), line bisection and line cancellation. Furthermore, this dramatic improvement was fully maintained two hours later. By contrast, there was no significant improvement in the control group. Note that, unlike previously reported physiological manipulations used to improve neglect which are typically short-lived (e.g. caloric stimulation (Rubens,

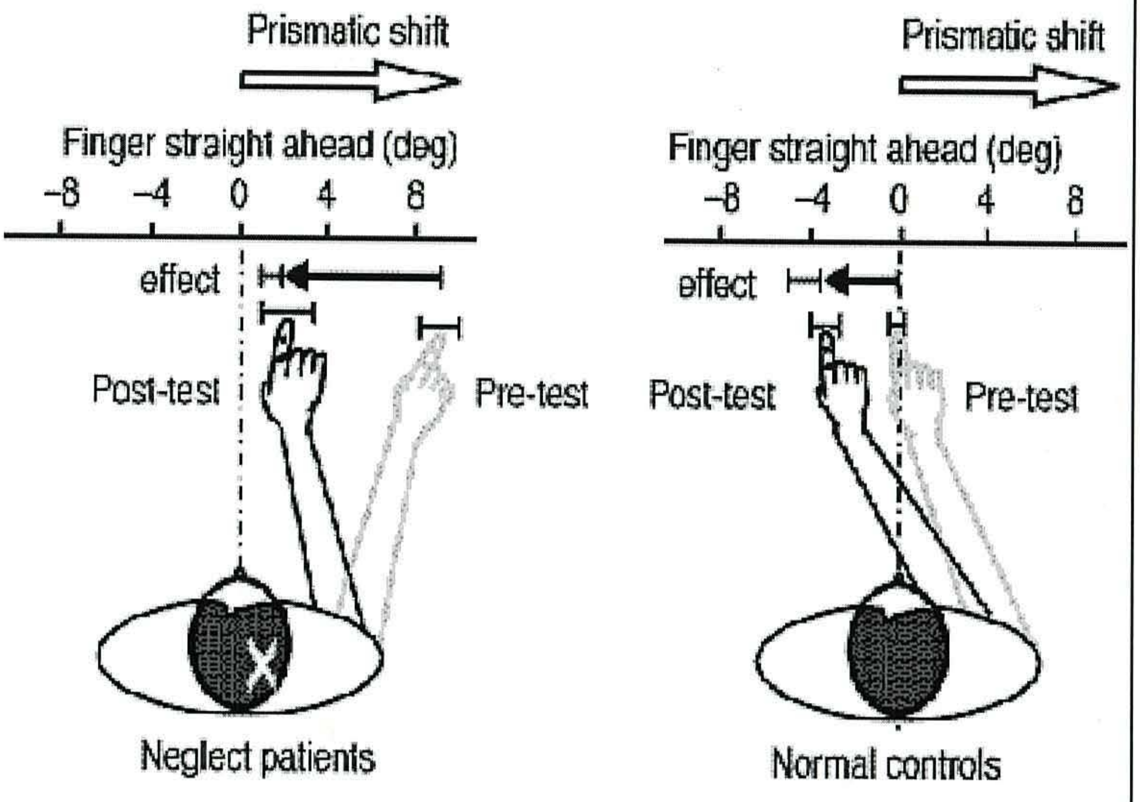

Figure 5.1: Midline demonstrations. Blindfolded subjects were required to point straight ahead while their head was kept aligned with the body's sagittal axis. From Rossetti et al., 1998.

1985; Rode and Perenin, 1994), neck tendon vibration (Karnath, 1994) or optokinetic stimulation (Pizzamiglio et al., 1990), prism adaptation led to a reliable long-lasting amelioration of neglect symptoms (in some cases for more than four days). The effects of 'concurrent' exposure prism adaptation (like the procedure used by Rossetti et al., 1998 which allowed vision of the second half of the arm trajectory as well as terminal errors)

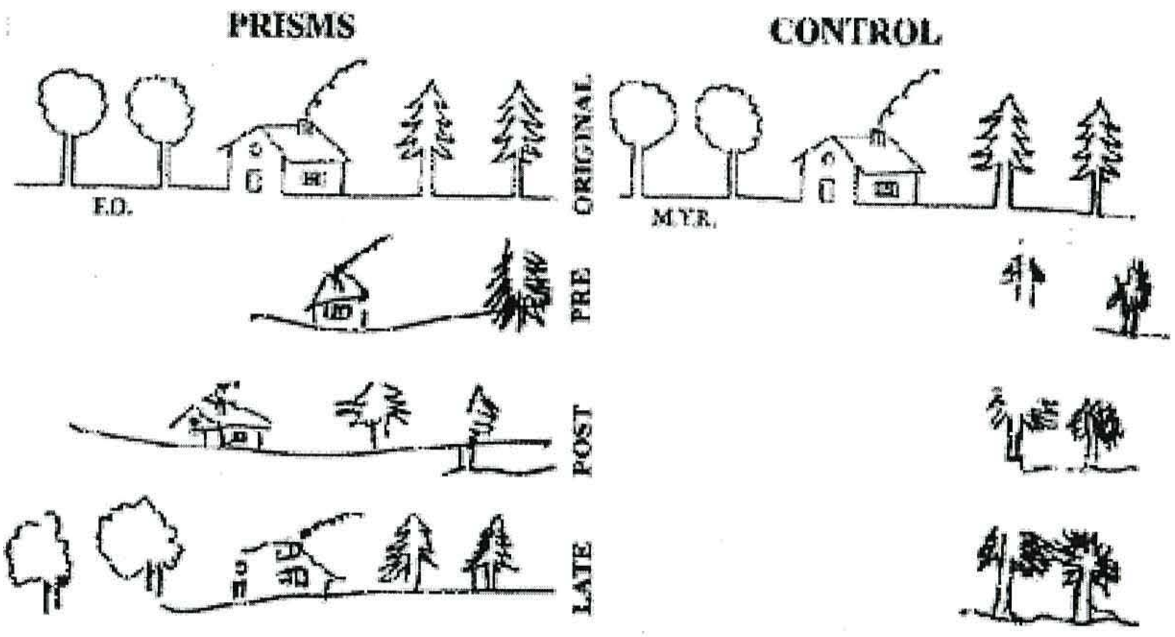

Figure 5.2: Representative example from neglect patient FD (left panel) on a copying task in which the drawing made before prism exposure (pre-test) demonstrates the complete neglect of three items. On prism removal (post-test), one item is added to the patient's drawing. After two hours (late test) all items are drawn. By contrast, patient MYR (right panel) was exposed to neutral goggles and did not improve in the post and late tests. From Rossetti et al., 1998.

are usually found to be task- and limb-specific whereas the effects of the Rossetti et al. (1998) experiment generalized to several widely varied tasks (see earlier). The authors took this as evidence that prism adaptation can affect the organization of higher levels of spatial representation and not just perceptual representations as previously supposed. They argued that the positive effect found for both sensorimotor and more cognitive spatial functions suggested that they share or depend on a common level of space representation linked to multisensory integration.

Neglect behaviour has been thought to result from an impairment in the ability to construct an appropriate representation of extrapersonal space (Halligan and Marshall, 1991; Milner and Harvey, 1995). It has also been argued (Karnath, 1994), that there is a causal link between the subjective shift of the midline and the other common features of neglect although other authors have found a lack of a consistent relationship between neglect and a change in the egocentric reference (Chokron and Bartolomeo, 1997; Farné et al., 1998). Nevertheless the results of the Rossetti et al. (1998) study suggest that prism adaptation can influence higher-level spatial representations and the co-occurrence of an effect of prism adaptation on straight-ahead pointing and on conventional tests of neglect suggests that a common level of space representation may be shared in both sensorimotor (straight-ahead pointing) and more cognitive (copying) spatial functions. Rossetti et al. (1998) argued that, contrary to previously held beliefs on the effects of sensory stimulation in neglect (Vallar et al., 1997), the effect of prism adaptation, as applied in their experiments, cannot be attributed solely to an effect of attention, non-specific activation of the right lesioned hemisphere, or improvement of defective left-sided sensory processes. Rather, they maintain that the effect of the prisms can be conceived of as 'stimulating active processes involved in the plasticity of sensorimotor correspondences, by activating brain functions related to multisensory integration and space representation.'

In Chapter 3 we demonstrated that patients recovering from neglect produce abnormally curved hand paths when executing reaching movements under visual guidance, but not when reaching to proprioceptively-defined targets without vision. We also suggested that the underlying cause of the misreaching observed in our neglect patients was not due to an impairment of motor control, but instead arose as a consequence of a spatial distortion in the visual representation of space used to plan movements. The finding that adaptation to a prismatic shift of the visual field results in a strong and reliable improvement in the clinical signs of neglect suggests that the origin of neglect behaviour may lie in the impairment of mechanisms responsible for normal patterns of intersensory coordination. If the aftereffect of rightward prism adaptation ameliorates neglect behaviour, then it is possible that the reaching behaviour of normals may mimic neglect patterns of reaching after adaptation to rightward displacing prisms. Furthermore, the aftereffect of rightward prism adaptation in normal subjects may produce behaviour which is opposite to the ameliorating aftereffect in neglect patients. In this chapter we will use the same proprioceptive matching task described in previous chapters to examine the changes in hand path curvature that occur after a short period of prism adaptation in normal subjects. Note that it is not our aim to produce neglect in our normal subjects, or even neglect-like behaviour, merely it is our aim to investigate the idea that prism adaptation and neglect may tap into common mechanisms.

5.2 Method

5.2.1 Subjects

Six right-handed adults from the University of Wales, Bangor participated as part of a student credit scheme. All were right-handed, right-eye dominant and had normal, or corrected to normal, vision. None had a history of neurological damage or impairment. The study comprised 2 males and 4 females who had an average age of 22.5 [7.0] years.

5.2.2 Data Analysis

Pointing movements were recorded from a single marker attached to the distal portion of the nail of the index finger of the pointing hand. Recordings were sampled at 86.1 Hz using the miniBIRD electromagnetic tracking system (Ascension Technologies Corp.). Raw data were filtered off-line using a 4th order zero-lag Butterworth filter.

5.2.3 Procedure

Subjects were seated in front of a horizontal, matt black, 90 cm x 90 cm wooden board, raised 15 cm above the table top. Four 6 mm cylindrical pegs were pushed into holes drilled through the board. These served as target locations and were laid out as in Figure 5.3. Subjects wore a pair of flat clear plastic goggles to which 25 dioptre displacing Fresnel prisms were attached and sagittal head movements were restricted by a chin rest. At 30 cm, the approximate distance of the eyes to the targets in this experiment, the lateral displacement for 25 dioptre prisms is 7.75 cm.

Subjects underwent a period of prism adaptation prior each the experimental condition. Prism adaptation consisted of performing a total of sixty radial plus sixty lateral point-to point movements across the workspace whilst wearing the prism goggles and with full vision of the target and pointing hand. The non-pointing hand was kept stationary and out of sight under the board throughout the adaptation period, which lasted for approximately ten minutes, and throughout each experimental procedure. The effects of prism adaptation on hand path curvature were

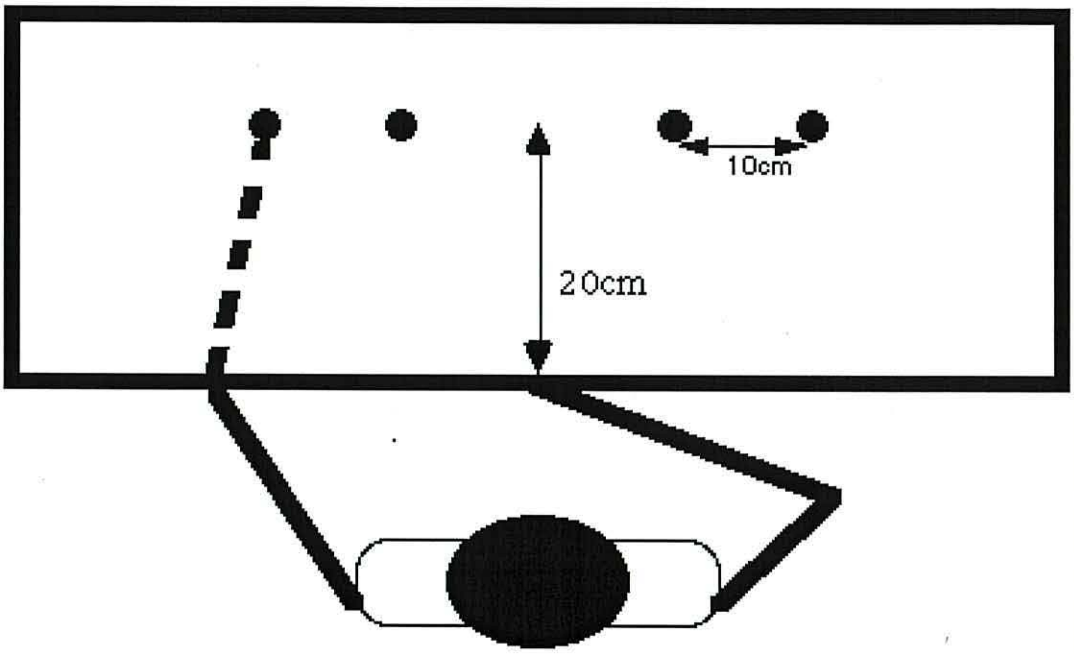

Figure 5.3: Overhead view of the experimental set-up. Reaches from a central start point were made to one of four target locations.

assessed by having subjects execute sixty reaching movements using their adapted limb in each of the experimental conditions which they performed in a pseudorandom order (the same target location was never presented more than twice in succession). The hand used during the adaptation phase was always the right hand.

The basic procedure for the experimental conditions was identical to the VV, VP and PP conditions used and described in previous chapters and as such will not be described in detail here. Baseline levels of hand path curvature were established prior to prism adaptation by having subjects execute reaching movements using their right (preferred) limb to: a) visually-defined target locations [**VV/base**]; b) proprioceptively-defined targets but with vision of the reaching hand and the table surface [**VP/base**]; and, c) proprioceptively-defined targets while blindfolded

[**PP/base**]. The order of the three baseline conditions was randomized for each subject. The remaining conditions were all immediately preceded by a period of adaptation as described above.

Levels of hand path curvature after adaptation were established by having subjects execute reaching movements using their adapted limb whilst still wearing the prisms to: a) visually-defined target locations [**VV/AH**]; b) proprioceptively-defined targets but with vision of the reaching hand and the table surface [**VP/AH**]; and, c) proprioceptively-defined targets while blindfolded [**PP/AH**]. Again, these conditions were performed in a randomized order.

The consequence of the prism aftereffect on levels of hand path curvature was then assessed by having subjects execute reaching movements using their adapted limb with the prisms removed to: a) visually-defined target locations [**VV/AE**] and b) proprioceptively-defined targets but with vision of the reaching hand and the table surface [**VP/AE**]. Finally, after a further period of adaptation, subjects executed the reaching movements to the same visually-defined targets with their non-adapted hand [**VV/NAH**] in order to establish that the repeated prism exposures had not transferred to the non-adapted hand being used to proprioceptively-define the targets in the experimental conditions. The order of target presentation was pseudorandomized such that targets were presented in randomized blocks of four with each target appearing only once in each block.

5.2.4 Dependent Measures

A signed index of hand path curvature (**HPC+-**) was calculated by the same method as that described in Chapter 2 (see Figure 2.4 for details). Briefly, this was calculated by dividing the maximum lateral deviation (in mm) from a straight line path from start position to movement end-point by the straight line distance from start position to movement end-point. A negative value indicates a leftward deviation from a straight-line path and a positive value a rightward deviation.

Direction errors (**DE**) were calculated as the angle (in degrees) formed between a straight line from start position to movement end-point and a straight line from the start position to the target location. A negative result indicates a leftward (or anti-clockwise) error and a positive result a rightward (or clockwise) error. For similar reasons to those outlined in the previous chapter, amplitude error and total error will not be reported here.

5.3 Results

Statistical analyses were based upon a set of a priori comparisons based upon linear contrasts between means. This study was only concerned with changes in HPC+- or DE either immediately after adaptation had taken place or immediately following prism removal (aftereffect) and was not concerned with any changes due to the processes of the adaptation procedure or recovery from the aftereffect of prism removal. For this reason reaches were separated into bins of four trials, with the first reach to each target location being placed in the first bin. Only the mean scores for the reaches in this first bin were analysed. The details of the planned comparisons were as follows: The effect of being subjected to a 25 dioptre visual field displacement, having already adapted to reaching within that environment, on each condition was assessed by comparing the baseline (pre-adaptation) mean scores with the AH (adapted hand) scores in each condition (i.e. VV/base vs. VV/AH; VP/base vs. VP/AH; PP/base vs. PP/AH). The effect of the removal of the visual field displacement, having adapted to it, was assessed by comparing the baseline (pre-adaptation) mean scores with the AE (aftereffect) scores in each condition (i.e. VV/base vs. VV/AE; VP/base vs. VP/AE). Finally, the effect on the left (non-adapted) hand of repeated adaptation of the right hand was assessed by comparing VV/base scores with NN/NAH scores.

Hand Path Curvature +-

F statistics and p values for all HPC+- a priori comparisons are given in Table 5.1. Mean HPC+- scores for each condition are given in Figure 5.4. Mean rotated hand paths are depicted in Figure 5.6.

Direction Error

F statistics and p values for all DE a priori comparisons are given in Table 5.1. Mean DE scores for each condition are given in Figure 5.5.

Table 5.1: F statistics and p values for each of the planned comparisons. Significant results are given in bold.

COMPARISON	DE RESULT	(HPC+-) RESULT
VV/base vs. **VV/AH**	$F_{[1]} = 0.8$ $p > 0.7$	**$F_{[1]} = 5.0$** **$p < 0.05$**
VV/base vs. **VV/AE**	**$F_{[1]} = 5.4$** **$p < 0.05$**	**$F_{[1]} = 15.4$** **$p < 0.01$**
VP/base vs. **VP/AH**	**$F_{[1]} = 44.8$** **$p < 0.001$**	**$F_{[1]} = 5.8$** **$p < 0.05$**
VP/base vs. **VP/AE**	**$F_{[1]} = 5.4$** **$p < 0.05$**	**$F_{[1]} = 5.1$** **$p < 0.05$**
PP/base vs. **PP/AH**	**$F_{[1]} = 28.7$** **$p < 0.001$**	$F_{[1]} = 0.1$ $p > 0.5$
VV/base vs. **VV/NAH**	$F_{[1]} = 1.1$ $p > 0.2$	**$F_{[1]} = 14.8$** **$p < 0.01$**

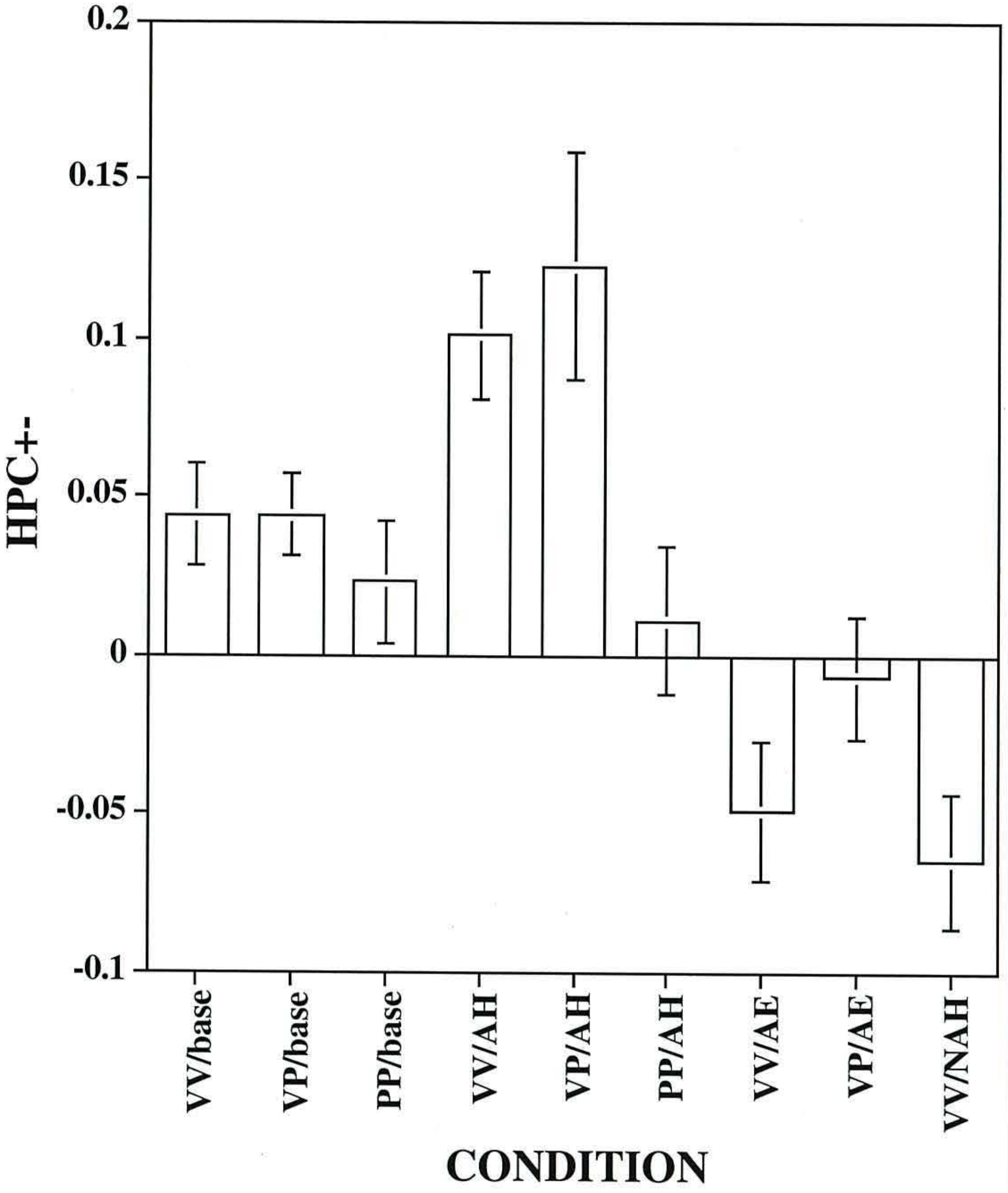

Figure 5.4: Mean HPC+- scores with SE bars for each condition.

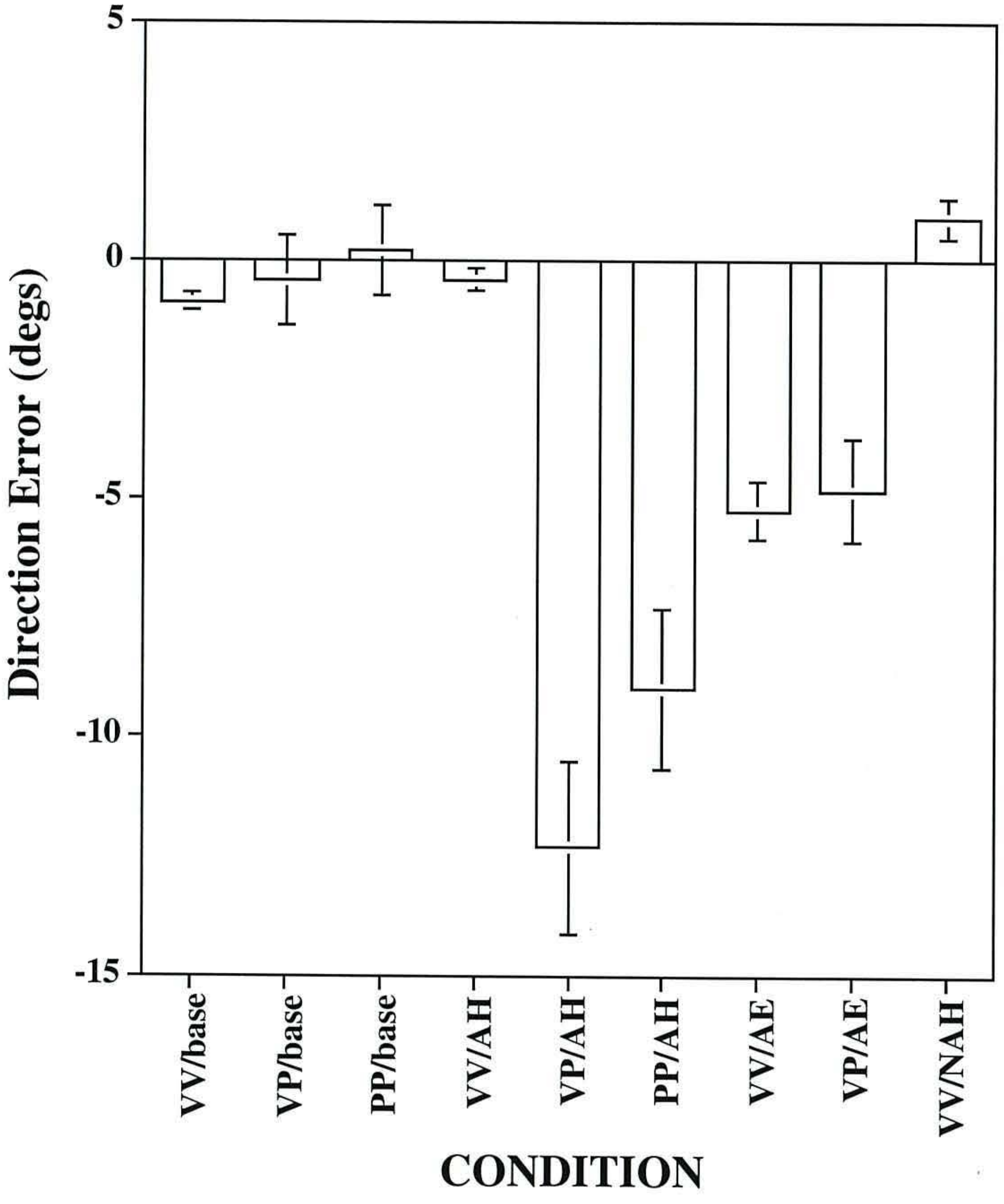

Figure 5.5: Mean DE scores with SE bars for each condition.

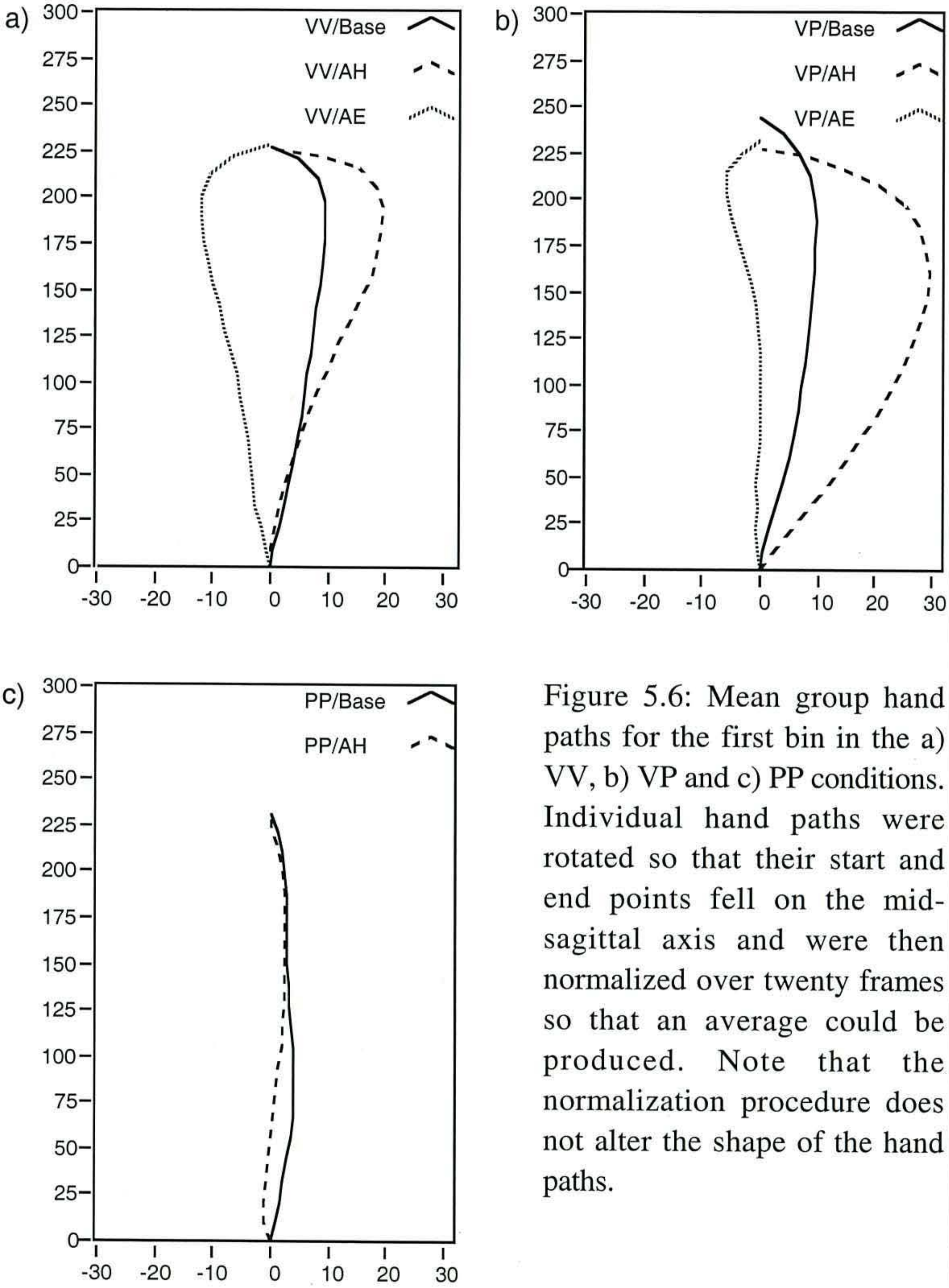

Figure 5.6: Mean group hand paths for the first bin in the a) VV, b) VP and c) PP conditions. Individual hand paths were rotated so that their start and end points fell on the mid-sagittal axis and were then normalized over twenty frames so that an average could be produced. Note that the normalization procedure does not alter the shape of the hand paths.

5.4 Discussion

The pattern of end-point errors observed in Chapter 4, for movements made with the adapted hand to the felt position of the non-adapted hand, was replicated in this experiment. That is, VV/AH reaches were accurate, PP reaches deviated approximately 10 degrees to the left of the target location and VP/AH reaches were almost 15 degrees leftward.

The analyses of hand path curvature demonstrated that a brief period of adaptation to rightward-displacing prisms resulted in a significant increase in the rightward curvature of subjects' hand paths for reaches executed using their adapted (right) hand toward visually-defined target locations whilst still wearing the prisms (VV/AH), relative to the equivalent baseline condition (see Figure 5.6a). It should be noted, however, that this increase in hand path curvature occurred independently of any change in movement accuracy relative to baseline, as end-point error scores (measured in terms of direction error) for reaches to visually-defined targets did not differ between before and after prism-adaptation trials. The fact that no difference in end-point errors was found before and after prism adaptation is hardly surprising as the definition of having adapted to prismatic displacement in such pointing tasks is that end-point errors no longer occur. Could the addiional curvature observed in the VV/AH condition simply be the result of an inaccurate initial movement vector, due to incomplete adaptation, followed by an on-line visual correction? This seems unlikely given that the accuracy of end-point errors demonstrates that adaptation to the visually-displaced targets had taken place. Accurate pointing to visually-displaced targets usually develops after only a few trials. In the current experiment subjects executed sixty such trials during the adaptation phase giving ample exposure to allow complete adaptation. Furthermore, an increase in rightward hand path curvature after prism adaptation, relative to baseline, was also observed for reaches executed using the adapted hand to proprioceptively-defined targets during which vision of the reaching hand and the workspace was provided (VP/AH) (Figure 5.6b). Note that in this case, any 'on-line' corrections to the movement trajectory could not be based upon a visual comparison of the relative positions of the reaching hand and the target location as visual information about the target location was not available. Finally, an inaccurate initial movement vector, due to incomplete adaptation, would have elicited rightward hand path deviations in the PP/AH condition when, again, no visual feedback was available for on-line corrections.

In contrast to the curvature observed in the two conditions with visual cues available (VV/AH; VP/AH), reaches in the PP/AH condition revealed no significant difference in curvature to reaches prior to adaptation (Figure. 5.6c).

The question arises of whether the additional curvature observed was simply as a result of wearing prismatic goggles and completely independent of the adaptation effect. This can be answered by examining the curvature of reaches made once the prisms have been removed. If there is an aftereffect on reach curvature then the curvature seen in the VV/AH and VP/AH conditions is unlikely to have been wholly independent of the adaptation effect. Inspection of Figures 5.6.a and 5.6.b show that removal of the prisms had a dramatic effect on hand path curvature. In both the VV and VP prism aftereffect conditions reaches still displayed a considerable curvature, but this time leftwards of a straight line path. It should be remembered that this leftward curvature was seen when using the right limb, the same limb as that used in the adapted hand conditions which rules out any simple biomechanical explanations. It should also be noted that the effect of removing the prisms on end-point accuracy was that reaches missed the target by several degrees to the left for the first few reaches, thus indicating a genuine prism aftereffect. The profound aftereffect on hand path curvature provides good evidence that the sensorimotor transformations used to plan reaches was altered by brief exposure to visually-displacing prisms. This change in sensorimotor transformation, however, was restricted to those conditions in which visual cues were available and were unaffected by adaptation when the subjects had to rely purely on proprioception to plan and guide reaches.

This last finding, that the hand path curvature of reaches made using the adapted hand in the PP/AH condition was not different from PP/baseline reaches executed prior to prism adaptation, is particularly important as it provides further evidence that reaches to visually-defined and proprioceptively-defined targets are dissociable (Rushworth et al., 1997a). Furthermore, it suggests that prism adaptation results in a distortion of the visual representation of peripersonal space, rather than in a distortion of any 'spatial' representation of the target position. That is, the distortion is restricted only to situations which involve the visual modality. These effects are analogous to those observed in the reaches of neglect patients in Chapter 3. In that chapter increases in hand path curvature were observed for neglect patients executing reaches under visual guidance, but not when patients execute reaches to proprioceptively-defined target locations without vision. We obtained a similar result in the present study for reaches executed by subjects using their prism-adapted hand toward proprioceptively-defined targets without visual guidance.

As outlined in the introduction to this chapter, if the aftereffect of rightward prism adaptation brings the performance of left neglect patients closer to that of normals, then the aftereffect of rightward prism adaptation in normals should produce something akin to an over-correction of neglect performance. That is, the aftereffect in normals should produce reaches which are abnormal, but in the opposite direction to those found in neglect patients, and this is what we found. The degree of curvature in the VV and VP aftereffect conditions was not only greater than in the equivalent baseline conditions, but also in the opposite direction (i.e. leftwards instead of rightwards). As mentioned previously, these results cannot be explained by biomechanical differences as the reaching limb, the targets and the start points were identical in these conditions.

Although the PP/AH condition has been described here as reaches made with the adapted hand in the same manner as the VV/AH and VP/AH conditions, the removal of the prisms and application of the blindfold meant that it could also be considered as being a PP aftereffect condition. In this respect, the difference in curvature between this and the other aftereffect conditions is just as remarkable. If the PP/AH condition is taken as an aftereffect condition then it further shows that neither exposure to displacing prisms, nor their subsequent removal, influences the curvature of reaches planned without access to visual information.

5.5 Summary

This study was motivated by the recent demonstration that the aftereffect of a short period spent adapting to rightward-displacing optical prisms can result in an improvement in the clinical signs of visuospatial neglect (Rossetti et al., 1998). Here we have demonstrated that after a short period spent adapting to rightward displacing prisms, healthy subjects exhibit increases in hand path curvature during reaches executed under visual guidance, but not during reaches executed to proprioceptively-defined targets without vision. In addition, we show that this prism-induced increase in hand path curvature occurs without any corresponding change in movement accuracy. Furthermore, we have shown that the direction of the increase in hand path curvature is different for reaches executed while wearing prisms to those executed after the prisms have been removed. We note that this pattern of effects is consistent with the increase in hand path curvature seen during visually-guided movements that we (and others, see Chapter 3) have noted in patients with, or recovering from, visuospatial neglect. What does this say about the commonality between the mechanisms involved in prism adaptation and neglect? Both the neglect disorder, as observed in our patients, and prism adaptation produce abnormally curved reaches on a task which requires the integration of visuomotor information. When visual information is removed from the equation, both produce relatively normal reaches. These findings provide support for the view that the origin of some aspects of visuospatial neglect may lie in the impairment of mechanisms responsible for normal patterns of intersensory coordination. They also suggest that neglect, at least in our patients, is a predominantly visual disorder rather than an inherently spatial one.

In the next two chapters we shall examine the other side of the visual/proprioceptive coin by testing a series of patients in whom visual processes are intact, but somatosensory processes are impaired.

Chapter Six

6. Sensorimotor integration as revealed by proprioceptive pointing in three patients with unilateral somatosensory impairment following central deafferentation.

6.1 Introduction

In the preceding chapters we saw how both pathological disturbances of the visual system and prismatically induced visual displacement caused abnormal reaching behaviour in a proprioceptive matching task which required the sensory integration of visual and proprioceptive information. In this chapter we will examine the other side of the coin and turn our attention to pathological disturbances of the somatosensory system. We will examine the performance of three patients recovering from unilateral somatosensory impairment following stroke. These patients all have an intact visual system, but have deficits of somatosensation in one limb.

As discussed in Chapter One, the optimal conditions for planning and executing a reach are knowledge of both the position of the target and the initial position of hand as well as having visual and kinaesthetic feedback from the position of the hand as it moves through space. It is widely accepted that the sensorimotor system controlling upper-limb movements can use either visual or proprioceptive inputs to formulate motor commands. Nevertheless, it is clear from experimental investigations of prehension movements that movement accuracy is maximized when both are available (Ghez et al., 1990; Ghez et al., 1995). In particular, visual information can serve to calibrate proprioceptive knowledge of initial limb position (Rossetti et al., 1994b; Rossetti et al., 1995) and to allow on-line corrections to a kinaesthetically controlled hand path (Goodale et al., 1986).

How sensory information is integrated to form motor plans has been a central issue in motor control as well as one of the major topics investigated in this thesis. Several alternative frames of reference have been postulated to account for the coordinate system in which the egocentric representation of the target is localized relative to the body (e.g. a head or trunk centred, shoulder centred, or hand centred coordinate system see Chapter 1). Whichever coordinate system is used, it must specify the current position of the reaching hand and the direction and amplitude of the movement required to get the hand to the target.

The relative contributions of proprioception and vision to the control of goal-directed movements is still unresolved. Recent anatomical evidence suggests that the frame of reference used to guide reaching movements may vary according to whether movements are directed to visually-defined or proprioceptively-defined target locations (Rushworth et al., 1997a; Rushworth et al., 1997b). (Rushworth and colleagues trained monkeys to reach to visually-defined targets in the light and to targets defined by remembered limb position in the dark. Removal of areas 7a, 7ab and LIP caused reaching errors in the light, but not in the dark, while removal of areas 5, 7b and MIP had the opposite effect).

Studying the performance of patients with a proprioceptive deficit on a task which requires the integration of visual and proprioceptive information in order to formulate the relevant motor commands may help to shed light on the relative contributions of proprioception and vision to the control of goal-directed movements. We chose to investigate the integration of visual and proprioceptive information by using the proprioceptive pointing matching task described in Chapters 2 and 3. Accurate and efficient performance in such a paradigm requires that subjects effectively make use of both somaesthetic information about the static position of the target hand and kinaesthetic information about the pointing limb as it moves through space towards the target. Without vision of the static arm we still have access to position sense derived most probably from muscle stretch receptors (Gandevia and McCloskey, 1976; McCloskey, 1978) and cutaneous afferents (Edin and Abbs, 1991). Muscle afferent input is crucial for detecting static limb position and changes in static limb position during slow movements (Jones, 1996). As movement velocity increases, changes in limb position can be inferred from sensations of movement resulting from the activation of muscle, skin and, probably, joint receptors (Clark et al., 1985; Ferrell et al., 1987). Thus, movement and position of the limb may well be encoded independently (Jones, 1996).

Although all of our patients had somatosensory deficits in one limb, they were all able to move their affected limb freely and without substantial loss of isometric force. This allowed us to test the pointing accuracy of both hands: the non-impaired limb indicating the felt position of the impaired limb and vice versa. In this way the performance of impaired and non-impaired limb could be directly compared in each condition. Despite the fact that all three patients presented with broadly similar symptoms, in the sense that they all had degraded somatosensation, they were, by lesion site and clinical testing, an extremely heterogeneous collection of patients and should not be considered as being part of a group. For this reason the three patients will be reported and discussed separately.

As in all these cases we are only interested in the somatosensation in the upper limbs of these patients it will be assumed that wherever either the 'affected limb' or unaffected limb' is described, it is the upper limb that is being referred to. Similarly the terms 'affected' and 'impaired' will be used interchangeably when describing the limb with somatosensory loss.

6.2 Method

6.2.1 Subjects

The case histories of each patient will be described in the relevant results section.

6.2.2 Data Analysis

Movements were recorded using the miniBIRD electromagnetic recording device described previously. Recordings were sampled at 86.1 Hz with a spatial resolution of 1.23 mm. Raw data were filtered off-line using a 4th order, zero-lag, Butterworth filter with a cut-off frequency of 10 Hz.

6.2.3 Procedure

The procedure used in this experiment was similar to that reported in Chapters Two and Three with the exception that a) both hands were tested (where possible) and b) the start location was varied to reduce prior knowledge of hand position. Subjects were seated at table upon which rested a raised wooden board (painted matt black) containing eight holes, each 6 mm in diameter. Subjects executed pointing movements above the raised board, using their index finger, from a randomly assigned starting position either 5 cm to the right or 5 cm to the left of the mid-saggital axis. Pointing movements were made to each of four target locations associated with each starting position (see Figure 6.1 for details). Throughout the experiment subjects wore an electromagnetic marker on the index finger of their pointing hand and a similar marker on the index finger of their target hand.

The study consisted of three pointing conditions identical to those described in Chapter 2. Briefly, they were as follows:

i. Vision/Vision **(VV)** trials - During VV trials target locations were defined visually by placing a small wooden 'target' dowel (coloured white) into the appropriate hole for that trial. This dowel did not protrude above the surface of the board. Subjects pointed with their eyes open and were allowed to move their head and eyes freely. Subjects' non-pointing hands were placed on the table-top beneath the target board in a central position that did not correspond to any of the target locations;

ii. Vision/Proprioception **(VP)** trials - During VP trials the target array was covered by a matt black board so that there were no longer any visual cues as to the location of the target. Instead, target locations were defined proprioceptively by passively placing the index finger of the subject's unseen non-pointing hand onto the relevant drilled hole on the underside of the raised board.

Subjects pointed with their eyes open so that visual information about the moving limb was available throughout the trial;

iii. Proprioception/Proprioception **(PP)** trials - These were identical to VP trials with the exception that subjects were blindfold throughout.

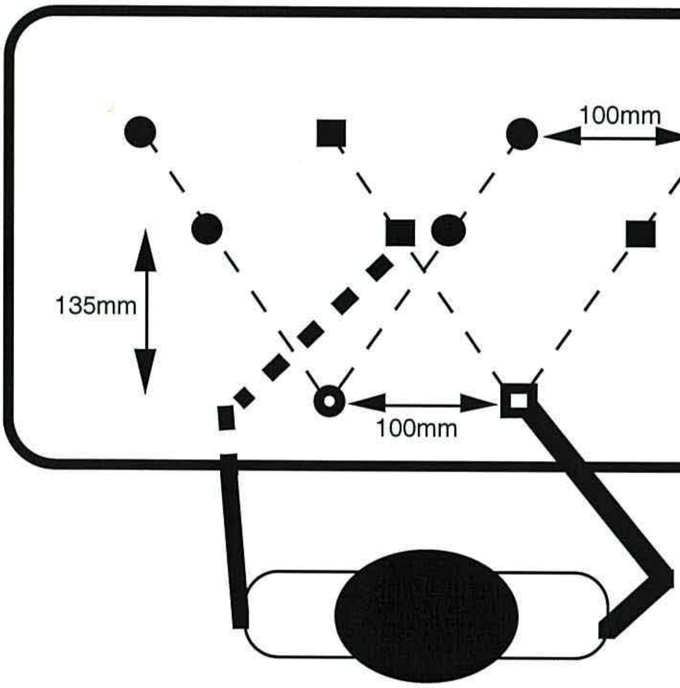

Figure 6.1: Overhead view of the experimental set-up. Reaches could begin from either an ipsilateral (open circle) or contralateral (open square) start position. Reaches from each start position were directed to one of four target locations associated with that start position and could be either contralateral or ipsilateral and two one of two distances (e.g. reaches starting from the open square could be directed to one of the four targets depicted by closed squares and from the open circle to targets depicted by closed circles). In reality, of course, all start points and targets were circular.

For each subject the order of presentation for the three pointing conditions was presented in an ABCCBA design within an ABBA design for the order of responding hand. The order of target presentation was randomized within each condition. Altogether, subjects made four pointing movements to each target location with each hand in each condition. Subjects pointed with the tip of their index finger, were encouraged to reach using a single smooth movement, and were not permitted to correct inaccurate reaches after they had made tactile contact with the board surface. A tone signalled the start of each trial . On VP and PP trials, this tone was always presented within 2 seconds of the passive placement of the target finger to avoid proprioceptive drift of the non-moving hand.

6.2.4 Dependent Measures

Movement onset was defined as the first frame in which the finger marker exceeded a velocity in the direction of movement of 2.5 cm/s. Movement end-point was defined as the first frame in which the velocity of the finger marker fell below 2.5 cm/s. All trials were visually checked to ensure that the movement end-point identified in the above manner coincided with the end of the movement. Two measurements of movement end-point accuracy were defined: a) Direction error (DE): Errors in movement direction were calculated as the angle (measured in degrees) formed between a straight line from movement start position to movement end-point and a straight line from the movement start position to the target location. A negative result indicates a leftward (or anti-clockwise) error and a positive result a rightward (or clockwise) error; b) Amplitude error (AE): Errors in movement amplitude were calculated as the difference, measured in mm from the movement start position, between the radial distance of the movement end-point and the radial distance of the target. Positive values represent *hyper*metric movements and negative values *hypo*metric movements; c) Hand path curvature

(HPC): An index of hand path curvature was calculated, as in previous chapters, by dividing the maximum lateral deviation (in mm) from a straight line path from start position to movement end-point by the straight line distance from start position to movement end-point. This index of curvature is independent of the movement amplitude and the direction (leftwards or rightwards) of the curvature.

6.3 Results

Data for patient RQ were entered in separate 2 X 3 repeated-measures analyses of variance (ANOVA) for each dependent variable. Each ANOVA consisted of the factors: POINTING HAND (impaired vs. non-impaired); and CONDITION (VV vs. VP vs. PP). To evaluate the effect of hand within each condition, planned comparisons between means were carried out using a linear contrast procedure (affected hand vs. unaffected hand for VV, VP and PP). The procedure used for HPC analysis was slightly different however, as in this case we were more interested in the effects of condition within each hand (Impaired hand: VV vs. VP; VV vs. PP; VP vs. PP. Non-impaired hand VV vs. VP; VV vs. PP; VP vs. PP).

Patient JH tired very easily and was thus considered unable to complete a full testing session. For this reason those blocks in which reaching movements were executed using his impaired limb were omitted from the design. In addition, as prior testing had established that JH showed no impairments when reaching with his non-impaired limb to visually-defined targets, no trials were recorded in the VV condition as these trials were considered to be of less theoretical importance than trials in which JH reached with his non-impaired limb to target locations defined by his impaired limb (VP and PP conditions). Furthermore, due to a spurious recording aberration, it was not possible to calculate JH's hand path curvatures. JH was not available for any subsequent retesting. For patient JH, therefore, data were entered in a t-test analysis.

Patient TJ was only tested on reaches made with her right limb as she found active movement of her left limb (specifically the shoulder) quite painful, especially to distant targets, due to a recently broken (but healed) arm. Although she consented to us passively moving her left limb in order for it to be a target, she was reluctant to use that hand for reaching. For patient TJ data were entered in a single factor ANOVA with the factor CONDITION (VV vs. VP vs. PP) for each dependent measure. A priori comparisons of means were conducted in the following contrasts: VV vs. VP; VV vs. PP and VP vs. PP.

6.3.1 Case RQ

RQ is a 75 year old right-handed male who suffered a right-sided CVA in February 1998. A CT scan carried out immediately after his stroke (Figure 6.2) revealed hydrocephalus involving the lateral and third ventricles, with a normal fourth ventricle. The scan also revealed infarction in the distribution of the right middle cerebral artery involving the right temporo-parietal junction and the right inferior parietal lobule. Neuropsychological assessment carried at 7 days and 21 days post event (the latter immediately prior to testing), revealed that RQ had a marked somatosensory loss in his left arm and hand. He was impaired at identifying

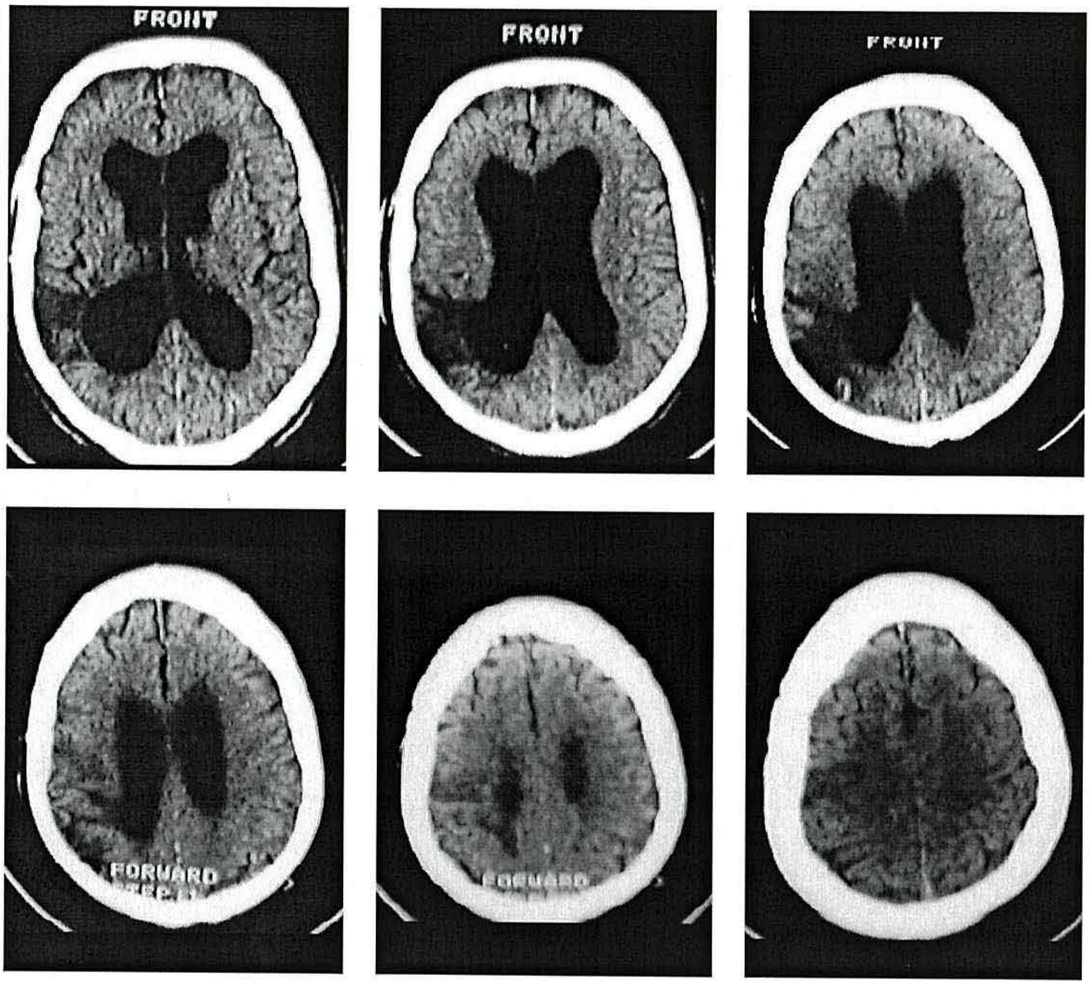

Figure 6.2: CT scan of patient RQ. The right hand side of the brain is shown on the left side of each scan and vice versa. See text for details of lesion.

objects placed in his left hand (0/4) using tactile cues alone (astereognosis), and he was unable to detect tactile (punctate) stimulation of the fingers (0/4), hand (0/4), wrist (0/4), forearm (0/4) and elbow (0/4) of his left arm. RQ was also impaired at detecting the joint rotations applied to the fingers (0/4), wrist (2/4) and elbow (0/4) of his left arm. However, he was able to detect rotations of the left shoulder (4/4). Extensive testing, identical to that for the left limb, revealed that RQ showed no somatosensory impairment in his right arm and hand (4/4), although a war wound restricted shoulder movement slightly. RQ was able to point correctly, while blindfold, to his own body parts with both hands (4/4), and could correctly pantomime (4/4) and copy (4/4) actions performed by the experimenter with either hand. With his eyes closed RQ was unable to copy the posture of his left (impaired) limb using his right (non-impaired) limb (1/4). He could, however, copy the posture of his right (non-impaired) limb using his left (impaired) limb (4/4). At the time of testing RQ showed no signs of any visual impairment including visual extinction and visuospatial neglect. Throughout the following analysis and discussion RQ's <u>left</u> limb will be referred to as his <u>impaired</u> limb.

RQ Amplitude Error

Analyses of patient RQ's AE scores revealed a significant main effect of CONDITION ($F_{[2,62]} = 180.9$, $p < 0.0001$), and a significant HAND x CONDITION interaction effect ($F_{[2,62]} = 23.8$, $p < 0.0001$). The main effect of HAND was not significant ($F_{[1,31]} = 2.4$, $p > 0.1$). Planned comparisons revealed that when reaching to visually-defined targets (VV condition), RQ's AE scores for each limb were small (< 10 mm) and did not differ statistically from one another ($F_{[1]} = 1.0$, $p > 0.1$). In contrast, when reaching to proprioceptively-defined targets (PP condition), RQ's showed a marked hypometria when using either hand. In this case, though, reaching with his affected limb proved to be more hypometric than with his unaffected limb $F_{[1]} = 15.3$, $p < 0.0005$). On VP trials, RQ's hypometria was substantially ameliorated, but only when his unaffected limb was the target ($F_{[1]} = 34.2$, $p < 0.0001$). Means for both hands in each condition are given in Figure 6.3a.

RQ Direction Error

Analyses of patient RQ's direction error scores revealed significant main effects of HAND ($F_{[1,31]} = 66.3$, $p < 0.0001$) and CONDITION ($F_{[2,62]} = 18.6$, $p < 0.0001$). In addition, there was also a statistically significant HAND x CONDITION interaction effect ($F_{[2,62]} = 32.8$, $p < 0.0001$). Planned comparisons revealed that when reaching to visually-defined targets (VV condition), RQ's direction errors for each limb were very small and did not differ statistically from one another ($F_{[1]} < 1.0$, $p > 0.1$). In contrast, when reaching to proprioceptively-defined targets (PP conditions), RQ's direction errors were significantly greater ($F_{[1]} = 125.1$, $p < 0.0001$), showing a marked anti-clockwise rotation, for reaches executed using his <u>non-impaired</u> limb compared to his impaired limb (the scores for which were close to zero). This directional inaccuracy was substantially ameliorated, though still significant ($F_{[1]} = 13.0$, $p < 0.005$) when reaching with his non-impaired limb to proprioceptively-defined targets on VP trials. Again, direction error scores for the impaired limb in this condition were close to zero. Means for both hands in each condition are given in Figure 6.3b.

RQ Hand Path Curvature

Analysis of RQ's hand path curvature index revealed a significant main effect of HAND ($F_{[1,31]} = 10.8$, $p < 0.005$) with reaches made with the affected hand exhibiting more curvature than reaches made with the unaffected hand. There was also a significant main effect of CONDITION ($F_{[2,62]} = 3.5$, $p < 0.05$). Overall, VP reaches curved less than VV and PP reaches. A priori comparisons revealed that for each hand there were no significant effects of condition (minimum: $F_{[1]} = 3.1$, $p > 0.08$). All relevant means are given in Figure 6.3c.

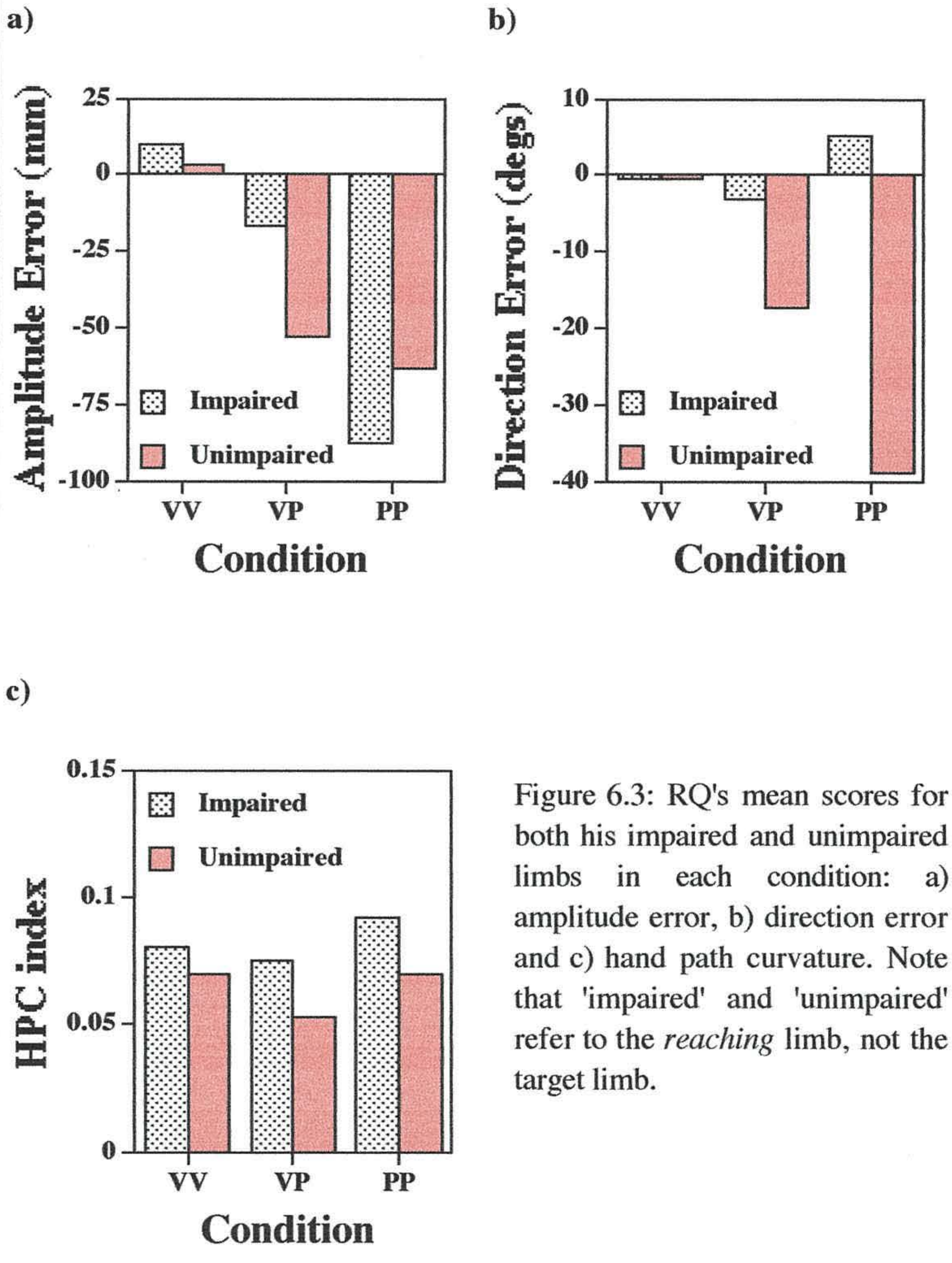

Figure 6.3: RQ's mean scores for both his impaired and unimpaired limbs in each condition: a) amplitude error, b) direction error and c) hand path curvature. Note that 'impaired' and 'unimpaired' refer to the *reaching* limb, not the target limb.

6.3.2 Discussion of Case RQ

When making visually-guided reaches to visually-defined targets (VV condition), RQ's amplitude and direction errors were minimal. Like the control subjects in Chapter 2 he overshot the target very slightly and was extrememly accurate in terms of direction errors. As he performed equally well with either hand it is clear that RQ was able to use vision to accurately control his reaching movements despite a dense sensory loss in his left upper limb. In contrast, when reaching to proprioceptively-defined targets without vision (PP condition), RQ's end-point errors displayed a large anti-clockwise deviation when his affected hand was the target and a marked hypometria when indicating the felt position of either hand. This is in contrast to the controls subjects (Chapter 2) who tended to overshoot the target distance on PP trials. On VP trials, with visual cues available, both the hypometria and anti-clockwise bias were substantially ameliorated, but only when his unaffected limb was the target (using his affected limb to indicate the target location) despite the fact that the visual cues that were available to RQ on VP trials could not directly signal the target location. When his affected limb was the target, directional and amplitudinal biases were improved, but largely persisted.

What is the basis for RQ's poor performance with both limbs on PP trials and why is this ameliorated when VP visual cues are available, particularly when his unaffected hand is the target? It is unlikely that RQ's poor performance stems from an inability to control or localize his unaffected limb. He was perfectly able to produce accurate movements of the correct amplitude and direction with his <u>unaffected</u> limb (see VV condition) as well as produce accurate movements <u>towards</u> the unaffected limb (VP condition). RQ's poor performance in the PP condition, therefore, probably stemmed from an inaccurate localization of his impaired hand. RQ's end-point errors in the PP condition when he was directing his unaffected limb to the felt location of his affected limb appear to suggest that he perceived the location of his impaired hand to be rotated and truncated towards his left (impaired) shoulder. It is conceivable that the proprioceptive map of space related to the left limb in RQ has been condensed or compressed towards the body or left shoulder. Spatial compression has long been one of the more robust and believed theories used to explain the abnormal behaviour seen in neglect patients. It is not clear whether spatial compression in neglect is for space as a whole, or just 'visual' space. There is now evidence to suggest that there are multiple maps of space represented in the brain and that these separate maps each relate to a different part of the body (e.g. Haggard et al., 2000; Boussaoud and Bremmer, 1999; Graziano and Gross, 1998). When an action is planned, the relevant maps are integrated into a coordinate system with a single frame of reference. When a reach is planned using proprioceptive information from the compressed spatial representation of the affected limb without reference to visual input, the result is a reach which terminates too close to the affected shoulder. This hypothesis is supported by data from the VP condition. When the affected hand is the target (unseen, beneath the table), reaches are still inaccurate, being rotated and truncated towards the affected shoulder. When the unaffected hand is the target, however, and the affected hand can be seen, RQ's reaches are accurate once more. In this condition (VP affected hand to unaffected hand) vision is able to calibrate the felt position of reaching limb, effectively overriding the compressed proprioceptive information, (Rossetti et al., 1994b; Rossetti et al., 1995) resulting in more accurately planned and executed reaches. The results in this condition also support the idea that the compression of proprioceptive space in RQ is limb specific as the felt position of the unseen unaffected limb in the VP condition has been correctly localized without visual calibration. It is not clear exactly how this compression of proprioceptive space might occur, but it may be an exaggerated or accelerated form of the proprioceptive drift that occurs naturally in normal subjects after a delay of around 8 seconds if the felt position of the limb is not updated by vision (Wann and Ibrahim, 1982).

The above findings are slightly at odds with the clinical evidence, however. Clinical assessment immediately prior to testing revealed that RQ was able to point correctly, without vision, to his own body parts with <u>both</u> hands, and could correctly pantomime and copy actions performed by the experimenter with <u>both</u> hands. With his eyes closed RQ was unable to copy the posture of his left (impaired) limb using his right (non-impaired) limb, but he <u>could</u> copy the posture of his right (non-impaired) limb using his left (impaired) limb with his eyes shut. RQ thus appeared perfectly able to direct his affected hand even in the absence of visual calibration. 'Bed-side' testing of pointing to body parts is a relatively gross measure of competency, however. Correctly pointing to the right knee with the left hand, for example, often involves only managing not to point to the left foot and managing to indicate the right leg somewhere between mid shin and mid thigh. Furthermore, the posture matching task only tests the ability to match identical joint angles and rotations. In the proprioceptive pointing experiment, on the other hand, the joint angle configurations of the upper and lower hands are different and efficient performance on the task requires more than the matching of joint information, rather it requires the sensory integration of <u>spatial</u> information regarding the locations of the fingertips. This is consistent with the site of RQ's lesion which involved the right temporo-parietal junction and the right inferior parietal lobule - a region of the brain which receives inputs from visual and somatosensory cortices and has long been thought of as an area important for sensory integration (Andersen 1987).

It is interesting to note that there was a slight, but noticeable, improvement in reaching accuracy between the VP and PP conditions when the target hand was the affected hand. As we have seen, proprioceptive localization of the unaffected hand was intact and it is possible that vision of that hand improved performance in the VP condition when the affected hand was the target. There is, however, an alternative possibility - that the visual cues available in the VP condition somehow improved, albeit slightly, the proprioceptive localization of the <u>unseen</u> affected hand despite the fact that is could not be seen directly. As they stand, however, RQ's results do not allow us to disentangle these two possibilities.

In Chapter 3 we showed that visual misrepresentations of space can be indexed by measuring the hand path curvature using this proprioceptive pointing paradigm. In the VV and VP conditions, which require the integration of visual information, patients who had suffered from neglect showed greater hand path curvature without a loss of overall end-point accuracy. With this in mind we analysed the hand path curvature of RQ whose results suggested a misrepresentation of somatosensory space, without an impairment visual space. Planned comparisons revealed that there were no significant differences between pointing conditions for either hand (the same as the control subjects described in Chapter 2, but not the same as the neglect patients in Chapter 3). We suggest that this, along the with evidence from standard clinical assessment immediately prior to testing, demonstrates that RQ has an impairment in the representation of somatosensory space that is not accompanied by an impairment in the representation of visual space.

6.3.3 Case JH

JH is a 74 year old right-handed male who suffered a right-hemisphere CVA in June 1999. A CT scan carried out three days after his stroke (Figure 6.4) revealed extensive infarction in the subcortical white matter of the right middle cerebral artery territory, sparing the basal ganglia and the internal capsule, undercutting the frontal and parietal opercula and involving the insula. There was also infarction in the distribution of the right posterior cerebral artery involving the medial occipito-temporal region and the posterior hippocampus. Neuropsychological assessment carried out at 9 days post event (immediately prior to testing) revealed that while JH could freely move his left arm, he had a marked somatosensory loss in his left arm and hand. He could not identify objects placed in his left hand using tactile cues alone (0/4), and he was unable to detect tactile (punctate) stimulation of the fingers, hand, forearm, and the upper arm of his left upper limb (0/4 for each). JH was also impaired at detecting joint rotation of the fingers, wrist, elbow, and shoulder of his left arm (0/4 for each), and showed no somaesthetic transfer from the left to right limb (0/4). Like patient RQ, JH was unable, with his eyes closed, to copy a passively positioned posture of his left (impaired) limb using his right (non-impaired) limb (0/4). However, he was able to copy the posture of his right (non-impaired) limb when using his left (impaired) limb (4/4). In addition, if JH was permitted to actively move his left (impaired) limb into a position to be copied, then he was able to copy that posture using his non-impaired (right) limb (4/4) . Extensive behavioural testing revealed that JH showed no somatosensory impairment in his right hand, and no signs of any visual impairment including visual extinction and visuospatial neglect. Throughout the following analysis and discussion JH's left limb will be referred to as his impaired limb.

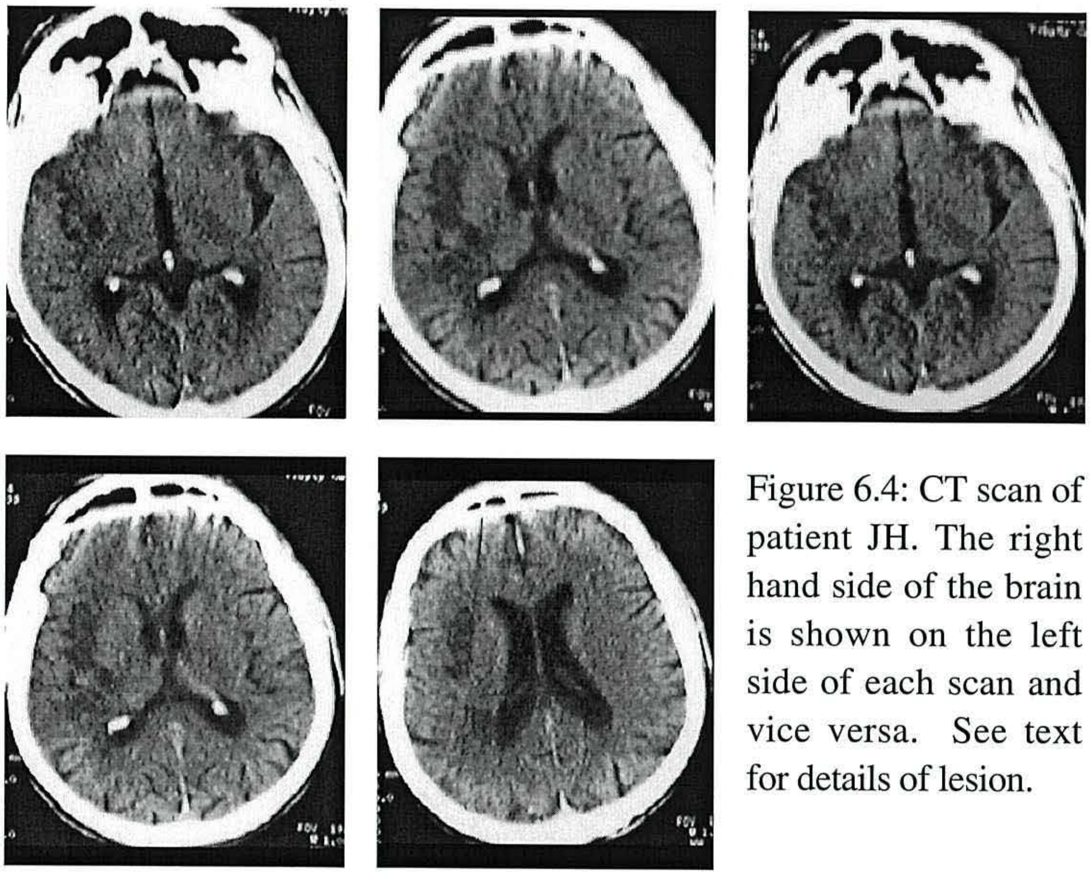

Figure 6.4: CT scan of patient JH. The right hand side of the brain is shown on the left side of each scan and vice versa. See text for details of lesion.

JH Amplitude Error

Analyses of patient JH's AE scores revealed a significant effect of CONDITION ($t_{[31]} = 37.8$, $p < 0.0001$). During both PP and VP trials patient JH, in common with patient RQ, produced reaches which were markedly hypometric. However, the magnitude of this hypometria was substantially reduced during VP trials (means: PP trials = -71 [26.2] mm vs. VP trials = -33.1 [26.6] mm). Means for both hands in each condition are given in Figure 6.5a.

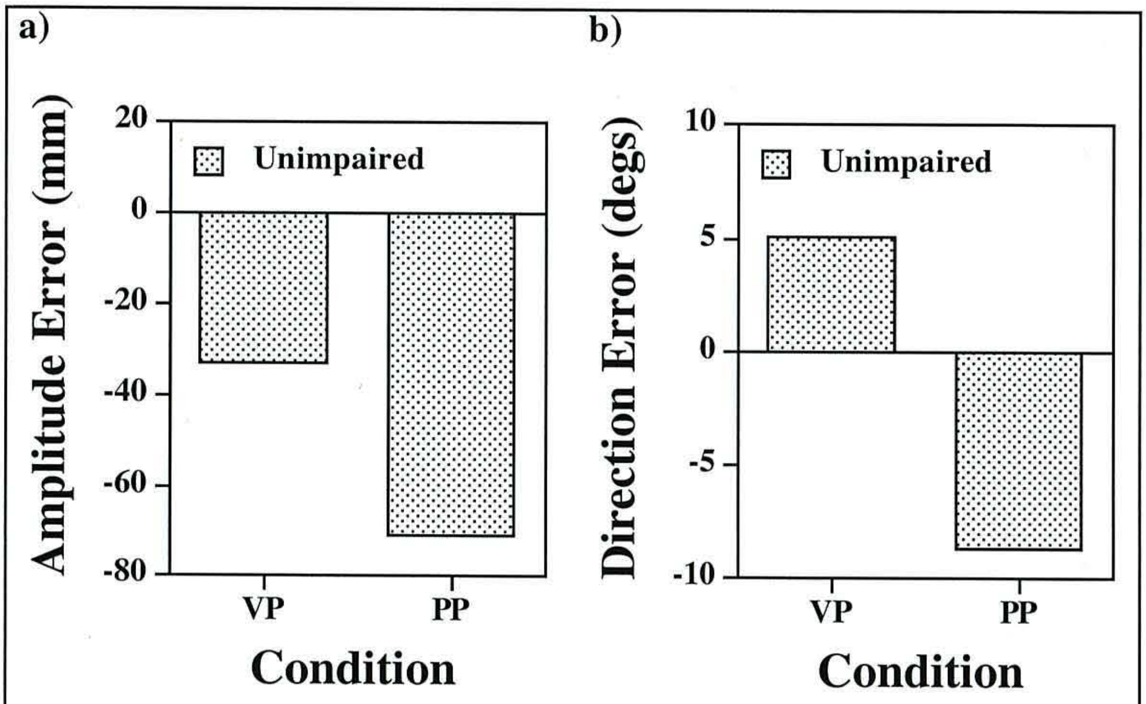

Figure 6.5: JH's mean scores for his unimpaired limb only in each condition: a) amplitude error and b) direction error. Note that 'unimpaired' refers to the *reaching* limb, not the target limb.

JH Direction Error

Analyses of patient JH's DE scores revealed a significant effect of CONDITION ($t_{[31]} = 5.1$, $p < 0.0001$). During VP trials patient JH produced reaches with a clockwise bias, whereas during PP trials, he exhibited an anti-clockwise bias (means: VP trials =

5.0 [8.2] degs. vs. PP trials = -8.7 [12.8] degs.). Means for both hands in each condition are given in Figure 6.5b.

6.3.4 Discussion of Case JH

At first sight JH's direction errors were not as illuminating as his errors in amplitude. During VP trials patient JH produced reaches with a clockwise bias of 5 degrees, whereas during PP trials, he exhibited an anti-clockwise bias of around -8.5 degrees. Although the absolute magnitude of errors is similar in each case, this nevertheless represents a considerable shift (13.5 degrees) in the perceived location of the affected target hand suggesting that a different frame of reference, or different weightings, may have been used, depending on whether or not vision was available, to plan otherwise comparable reaches.

JH's amplitude errors displayed an equally large shift in the indicated location of the target hand. In common with RQ, and unlike control subjects, JH produced reaches which were markedly hypometric when reaching to the felt location of his affected hand with his unaffected hand. We suggest that JH, like RQ, exhibits a marked compression of somatosensory space although, as he was only tested reaching with one hand, it is not possible to say whether this is limb specific. The magnitude of JH's hypometria was substantially reduced during VP trials, when vision was available, even though he still could not see his affected hand directly. These data illustrate that amplitude errors observed when reaching to proprioceptively-defined target locations using his non-impaired limb are substantially improved when visual cues are made available, even where such cues cannot signal the spatial location of the target. These were movements made with his unaffected hand; a hand which revealed no somatosensory deficits whatever and a hand with which, in an unrecorded pre-test examination, it was shown that JH was able to point to visually-defined targets with unrestricted ease. It is unlikely, therefore, that visual calibration or control of the limb played a great part in this massive improvement in performance. How can vision improve the localization of a target which cannot be seen? There are numerous possibilities including the role of gaze angle and the advantage of being able to see the area adjacent to the unseen limb. Unfortunately JH was not available for further examination, so it would be fruitless to explore possibilities here which cannot be answered. This fascinating finding, however, will be raised again and discussed in greater length in the next chapter in which we test a similar patient in more detail.

6.3.5 Case TJ

TJ is a 70 year old female who suffered a right-hemisphere CVA in June 1998 three months prior to testing. A CT scan one week post-CVA (Figure 6.6) revealed extensive unilateral damage to her right frontotemporal cortex. When admitted to hospital she complained of sensory loss in left upper limb. Clinical assessment at the time of testing revealed that on both limbs she had no difficulty in discriminating rotations of the finger, wrist and elbow (4/4 for each) and could also correctly identify cutaneously stimulated fingers on both hands without vision (4/4). She was also able to identify correctly objects presented haptically (4/4). TJ was impaired, however, at discriminating whether she was being touched by one or two stimuli on her left hand (1/4) and arm (2/4). She was not impaired on this task for stimuli on her right hand and arm (4/4 for each). On a gross measure of peripheral limb proprioception she could point (without vision) to the area of the arm or hand touched by the experimenter with both limbs although she was considerably more accurate and more certain of her performance when the right limb was the stimulated limb. She was only moderately successful when mirroring limb postures, but this may have been confounded by the general lack of mobility in her left limb which had been broken a few weeks prior to her CVA. TJ also displayed signs of tactile extinction, failing to report left-sided tactile stimuli when given bilateral stimulation to the

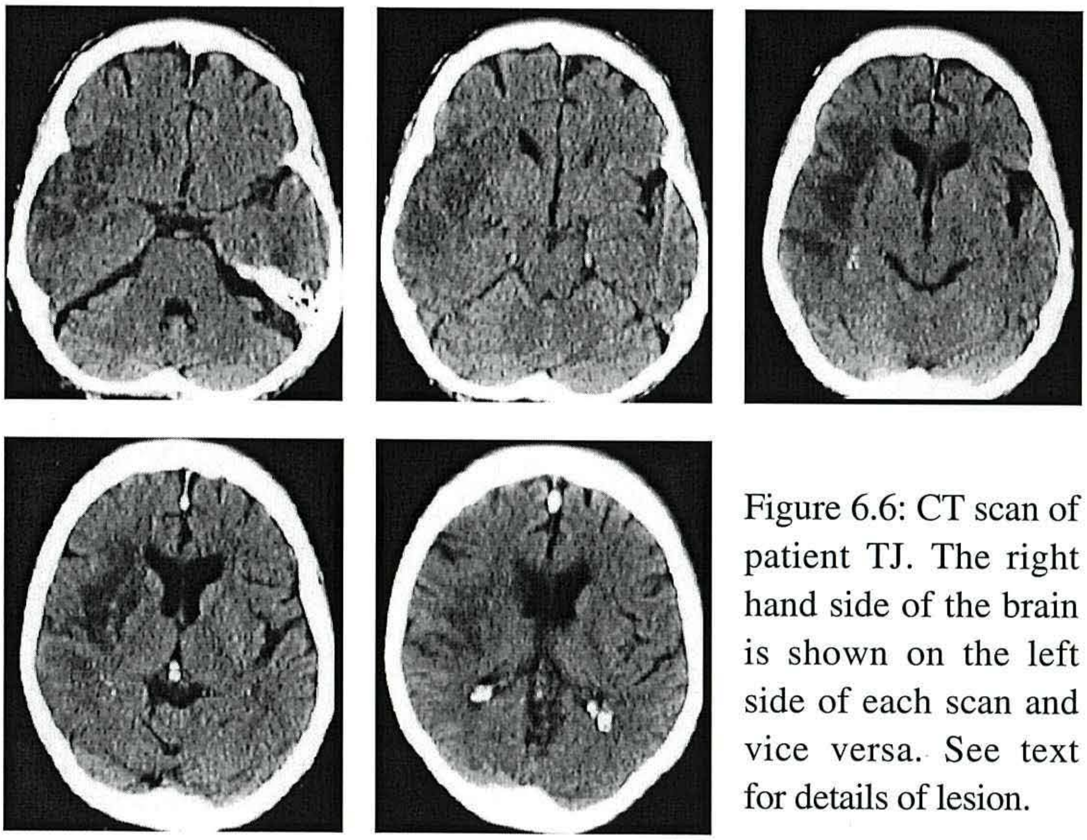

Figure 6.6: CT scan of patient TJ. The right hand side of the brain is shown on the left side of each scan and vice versa. See text for details of lesion.

back of the hands. There were no clinical signs of visual neglect or visual extinction at the time of testing and none had been reported at the time of admission to hospital. Throughout the following analysis and discussion TJ's left limb will be referred to as her impaired limb.

TJ Amplitude Error

Analysis of TJ's amplitude errors revealed a significant main effect of CONDITION ($F_{[2,62]} = 7.8$, $p < 0.001$). Comparisons revealed that reaches in the VP condition were significantly hypermetric compared to VV ($F_{[1]} = 10.4$, $p < 0.005$) and PP ($F_{[1]} = 13.0$, $p < 0.005$) reaches. No significant difference between VV and PP reaches was found ($F_{[1]} = 0.1$, $p < 0.5$). Means for both hands in each condition are given in Figure 6.7a.

TJ Direction Error

Analysis of TJ's direction errors also revealed a significant main effect of CONDITION ($F_{[2,62]} = 53.3$, $p < 0.0001$). Comparisons revealed that reaches in the PP condition were rotated significantly anti-clockwise compared to VV ($F_{[1]} = 63.5$, $p < 0.0001$) and VP ($F_{[1]} = 93.4$, $p < 0.0001$) reaches. No significant difference between VV and VP reaches was found ($F_{[1]} = 2.9$, $p < 0.1$). Means for both hands in each condition are given in Figure 6.7b.

TJ Hand Path Curvature

Hand path curvature analysis revealed the there was no main effect of CONDITION ($F_{[2,62]} = 2.4$, $p > 0.1$). Further analysis of the means revealed that there was no significant difference in HPC between PP reaches and either VV or VP reaches (minimum: $F_{[1]} = 1.4$, $p > 0.2$). VP reaches were, however, significantly more curved than VV reaches ($F_{[1]} = 4.7$, $p < 0.05$). Means for both hands in each condition are given in Figure 6.7c.

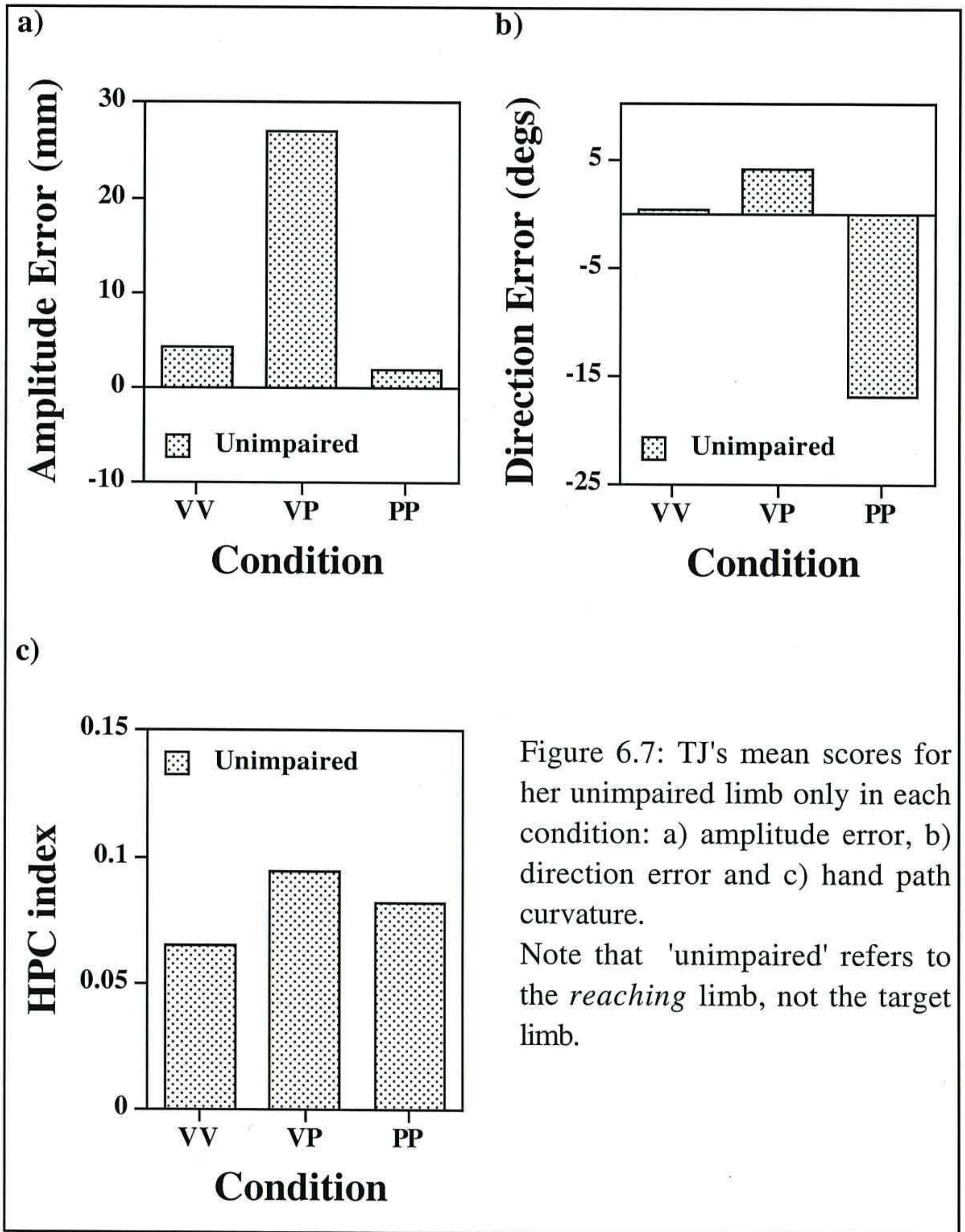

Figure 6.7: TJ's mean scores for her unimpaired limb only in each condition: a) amplitude error, b) direction error and c) hand path curvature.
Note that 'unimpaired' refers to the *reaching* limb, not the target limb.

6.3.6 Discussion of Case TJ

In TJ we find yet another pattern of reaching deficits on this proprioceptive pointing task. Like all the other patients, and control subjects, her visually-guided reaching to visually-defined targets (VV condition) was perfectly accurate. When reaching with visual guidance towards proprioceptively-defined targets, however, she exhibited extreme hypermetria although her movement direction was unimpaired. These results were quite unlike her reaches to proprioceptively-defined targets without vision. In this condition (PP) her movement amplitude was correct, but her movement direction was impaired, skewing markedly anti-clockwise, towards her left shoulder. The difference in movement direction between VP and PP reaches was in the order of 20 degrees, a considerable shift. Given that both sets of reaches were made from identical start positions to identical target locations, we suggest that this is further evidence of a change in the frame of reference being used to plan and control reaches in the two conditions. Moving from a purely proprioceptive coordinate system to one which involved visual input rotated the apparent location of here unseen hand more than twenty degrees clockwise and extended it more than 25 mm from the body. We suggest that the changes in directional and amplitudinal errors here do not show an improvement in end-point accuracy, but a shift in end-point accuracy. To further investigate this we examined TJ's total errors post hoc. Total error is measured as the Euclidean distance from the target to the final position of the finger. Analysis of TJ's Total error scores revealed a significant main effect of CONDITION ($F[,62] = 83.0$, $p < 0.0001$). Comparisons revealed that reaches in the VP and PP conditions were significantly less accurate than VV reaches (VP: $F_{[1]} = 116.2$, $p < 0.0001$; PP: $F_{[1]} = 132.3$, $p < 0.0001$). In contrast there was no significant difference found between VP and PP reaches ($F_{[1]} = 0.5$, $p > 0.4$) (means: VV = 5.4 mm [2.1]; VP = 56.9 mm [28.9]; PP = 61.3 mm [21.2]. In terms of total error scores, therefore TJ's VP reaches were no more accurate overall than her PP reaches which suggests that the change in her final finger position is not due to vision improving the accuracy in the perceived location of her target finger (as was the case with JH), or an improvement in the control of her reaching limb. Rather, these results point towards an impairment in the sensorimotor computations which take place both with and without visual cues when calculating the proprioceptively-defined position of her affected limb and that the change in amplitude and direction errors point to different frames of reference, or different weightings, being used to compute reaches either with or without vision.

Although TJ had suffered right parietal damage she had never shown any signs of neglect. In keeping with the findings presented in Chapter 3, TJ, like RQ and the control subjects (Chapter 2), did not show the same patterns of increased hand path curvature as the three patients who had suffered from neglect.

6.4 Summary

In this chapter we described the cases of three patients, all of whom presented with similar unilateral somatosensory impairments. Although the three patients were neuropsychologically heterogeneous there was a commonality in their performance. All were relatively unimpaired when reaching to visually-defined targets, whether reaching with their affected or unaffected limb. Without any visual cues available, and pointing to proprioceptively-defined targets, the end-point accuracy of all three patients was severely affected - in most cases consistent with a compressed representation of somatosensory space. Allowing vision of the workspace/reaching limb altered the patients' reaching performance, in terms of end-point accuracy and, in two of the three cases, clearly improved performance over the no-vision condition.

For each patient we proposed a hypothesis as to the underlying basis of their sensorimotor impairment. In no case were we able to test these hypotheses further. JH tired too quickly, was not fully compliant and was unavailable for further testing, RQ became increasingly confused and TJ became unavailable through family illness. In the next chapter, however, we will present the case study of a unilaterally impaired patient who we were able to test over a number of sessions in order to explore further the mechanisms by which visual cues can improve pointing performance on our proprioceptive pointing paradigm.

Chapter Seven

7. The role of vision in the proprioceptive localization of the unseen hand.

7.0.1 Introduction

Our examination of this patient began one year before the three patients described in the previous chapter became available and finished some time after the others were no longer available for testing. During this time CT's somatosensory impairment gradually improved, but we were still able to reliably demonstrate the same pattern of hypometric reaching over a number of experiments as we sought to determine the underlying mechanisms responsible for this behaviour. The first experiment to be described in this chapter examines CT's performance on our original proprioceptive pointing task with a single start location. Experiment 2 extends those findings by reversing the paradigm such that CT points to targets presented above the board with her reaching hand positioned beneath the board so that it cannot be seen during reach execution. As a full year had elapsed between the initial two experiments and subsequent follow-up experiments, the third experiment replicates the findings of the first experiment. In Experiments 4 and 6 we investigate the role played by vision in the VP condition by varying the amount of visual information available to the patient. Experiment 7 takes a closer look at the role of vision by manipulating not only what the patient can see, but also where the patient is looking. Because the investigations in Experiments 6 and 7 were conducted four months after Experiment 4 we again retested the patient on the basic paradigm, the results of which are presented in Experiment 5.

7.1 Experiment 1: Proprioceptive pointing performance in a single patient with unilateral somatosensory loss following a lesion to the thalamus.

In the previous chapter we described the results of our basic proprioceptive pointing task on three patients, all of whom exhibited similar reaching abnormalities following unilateral somatosensory impairment. In essence, when indicating the felt position of their impaired limb they all displayed a limb specific hypometria which was substantially ameliorated when vision of the workspace, but not the target limb, was made available. The focus of this chapter will be the case study of another unilaterally impaired patient who we were able to study over a period of two years. The patient in question, CT, sustained a thalamic lesion following a stroke and it may be useful to begin by discussing how such a lesion may impact on sensorimotor integration in the planning and execution of upper limb movements.

Subcortical inputs from both the basal ganglia and the cerebellum gain access to the primate primary cortical motor areas via the ventrolateral thalamus and directly influence hand representations in M1 (primary motor cortex) and SMA (supplementary motor area) (Strick, 1985; Holsapple et al., 1991; Rouiller, 1996). Studies using cynomolgous monkeys (Asanuma and Arissian, 1984) demonstrated that direct sensory input to the motor cortex from the thalamus plays an important role in the control of voluntary movements. Further monkey work by Hepp-Reymond and Maier (1991) showed that the control of proprioceptively-informed movements depends on the integration of somatosensory input from the muscles, joints tendons and skin receptors - inputs which can be forwarded to the motor cortex by way of the thalamic nuclei. The ventral nuclei of the human thalamus can be divided into four channels that transfer information from the substantia nigra, globus pallidus, cerebellum, and proprioceptive components of the medial lemniscus to prefrontal, premotor, motor, and somatosensory areas of the cerebral cortex. The lemniscal relay can be further divided into a proprioceptive component and a cutaneous component known as VPLa and VPLp respectively (Jones, 1990; Macchi and Jones, 1997). Thus, it seems that information which plays a major role in movement execution and which originates in the periphery and subcortical regions may pass through the thalamic nuclei and be forwarded from there to motor and premotor cortical areas.

In an earlier chapter (Chapter 3) we reported the data from three patients recovering from right-hemisphere cortical lesions which had resulted in left visual hemispatial neglect. For these patients spatial hand paths were comparable to controls when reaching without vision on PP trials, but were substantially more curved than control subjects when vision was available on VV and VP trials. We interpreted this effect as being a consequence of a distortion in the visual (but not spatial) representation of peripersonal space, a representation which was not utilized during reaches executed to proprioceptively-defined target locations in the PP condition. With this in mind, we examined the hand path curvature of patient CT's under identical experimental conditions. Our assertion in Chapter 3 was that a distortion of visual space in neglect patients led to exaggerated curvature under visually-guided reaching conditions. Patient CT was not identified as having any visuospatial disorders by standard clinical testing and if our conclusions from Chapter 3 are to hold water then we would hope not to see identical changes in hand path curvature for CT when reaching under the same conditions.

The VV hand path curvature of the neglect patients (Chapter 3) and the control subjects (Chapter 2) bowed leftward for reaches into left space and rightward for reaches into right space. Averaging across a signed hand path curvature score for reaches into left and right space could disguise any main effect of CONDITION which, for the neglect patients, was only revealed by analysing unsigned hand path curvature scores. For this reason only the unsigned HPC measure of hand path curvature will be used for this analysis.

7.1.1 Subjects

Control Subject IJ

A healthy, right-handed age-matched female volunteer (**IJ**) was recruited from the University of Wales paid subject panel as a control subject for patient CT. Subject IJ was 86 at the time of testing and had no history of head injury or neurological disorder, and had corrected-to-normal vision. Clinical assessment prior to testing revealed no somatosensory or visuospatial impairments.

Case CT

Patient CT is an 88 year old woman who suffered a cardio-vasculo-cerebral accident (CVA) in February 1998. A CT scan, carried out 8 days post CVA, showed a rounded intracerebral haematoma centred in the lateral pulvinar and involving the posterior limb of the internal capsule (see Figure 7.1.1). She was diagnosed as having right-sided tactile neglect and right-sided tactile extinction one day post CVA. However, at no time did she show any clinical signs of either visual extinction or visual neglect. CT's subjective report was that although she could feel it, she had reduced sensation in her right hand. At the time of testing CT continued to exhibit tactile extinction during simultaneous bilateral stimulation of her right and left hands. During such trials she would consistently report perceiving stimulation to her left hand only. Further testing of her right (impaired) hand showed that she was also only moderately successful when identifying objects presented to her right hand by tactile sensation alone (astereognosis) (2/4). However, when blindfold she was able to correctly identify the site of cutaneous stimulation to each finger of her right hand and she could mirror postures of her left (good) arm with moderate success. She was impaired at reporting rotations around her right wrist and elbow (0/4). She was also able to point to various body parts (4/4) and was able to make and copy both abstract and meaningful gestures (4/4 for each). Identical testing of her left upper limb revealed no signs of

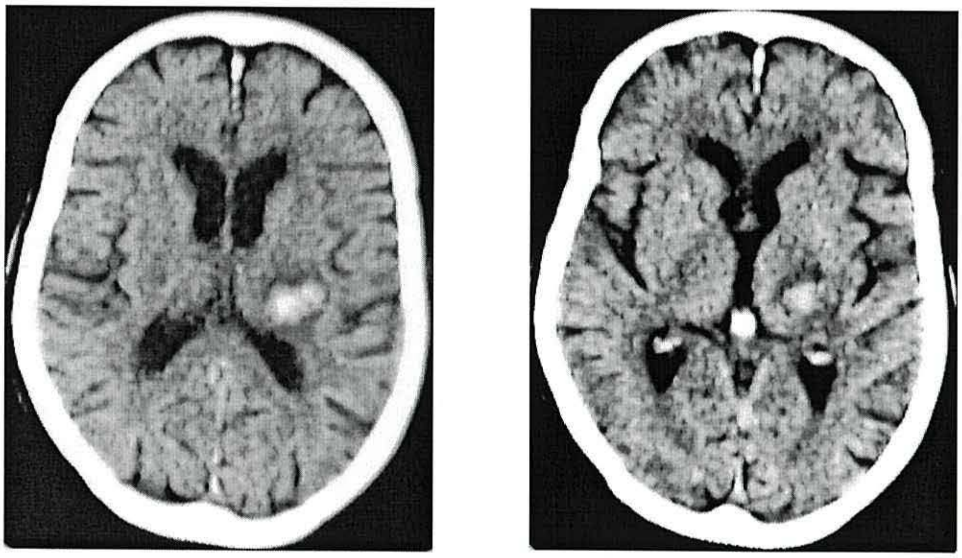

Figure 7.1.1: CT scan of patient CT showing a rounded intracerebral haematoma centred in the lateral pulvinar and involving the posterior limb of the internal capsule. The right side of the brain is shown on the left of each scan and vice versa.

somatosensory deficit on that side. Clinical testing revealed that tone and power were normal in both of her upper limbs. This was confirmed behaviourally in a test of fine-grained grasping involving the modulation of precision grip force similar to that used by Shaw et al., (1997). Briefly, CT was seated at a table and made prehension movements, from a fixed start position on her mid-saggital plane, toward a single target object located either to the left or right of the mid-saggital plane (200 mm forward of the start position and 200 mm to either side). The targets consisted of a rectangular object formed from two wooden blocks (20 mm x 20 mm x 26, 28, 30, 32 or 34 mm) each mounted on the shafts of a force transducer (Novatech, model F250). The overall width of the object could be adjusted to produce symmetrical targets of 60, 64, 68, 72 or 76 mm along their principle axis. CT grasped the objects between the index finger and thumb. She executed 40 trials (4 x 10 trial blocks) for each hand. The order of trials within blocks was randomized. CT showed equivalent peak grip force values for each hand (means: non-impaired (left) hand = 2.7 [1.2] N vs. impaired (right) hand = 3.1 [1.0] N; $F_{[1,31]} < 1.0$, $p > 0.1$). When picking up the small objects, however, CT exhibited increased grip force in her impaired hand relative to her non-impaired hand (means: non-impaired (left) hand = 2.3 [0.9] N vs. impaired (right) hand = 3.2 [0.9] N; $F_{[1,31]} = 11.6$, $p < 0.005$). This latter finding is consistent with CT's anecdotal reports that she tended to drop small objects held in her right hand if she did not look at her hand whilst holding them. Behavioural testing using a large range of copying, line-bisection, and cancellation tests confirmed that CT did not exhibit any signs of visual impairments, including visual neglect or visual extinction. Throughout the following analysis and discussion CT's <u>right</u> limb will be referred to as her <u>impaired</u> limb.

7.1.2 Data Analysis

Subjects wore an electromagnetic receiver on the index finger of their pointing hand throughout the experiment, and movements were recorded using the miniBIRD electromagnetic recording device described previously. Recordings were sampled at 86.1 Hz with a spatial resolution of 1.23 mm. Raw data were filtered off-line using a 4th order, zero-lag, Butterworth filter with a cut-off frequency of 10 Hz.

7.1.3 Procedure

The procedure used in Experiment 1 was identical to that reported in Chapters Two and Three with the exception that both hands were tested rather than only one hand. Subjects were seated at a table upon which rested a raised wooden board (painted matt black) containing eight holes each 6 mm in diameter (see Figure 7.1.2). Subjects executed pointing movements above the raised board, using the index finger, from a starting position on the saggital axis, to each of the eight target locations. The study consisted of three pointing conditions as follows:

i. Vision/Vision **(VV)** trials - During VV trials target locations were defined visually by placing a small wooden 'target' dowel (coloured white) into the appropriate hole for that trial. This dowel did not protrude above the surface of the board. Subjects pointed with their eyes open and were allowed to move their head and eyes freely. Subjects' non-pointing hand was placed on the table-top beneath the target board in a central position that did not correspond to any of the target locations.

ii. Vision/Proprioception **(VP)** trials - During VP trials the target array was covered by a matt black board so that there were no longer any visual cues as to the location of the target. Instead, target locations were defined proprioceptively by passively placing the index finger of the subject's unseen non-pointing hand onto the relevant drilled hole on the underside of the raised board. Subjects pointed with their eyes open so that visual information about the moving limb was available throughout the trial.

iii. Proprioception/Proprioception **(PP)** trials - These were identical to VP trials with the exception that subjects were blindfold throughout.

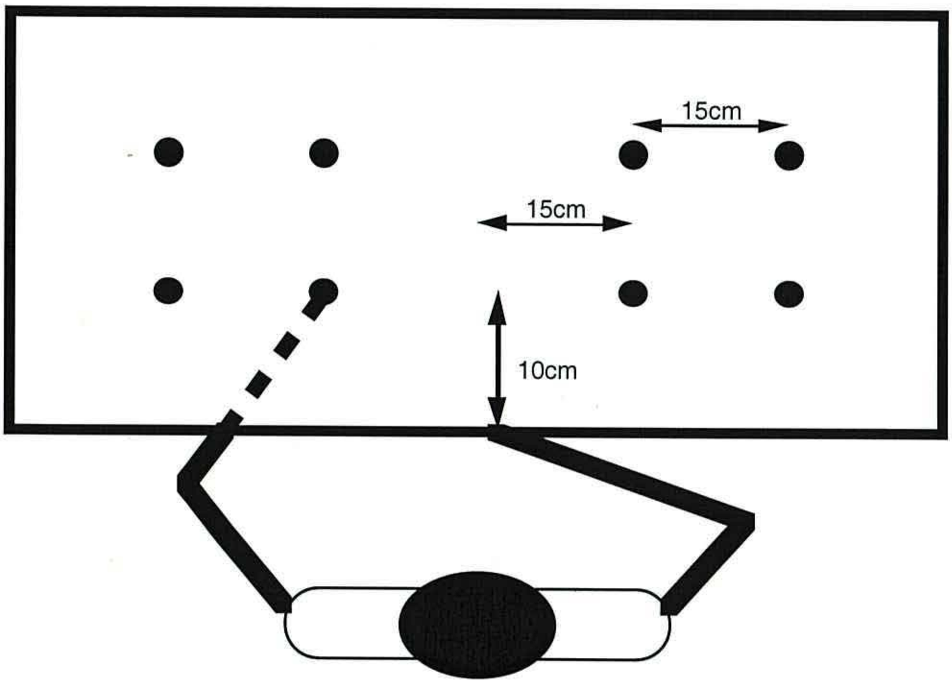

Figure 7.1.2: Depiction of the target apparatus used in Experiment 1. The subject was seated in front of a horizontal board. Targets could be defined either visually, on the upper surface of the board, or proprioceptively, by placing the subject's contralateral (non-reaching) finger on the under surface of the board.

For each subject the order of presentation of the three pointing conditions was presented in an ABCCBA design within an ABBA design for the order of responding hand. The order of target presentation was pseudorandomized within each condition. Altogether, subjects made four pointing movements to each target location with each hand in each condition. Subjects pointed with the tip of their index finger, were encouraged to reach using a single smooth movement, and were not permitted to correct inaccurate reaches after they had made tactile contact with the board surface. A tone signalled the start of each trial. On VP and PP trials, this tone was always presented within 2 seconds of the passive placement of the target finger in order to avoid proprioceptive drift of the non-moving hand. Patient CT was tested over two sessions. There was no significant change in her somatosensory function between sessions.

7.1.4 Dependent Measures

Movement onset was defined as the first frame in which the finger marker exceeded a velocity in the direction of movement of 2.5 cm/s. Movement end-point was defined as the first frame in which the velocity of the finger marker fell below 2.5 cm/s. All trials were visually checked to ensure that the movement end-point identified in the above manner coincided with the end of the movement.

Two measurements of movement end-point accuracy were defined:
a) direction error (**DE**): Errors in movement direction were calculated as the angle (measured in degrees) formed between a straight line from movement start position to movement end-point and a straight line from the movement start position to the target location. Negative values indicate a leftward error and positive values a rightward error;
b) amplitude error (**AE**): Errors in movement amplitude were calculated as the difference between the radial distance of the movement end-point and the radial distance of the target relative the movement start position measured in mm. Positive values represent hypermetric movements and negative values hypometric movements.
A hand path curvature Index (**HPC**) was also calculated: subjects' hand paths on each trial were spatially resampled and translated, and an index

of hand path curvature (**HPC**) was computed using the procedure reported in previous chapters. This procedure resulted in a set of hand paths aligned along a single axis. The HPC index consisted of the ratio between the magnitude of the maximum lateral deviation achieved at any point during the movement (mm), and the straight line length joining the kinematically-determined start and end positions of the movement (mm).

7.1.5 Results

Data for the patient CT and the control subject IJ, were entered in separate 2 X 3 repeated-measures analyses of variance (ANOVA) for each dependent variable. Each ANOVA consisted of the factors POINTING HAND (left vs. right) and CONDITION (VV vs. VP vs. PP). To evaluate the effect of CONDITION for each hand, planned comparisons between means for each hand were carried out using a linear contrast procedure for amplitude and direction error scores (i.e. VV impaired vs. VV unimpaired etc.). To evaluate the effect of CONDITION on hand path curvature, planned linear contrasts were performed in the following manner: VV vs. VP; VV vs. PP; VP vs. PP.

Direction Error (DE)

Case CT

Analyses of patient CT's direction errors revealed a significant main effect of CONDITION ($F_{[2,62]} = 19.8$, $p < 0.0001$) with PP reaches exhibiting an anti-clockwise rotation. The main effect of HAND ($F_{[1,31]} < 1.0$, $p > 0.1$) and the HAND x CONDITION interaction effect ($F_{[2,62]} < 1.0$, $p > 0.1$) did not reach statistical significance. Furthermore, planned comparisons revealed that DE scores were not significantly different for reaches executed using her impaired (right) compared to her non-impaired (left) hands for any of the reaching conditions (minimum: $F_{[1]} = 1.4$, $p > 0.1$). Relevant mean scores for CT are given in Figure 7.1.3.

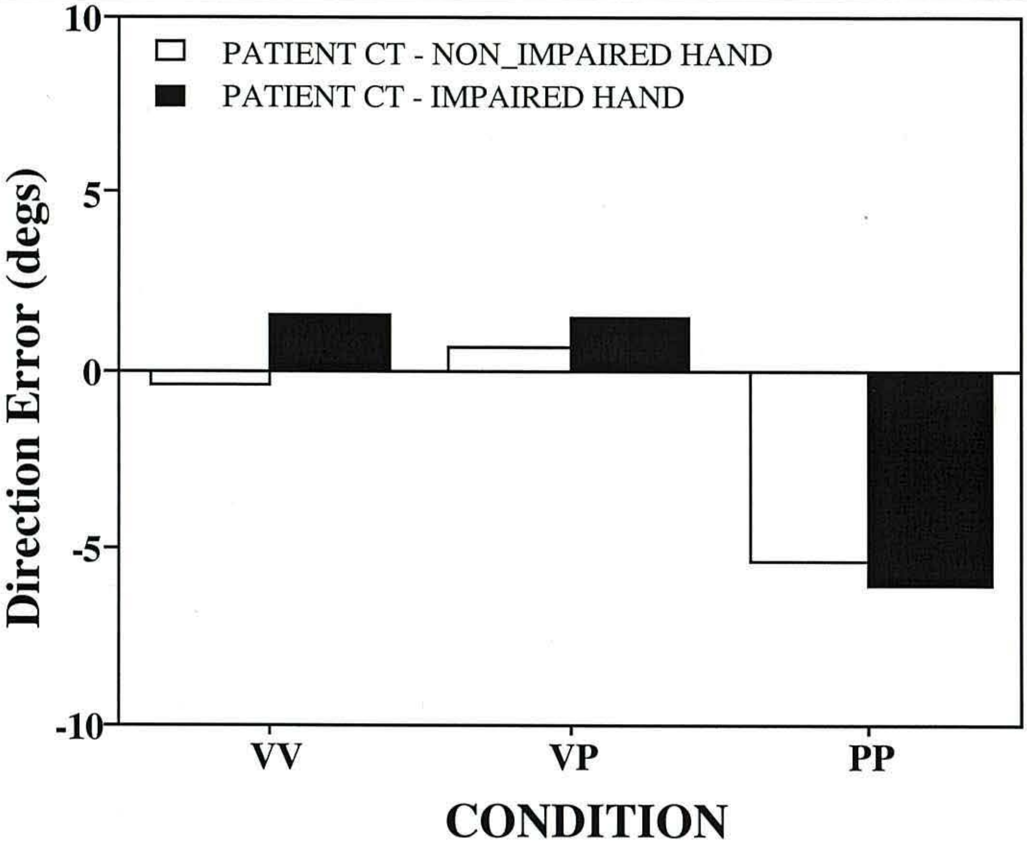

Figure 7.1.3: Mean direction error scores for Patient CT.

Control subject IJ

Analyses of IJ's DE scores also revealed a significant main effect of CONDITION ($F_{[2,62]} = 23.1$, $p < 0.0001$). The main effect of HAND for this subject was not significant ($F_{[1,31]} < 1.0$, $p > 0.1$). However, the analysis did reveal a significant HAND x CONDITION interaction effect ($F_{[2,62]} = 3.4$, $p < 0.05$). Planned comparisons revealed that this interaction effect was due to IJ being marginally more accurate during the PP condition when pointing using her right (preferred) hand ($F_{[1]} = 5.3$, $p < 0.05$) with no significant difference between the hands in either the VV or

PP condition (minimum: $F_{[1]} = 1.1$, $p > 0.25$). Relevant mean scores for IJ are given in Figure 7.1.4.

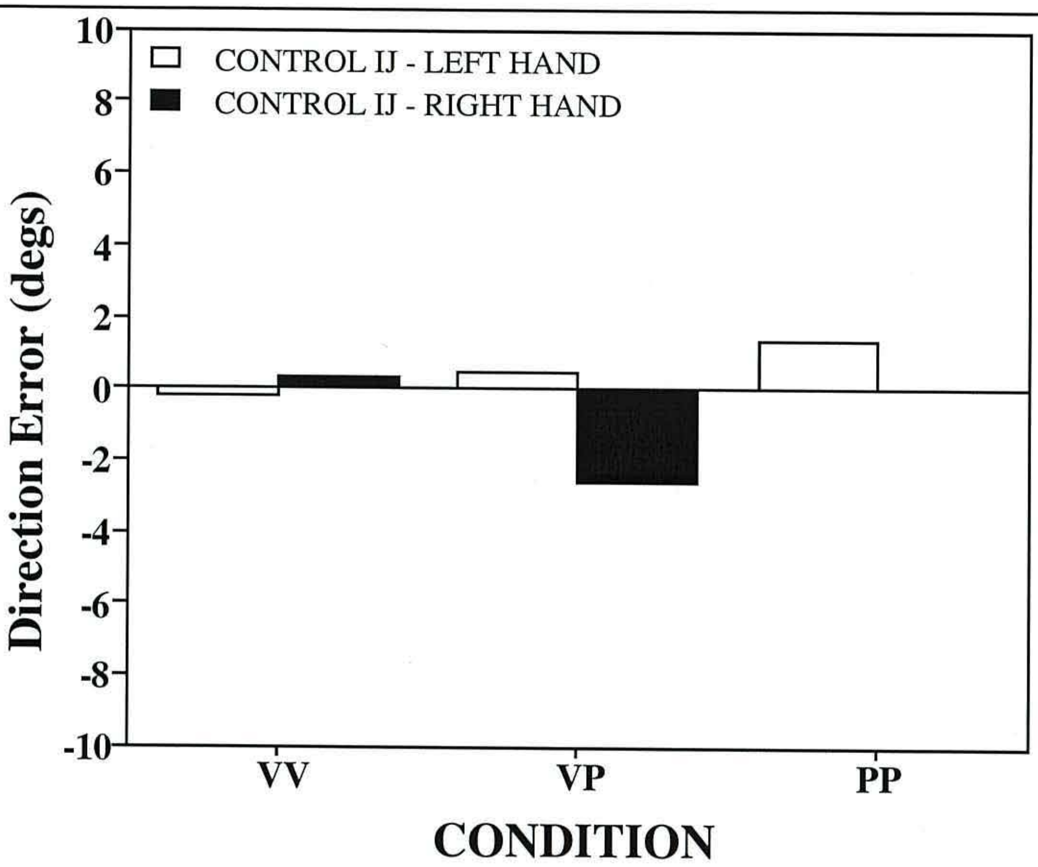

Figure 7.1.4: Mean direction error scores for control subject IJ.

Amplitude Error (AE)

Case CT

Analyses of patient CT's amplitude errors revealed significant main effects of HAND ($F_{[1,31]} = 30.9$, $p < 0.0001$) and CONDITION ($F_{[2,62]} = 34.7$, $p < 0.0001$) as well as a significant HAND x CONDITION interaction effect ($F_{[2,62]} = 23.4$, $p < 0.0001$). Planned comparisons revealed that the AE scores for reaches made by CT using her non-impaired and impaired hands did not differ statistically from one another in either the VV or VP conditions (minimum: $F_{[1,31]} < 1.0$, $p > 0.1$). In contrast, on PP trials amplitude errors were substantially greater (hypometric) when CT reached using her non-impaired hand (reaching to a target defined by her impaired hand) compared to when she reached using her impaired hand ($F_{[1,31]} = 75.6$, $p < 0.0001$). Relevant means are given in Figure 7.1.5

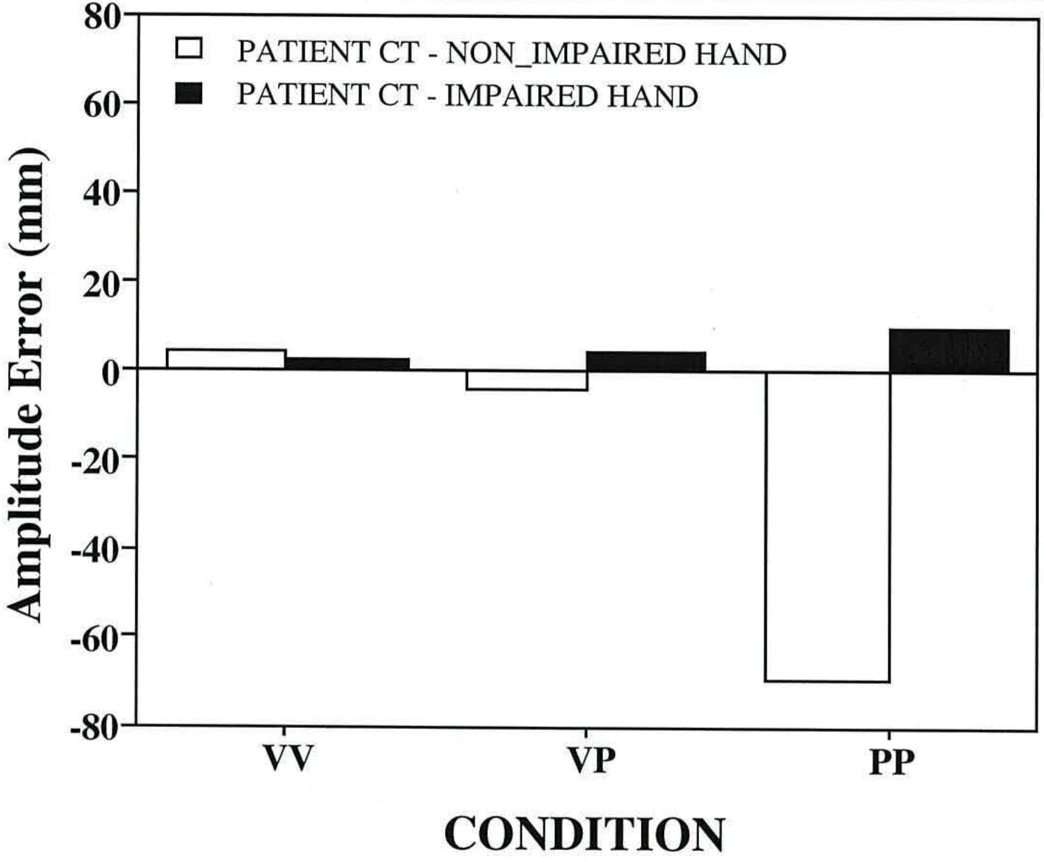

Figure 7.1.5: Mean amplitude error scores for patient CT.

Control subject IJ

Analyses of IJ's AE scores revealed a significant main effect of CONDITION ($F_{[2,62]} = 9.1$, $p < 0.001$). The main effect of HAND ($F_{[1,31]} < 1.0$, $p > 0.1$) and the HAND x CONDITION interaction ($F_{[2,62]} = 1.8$, $p > 0.1$) were not, however, statistically significant. The planned comparisons also confirmed that there were no differences in AE scores across the hands in any of the experimental conditions (minimum: $F_{[1,31]} = 1.7$, $p > 0.1$). Relevant mean scores for IJ are given in Figure 7.1.6.

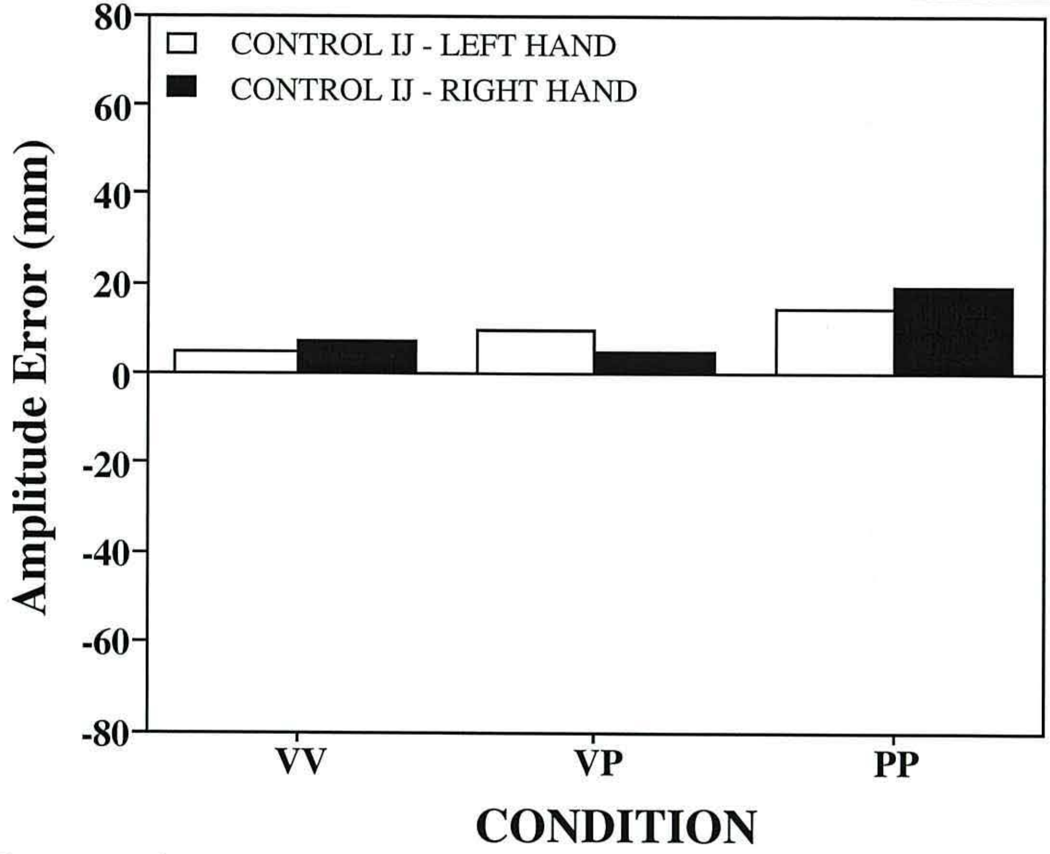

Figure 7.1.6: Mean amplitude error scores for control subject IJ.

HPC-index

Case CT

Analyses of patient CT's HPC scores revealed a significant main effect of HAND $F_{[1,31]} = 11.4, p < 0.0025$), with her affected right hand displaying more overall curvature than her unaffected left hand. There was also a significant HAND x CONDITION interaction effect ($F_{[2,62]} = 6.6, p < 0.005$). The main effect of CONDITION was not statistically significant ($F_{[2,62]} = 2.5, p = 0.09$). Relevant means are given in Figure 7.1.7. Inspection of this figure indicates that the basis of the HAND x CONDITION interaction effect is that there is a decrease in hand path curvature for CT's non-impaired hand only when reaching in the PP condition only. Linear contrasts between the conditions revealed that PP reaches curved significantly less than the VP condition ($F[1] = 4.4$, $p < 0.05$) while there was no difference between either PP and VV ($F[1] = 2.9$, $p > 0.05$) or VP and VV reaches ($F[1] = 0.2$, $p > 0.6$). HPC mean scores for CT are given in Figure 7.1.7.

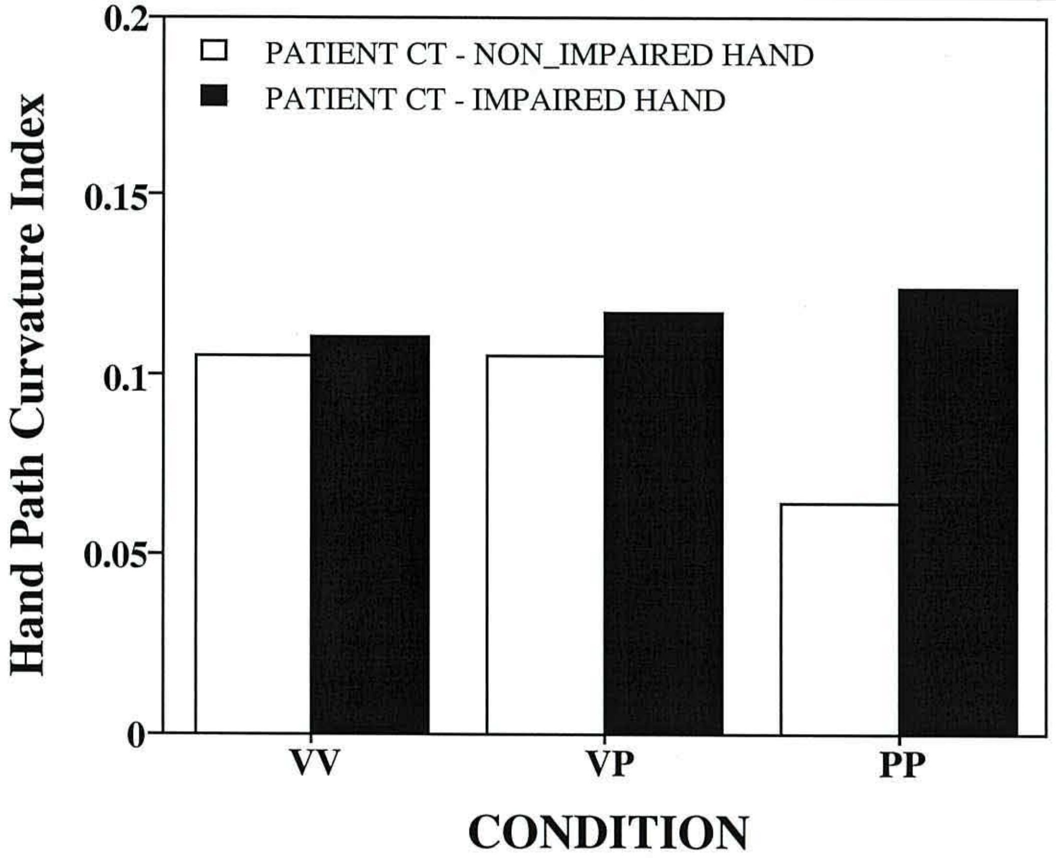

Figure 7.1.7: Mean hand path curvature scores for Patient CT.

Control subject IJ

Analysis of IJ's HPC scores revealed a significant main effect of HAND ($F_{[1,31]} = 18.4$, $p < 0.0005$). There was no significant main effect of CONDITION ($F_{[1,31]} = 0.7$, $p > 0.4$) and there was no HAND x CONDITION interaction ($F_{[2,62]} = 0.1$, $p > 0.8$). Planned comparisons revealed no significant differences between the conditions (minimum: $F_{[1]} = 1.2$, $p > 0.25$). Relevant means HPC scores for IJ are presented in Figure 7.1.8.

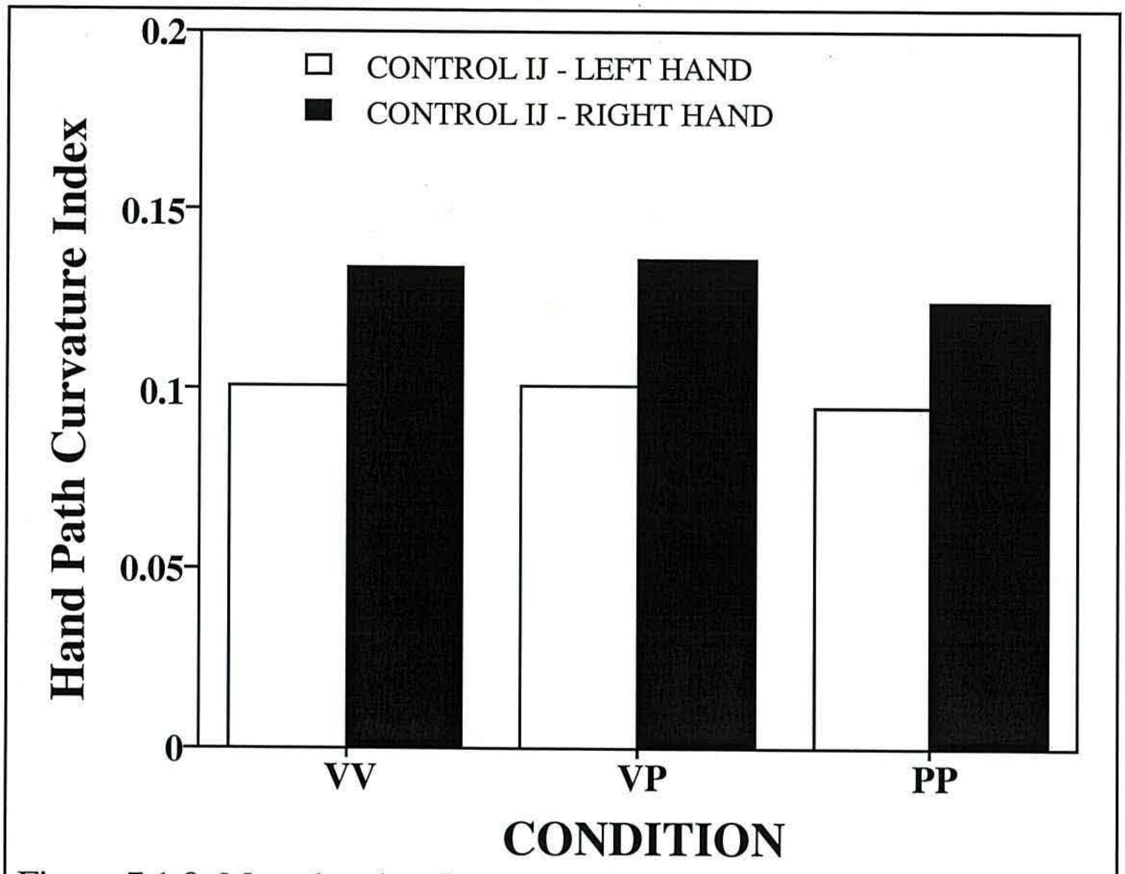

Figure 7.1.8: Mean hand path curvature scores for control subject IJ.

7.1.6 Discussion

Control subject IJ shows a similar pattern of results to the younger control group described in Chapter 2. She shows no discernible abnormalities in terms of her hand path curvature, which does not change between conditions, and (apart from a slight anti-clockwise rotation in one of the VP conditions) her end-point errors are also normal: displaying the same slight overshoot, or 'overlap' effect seen in control subjects in the PP condition with both hands (Crowe et al., 1987; Slinger and Horsley, 1906; van Beers et al., 1998). Any effects we see in CT, therefore, should not be attributed to her advanced years.

CT, as we have mentioned, was clinically assessed as having a unilateral somatosensory impairment and as having no visuospatial deficit. In Chapter 3 we suggested that the abnormal hand path curvature observed in the patients covered in that chapter arose as a result of an impairment in their representation of visual space (i.e. a visuospatial neglect). It follows from that supposition that CT, having no such clinically-assessed visuospatial impairment, should not exhibit similar patterns of abnormal hand path curvature. Inspection of Figure 7.1.7 confirms that this was not the case. Apart from PP reaches, and only then when indicating the felt position of her affected hand with her unaffected hand, CT's hand path curvature was comparable to that of the age-matched control subject. The relative straightness of PP reaches when indicating the felt position of her affected hand with her unaffected hand will be discussed shortly in relation to her overall performance in that condition.

The majority of CT's direction errors were also comparable to those of IJ, the main exceptions again being in the PP condition. Figure 7.1.3 shows that CT's direction errors were rotated anti-clockwise when reaching to proprioceptively-defined targets without vision with either hand equally. We saw this kind of anti-clockwise rotation in the previous chapter in two other patients with somatosensory dysfunction, RQ and TJ. With these patients, however, this directional impairment was unilateral, whereas with CT the impairment is bilateral. CT should not be compared directly with RQ or TJ, however, as discussed in the previous chapter, because the neuropsychological profile of each patient is different.

The most striking of all CT's results is that of her errors in movement amplitude, in one condition undershooting the target distance by an average of 60 mm. Again, this effect is only observed in the PP condition when indicating the felt position of her affected hand with her unaffected hand (see Figure 7.1.5). Her marked hypometria in this condition, taken in conjunction with her straightened reaches and the anti-clockwise rotation of her movement end-points, we suggest, points to a severe disruption of the somatosensory representation of space in relation to her right (impaired) hand. Clearly this observed hypometria cannot be as a result of a motor weakness in her unimpaired limb as she is well able to execute reaches of the correct amplitude and direction with this limb in all three reaching conditions. Neither can these results be attributed to a biomechanical artefact - reaches in all conditions being directed to identical target locations from identical start positions. It is highly unlikely, also, that her hypometria is a result of an impaired ability to control her good limb without the aid of vision, simply because it is her unaffected ipsilesional limb and clinical assessment immediately prior to testing showed no signs of any such impairment. The end-point errors are most readily explained by a representation of space for the affected limb which is rotated and truncated, or compressed, towards the body. Again, it is not clear exactly how such a compression of proprioceptive space might occur, but it may be an exaggerated or accelerated form of the proprioceptive drift that occurs naturally in normal subjects after a delay of around 8 seconds if the felt position of the limb is not updated by vision (Wann and Ibrahim, 1982). As discussed in Chapter 3, in a re-examination of control data, reaches of a shorter amplitude are not necessarily straighter reaches and we would like to think that this also applies to CT, meaning that the straightness of her reaches in this one particular condition are not as a result of the reaches being substantially shorter. Rather, we suggest it is the compression of the somatosensory space associated with her target hand which results in the relative straightness of the reach in this condition.

As striking as CT's hypometria is, the most fascinating aspect of her performance is the complete amelioration of this hypometria by the introduction of visual cues - despite the fact that such visual cues cannot directly inform as to the location of the target limb. We saw a similar effect for the control data in Chapter 2 and for patient JH in the previous chapter. He too displayed a marked hypometria which was substantially ameliorated by the introduction of visual cues which could not signal the location of the target. Before discussing the possible mechanisms by which vision could improve pointing performance, it might be interesting to compare the above results with those obtained by Desmurget et al. (1997b) who investigated the accuracy of pointing to proprioceptively-defined targets in normal subjects. The experiment reported by Desmurget et al. (1997b) used a similar proprioceptive pointing task (but vertically-

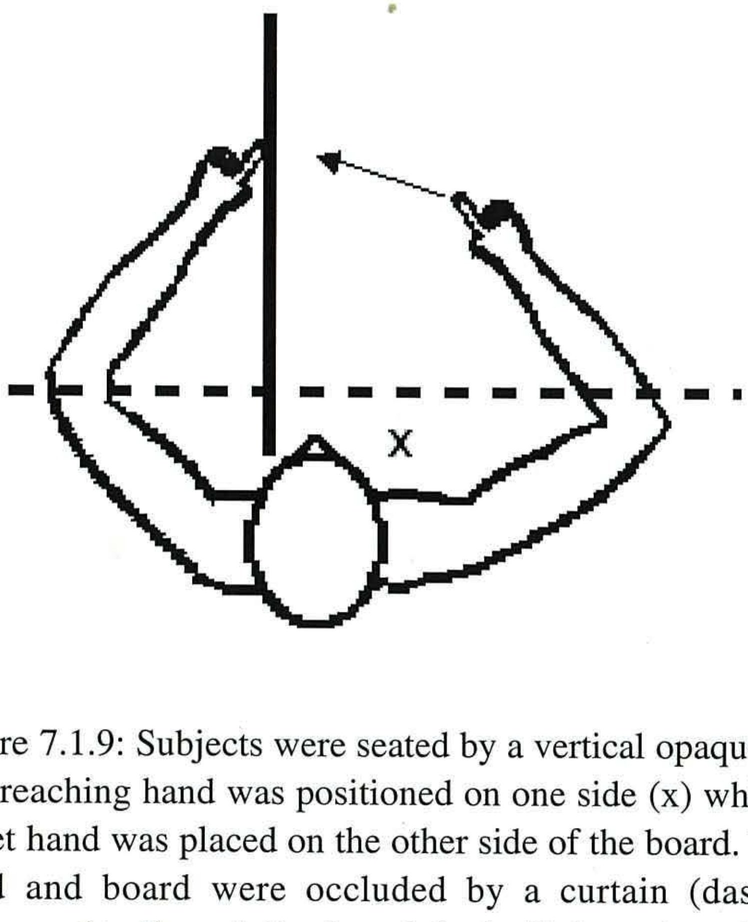

Figure 7.1.9: Subjects were seated by a vertical opaque board (solid line). The reaching hand was positioned on one side (x) while the contralateral target hand was placed on the other side of the board. Vision of the target hand and board were occluded by a curtain (dashed line) running orthogonal to the pointing board. In the 'lights on' condition subjects could see their initial hand position whilst in the 'lights off' condition they could not. Adapted from Desmurget et al., (1997b).

oriented along the midline; see Figure 7.1.9) to that reported here to examine the whether vision of the reaching hand operated to calibrate the proprioceptive map during reaching. The authors noted that viewing the static hand prior to movement when pointing to visual targets improved end-point accuracy and they used their proprioceptive target paradigm to explicitly test the following hypotheses: i. that viewing the position of the static hand relative to a visual target during movement planning results in a within-modality encoding, leading to a more accurate computation of the movement vector as a consequence or ii. that viewing the static hand (the origin of the movement vector) prior to movement onset results in a more accurate encoding of the initial state of the reaching limb, also resulting in a more accurate reaching movement. Thus, vision improves accuracy by providing a within-modality encoding of the position of the reaching limb relative to the target (hypothesis i.), or, vision improves accuracy by calibrating the proprioceptively-derived position of the reaching hand prior to movement onset (hypothesis ii.). It is important to note, however, that in both of these cases it is assumed that, as the target hand is never visible, vision can only act to improve the accuracy of the reaching limb. It is not considered that vision might operate to enhance, or otherwise improve, the accurate localization of the unseen target limb.

The results of the Desmurget et al. (1997b) study demonstrated a clear improvement in pointing accuracy in the VP condition relative to the PP condition, which the authors interpreted as evidence in favour of hypothesis ii. above; that viewing the static hand prior to movement onset results in a more accurate encoding of the initial state of the reaching limb, and thus to more accurate movements. At first sight, our findings in the current experiment (that access to visual cues resulted in a significant increase in movement end-point accuracy when reaching to target locations defined proprioceptively by her unseen hand) provide a clear replication of the Desmurget et al. (1997b) result in patient CT. However, our finding that patient CT shows a limb-specific impairment in movement end-point accuracy, which is selectively improved by the presence of visual cues, is not consistent with Desmurget et al.'s interpretation of their findings for the following reasons. Our results show that when patient CT reaches to a target location defined proprioceptively by her impaired hand, she exhibits large errors in end-point accuracy. This is understandable if we assume that, unable to see it, she has mislocalized her impaired hand. When she points to the felt location of her impaired hand in the VP condition, however, her end-point errors are substantially reduced - evidently now correctly localising her impaired hand even though she still cannot see it. This improvement in performance cannot be due solely to having vision available to calibrate the felt position of her unimpaired reaching hand. Even with a correctly calibrated unimpaired hand she should still be mislocalizing her unseen impaired hand. As this was explicitly not the case, we conclude that the presence of visual and/or oculomotor cues during VP trials must operate to enhance, or otherwise improve, the localization of the unseen target limb. Some possible mechanisms through which this might occur will be considered in later experiments.

Finally, CT's limb- and condition-specific hypometria provides good support for two growing theories. Firstly, that her hypometria is limb-specific supports the now widely accepted the notion that there are multiple frames of reference associated with the body and that the hands each have separate coordinate systems attached (e.g. Haggard et al., 2000; Graziano and Gross, 1998). We suggest that the frame of reference associated with CT's affected limb is distorted whereas that associated with her unaffected limb is not and that this is reflected in her end-point errors. Secondly, there is growing evidence to suggest that reaches made to visually- and proprioceptively-defined targets may be modulated by different brain regions (Rushworth et al., 1997a). Here we show that reaches planned with respect to proprioceptively-defined targets differ markedly form those planned with respect to both visually-defined targets and proprioceptively-defined targets when vision is available.

7.2 Experiment 2: The importance of viewing the reaching hand after movement onset.

In the previous experiment we reported how CT was unable to indicate the location of her impaired hand accurately when blindfolded. When vision was available, however, localization of the impaired hand improved dramatically. It was not possible to draw any firm conclusions from Experiment 1 as to why this might be. One possibility is that, because she was able to see the static position of her reaching hand, vision served to calibrate the position of her reaching limb and so improve accuracy (Desmurget et al., 1997b; Rossetti et al., 1994b). Other visual cues were available to CT, though, such as vision of the workspace and vision of the reaching hand as it moved through space towards the target area. In addition, proprioceptive orienting (i.e. looking towards the limb) has been found to facilitate touch in terms of improved reaction times in tactile stimulus detection tasks (e.g. Tipper et al., (1998); Pierson et al., (1991); Honoré et al., (1989)). In order to investigate whether one of these visual cues was a factor in her improved performance we tested CT, one week after completing Experiment 1, on a variation of our proprioceptive pointing task in which vision of the moving hand was never available. Visual feedback of the reaching hand is known to be important for accurate performance of fine-grained actions such as grasping small objects (Jeannerod 1988) and we sought to remove vision of the reaching hand, to gauge its importance not only when reaching towards the impaired hand, but also when reaching with the impaired hand.

In Experiment 1 patient CT executed reaching movements above the table surface toward target locations, defined proprioceptively (in the VP and PP conditions), by a passively placed index fingertip beneath the table surface. In the current study we varied the task so that CT was now required to reach underneath the table to targets which were defined proprioceptively by passively placing the index finger of the non-moving hand on top of the table. This VP condition is now the same as the VP:P condition described by Haggard et al., (2000) (see Chapter 2). Note that by reconfiguring the task in this way, the VP condition becomes different in two ways. The target location can now be both seen and felt while the moving hand is occluded from view. By allowing vision of the proprioceptively-defined target, but not the reaching hand, this configuration allows us to directly test whether vision of the moving hand is critical for CT's end-point accuracy when reaching with either her impaired or unimpaired limb.

The PP condition in this experiment is essentially equivalent to the PP condition in Experiment 1, except for the new limb configuration, with reaches being made without vision to proprioceptively-defined target locations, and as such we would expect to see a similar pattern of results (i.e. limb-specific hypometric reaches). The VV and VP results may not be as straight forward to predict. Under equivalent reaching conditions to our 'reaching under' VV and VP condition several authors have found VP reaching to be more accurate than VV reaching (Haggard et al., 2000; Wann, 1991; Von Hofsten and Rosblad, 1988). We cannot predict with certainty that the same will be true for CT. Removal of visual feedback may lead to both VV and VP reaches being inaccurate when reaching with her impaired limb as the CNS, when denied vision, is unable to update the felt position of the reaching limb. When reaching with her unimpaired hand towards her impaired hand constant visual information about the target location should, in theory, produce very accurate reaches, more accurate in VP than VV. This rather depends, however, on how well that visual information is used. VP reaches (reaching under the table) are more accurate than VV reaches in normal subjects presumably because the CNS has two sources of information about the target location (VP) rather than only one (VV). This seems to suggest that both sources of information are integrated into the motor plan. In CT, however, one of those information sources is faulty. If vision can calibrate completely for her impaired position sense, or if that position sense is completely ignored, then her VP reaches should be as accurate as her VV reaches. If vision does not calibrate her position sense completely and if faulty proprioceptive information is integrated into the motor plan along with the visual information, then her VP reaches may be less accurate than her VV reaches. To test these theories directly, mean scores for VV and VP reaches for each hand will be compared in a set of a priori comparisons. Differences between each condition for each hand will also be compared as in Experiment 1.

7.2.1 Case CT

Experiment 2 was carried out exactly one week after Patient CT had completed the task described in Experiment 1. Extensive clinical and behavioural testing performed immediately prior to the experiment revealed no discernible change in CT's condition since her examination prior to Experiment 1. Throughout the following analysis and discussion CT's right limb will be referred to as her impaired limb.

7.2.2 Procedure

The apparatus and procedures used in Experiment 2 were identical to those outlined for Experiment 1 except that reaching movements were now made beneath the table surface towards targets defined proprioceptively by the index finger of the non-moving hand placed on the upper surface of the table. The starting position of the reaching hand was approximately 2 cm in from the leading edge of the table and as such the tip of the index finger, or any part, of the reaching hand could not be seen directly, but the rest of the limb could. The orientation of the reaching hand was identical to that used in the previous experiment - in line with the forearm, but rotated slightly away from the body.

7.2.3 Results

Data for patient CT were entered in separate 2 X 3 repeated-measures analyses of variance (ANOVA) for each dependent variable. Each ANOVA again consisted of the factors: HAND (Impaired vs. Non-impaired) and CONDITION (VV vs. VP vs. PP). As in Experiment 1, linear contrasts were used to evaluate a set of planned comparisons between relevant means. HPC-index scores will not be reported for Experiment 2 as these measures are not central to the theoretical issues raised by Experiment 1.

Direction Error (DE)

Analyses of patient CT's DE scores revealed statistically significant main effects of HAND ($F_{[1,31]} = 5.0$, $p < 0.05$) and CONDITION ($F_{[2,62]} = 22.3$, $p < 0.0001$), and a statistically significant HAND x CONDITION interaction effect ($F_{[2,62]} = 7.7$, $p < 0.005$). Relevant means are presented in Figure 7.2.1. Planned comparisons revealed that on VV and VP trials CT's DE scores for reaches executed using her non-impaired limb did not

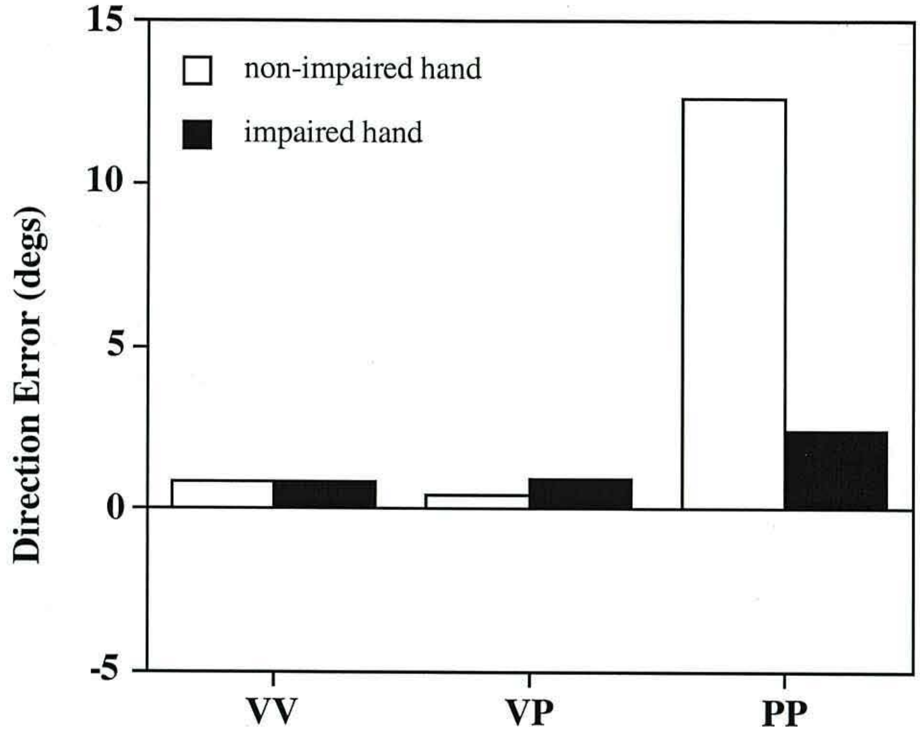

Figure 7.2.1: Mean direction error scores for Patient CT when pointing beneath the board.

differ statistically from reaches executed using her impaired limb (minimum $F_{[1]} < 0.2$ $p > 0.5$). In contrast, during PP trials, there was a significant difference between the limbs ($F_{[1]} = 23.4$, $p < 0.0005$) with CT's non-impaired limb being considerably less accurate than her impaired limb. Importantly, further planned comparisons revealed no differences between the VV and VP conditions in DE for reaches executed by either hand (minimum: $F_{[1]} < 0.2$ $p > 0.5$).

Amplitude Error (AE)

Analyses of CT's AE scores revealed significant main effects of HAND ($F_{[1,31]} = 21.6$, $p < 0.0001$) and CONDITION ($F_{[2,62]} = 26.1$, $p < 0.0001$). There was also a statistically significant HAND x CONDITION interaction ($F_{[2,62]} = 6.9$, $p < 0.005$). Relevant means are presented in Figure 7.2.2. Planned comparisons revealed that in the PP conditions, amplitude errors were substantially greater (hypometric) when CT reached with her non-impaired hand when compared to her impaired hand ($F_{[1]} = 39.7$, $p < 0.0001$). In the VP condition the difference between the hands was not statistically significant ($F_{[1]} = 1.9$, $p > 0.1$) whereas in the VV condition, reaches made with CT's impaired limb were significantly hypermetric ($F_{[1]} = 5.2$, $p < 0.05$). The difference between the VV and VP conditions was not significant for CT's unaffected limb ($F_{[1]} = 3.2$, $p > 0.05$), but was significant for her affected limb ($F_{[1]} = 8.1$, $p < 0.05$) with VV reaches being less accurate than VP reaches.

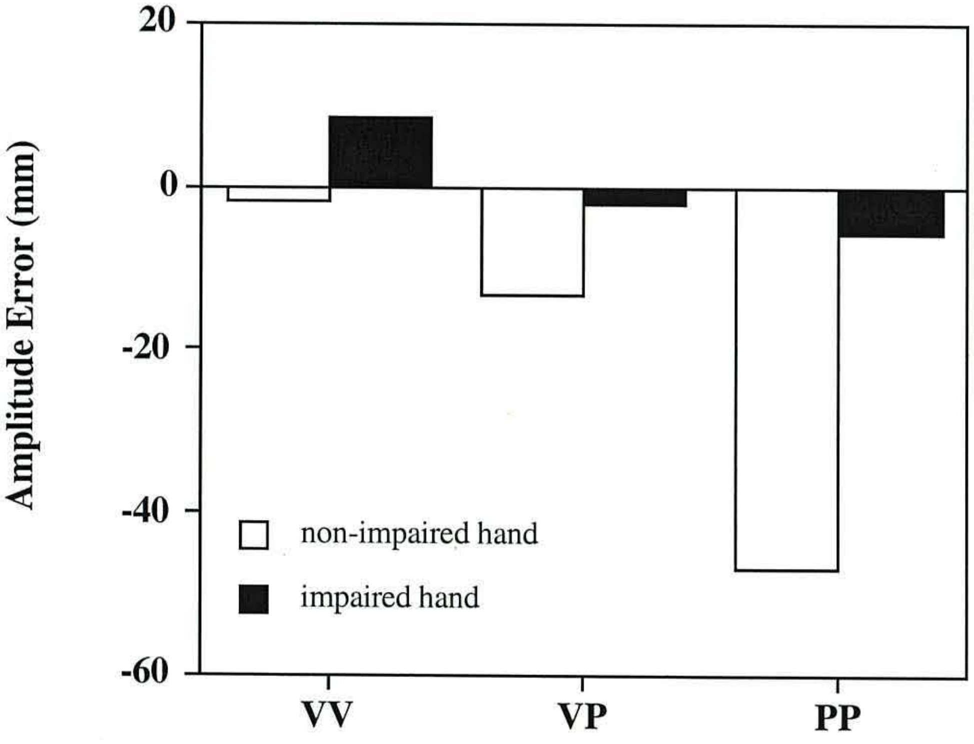

Figure 7.2.2: Mean amplitude error scores for Patient CT when pointing beneath the board.

7.2.4 Discussion

Compared to equivalent VP reaches, VV reaches made with the affected limb were slightly hypermetric (Figure 7.2.2). We suggested in Experiment 1 that CT's proprioceptive representation of space for her impaired limb was compressed towards the body. If CT feels that her hand is closer to her body than it really is then it makes sense that she moves it too far in order to indicate the location of visual targets. This overshoot is negated, however, when she has both visual and good proprioceptive information available regarding target location. Perhaps, because both limbs can be seen simultaneously before movement onset, the position of the impaired limb is calibrated in relation to the position of the unimpaired limb within both the proprioceptive modality and the visual modality.

VP reaches with her unimpaired limb to the felt and seen location of her impaired limb were not significantly different from equivalent VV reaches. This suggests either that the felt position of her impaired hand was successfully calibrated and integrated into the motor plan, or that the reaches were guided by visual information about the target alone and that proprioception was ignored completely. This latter suggestion seems the more unlikely given the finding that the combined availability of vision and proprioception improved performance in the reverse VP condition when CT indicated the felt position of her unaffected hand with her affected hand.

As in Experiment 1, the most striking result is that of CT's amplitude and direction errors in the PP condition. When indicating the felt position of her unaffected hand with her affected hand without the aid of vision CT was reasonably accurate. Conversely, when her affected hand was the target and she was using her unaffected limb to indicate its location she was severely impaired. As in Experiment 1, CT was grossly hypometric and her direction errors were also inaccurate, but this time skewing clockwise, rather than anti-clockwise. This may well have been largely as a result of postural changes in the task with her forearm and wrist muscles in the opposite configuration to that in Experiment 1. Comparisons between the means for each hand in the VV and VP conditions were likewise very similar to those obtained in Experiment 1. Reaches in both the VV and VP conditions displayed a high degree of accuracy and end-point errors did not vary across the two conditions with either hand (except for an overshoot with the impaired hand in the VV condition). This important result strongly suggests that the highly accurate performance we saw in the VP condition in this, and the previous, experiment does not rely heavily upon vision of the moving (non-impaired) limb. There is a slight problem with this view however. The advantage in the current VP condition (of being able to see and feel the target) compared to the VP condition in Experiment 1 (in which the target could only be felt) may, to some extent, have compensated for the fact that CT could not see the moving limb. That is, the lack of a detriment to performance by not seeing the moving limb may have been clouded by an improvement in performance due to being able to see the target location. We cannot therefore completely rule out the possibility that vision of the moving limb still has an important role to play in the VP condition based solely upon the methods employed in Experiment 2. This issue will be re-examined in Experiment 4.

7.3 Experiment 3: 12 month retest.

In Experiment 2 we presented results which suggested that the improvements observed in CT's performance for the VP compared to the PP condition, when using her unaffected hand to indicate the position of her affected hand, were not solely a result of CT being able to view the moving limb. As discussed in the previous chapter, the paradigm in which this result was seen allowed vision as well as proprioception of the target location. To address this problem we devised a variation of the original paradigm (pointing above the table) which is described in Experiment 4. Between our original findings and Experiment 4, however, 12 months had elapsed, during which time CT had shown some improvement in her somatosensory skills. Accordingly, in Experiment 3 we repeated Experiment 1 in order to ascertain whether CT's performance in Experiment 1 was replicated.

7.3.1 Case CT

Patient CT was re-tested in February 1999, 12 months after our original investigation. At that time she continued to show somatosensory loss in her right upper limb, although it was less severe than when previously examined. She was still unable to detect vibrotactile stimulation of her right fingertips (0/4) , or the palmar surface of her right hand (0/4), and she consistently failed to discriminate between single and double (simultaneous) punctate stimuli applied to her right hand. In addition, localization of tactile stimulation applied to the right forearm and upper arm was very poor (1/4). However, she could now only copy and pantomime limb postures with her right arm with moderate success (3/4). CT was still able to detect punctate stimulation of her fingers though she complained of a sensation of 'pins and needles' throughout her right upper limb.

7.3.2 Procedure

The apparatus and procedures used in Experiment 3 were identical to those outlined for Experiment 1.

7.3.3 Results

Data for patient CT were entered in separate 2 X 3 repeated-measures analyses of variance (ANOVA) for each dependent variable. Each ANOVA again consisted of the factors: HAND (impaired vs. non-impaired) and CONDITION (VV vs. VP vs. PP). As in Experiment 1, linear contrasts were used to evaluate a set of planned comparisons between relevant means. In light of the findings in Experiment 1 an additional means contrast will be performed to directly test whether there is an improvement in performance between the VP and PP conditions when CT reaches with her unaffected hand to the felt position of her affected hand. In the interests of brevity, only amplitude and direction error values will be reported for Experiment 3 as other measures are not central to the theoretical issues raised by Experiments 1 and 2.

Direction Error (DE)

Analyses of patient CT's DE scores revealed that neither the main effect of HAND ($F_{[1,31]} < 1.0$, $p > 0.1$) or the main effect of CONDITION ($F_{[2,62]} < 1.0$, $p > 0.1$) were statistically significant. There was however a statistically significant HAND x CONDITION interaction effect ($F_{[2,62]} = 4.1$, $p < 0.05$). Relevant means are given in Figure 7.3.1. Planned comparisons revealed that in the VV and VP conditions, CT's DE scores for reaches executed using her non-impaired limb did not differ statistically from reaches executed using her impaired limb (minimum: $F_{[1]} = 0.6$, $p > 0.4$). For PP trials there was a significant difference in DEs between the limbs ($F_{[1,31]} = 8.2$, $p < 0.01$). Mean scores for the two hands in this condition were of a similar magnitude, but in opposite directions (means: non-impaired limb = 2.7 [10.2] degs.; impaired limb = -1.5 [10.3] degs. Importantly, CT showed an improvement in performance (the magnitude of her direction errors was substantially reduced) in the VP condition,

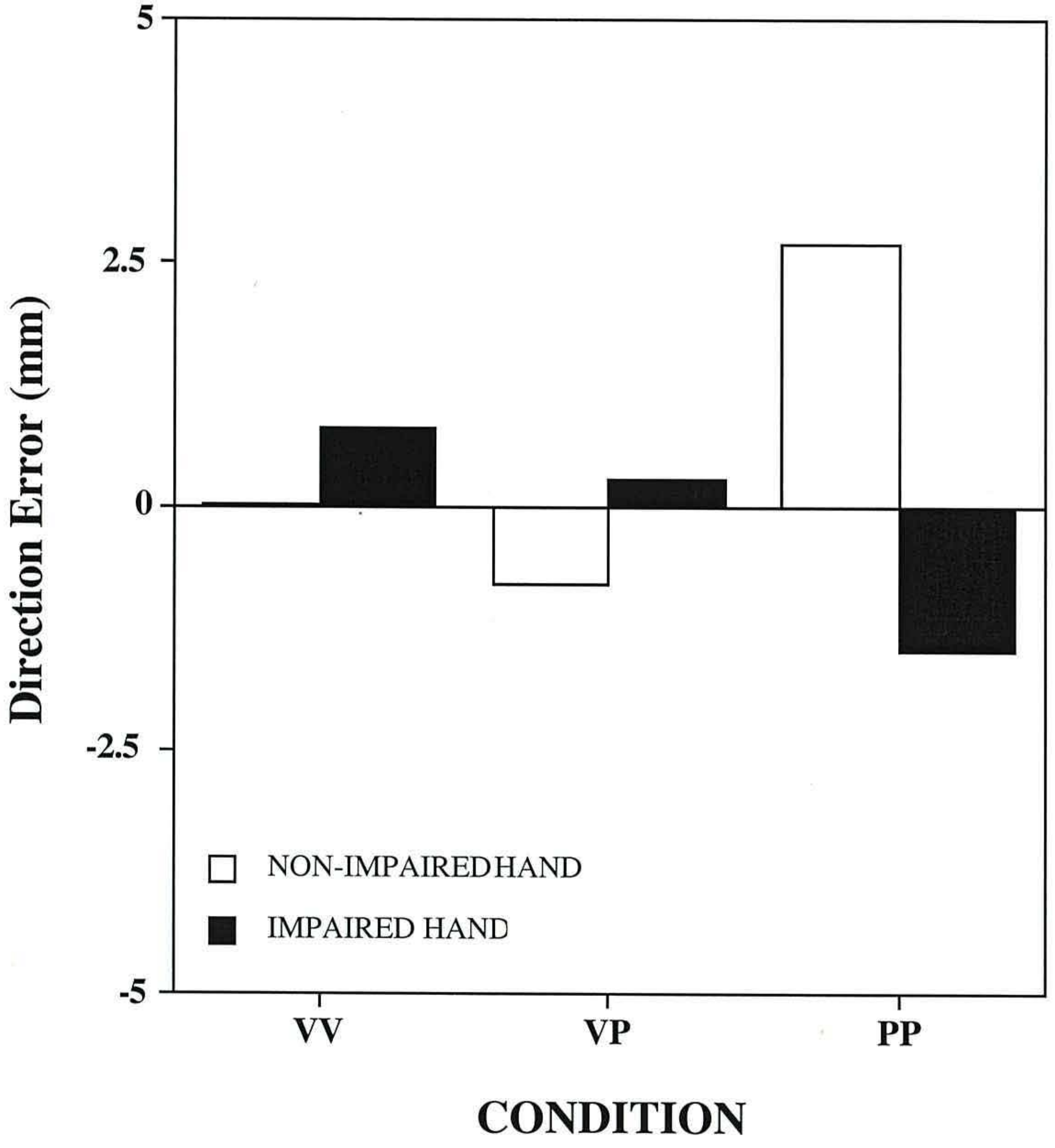

Figure 7.3.1: Mean direction error scores for Patient CT.

compared to the PP condition, when reaching with her unimpaired limb towards her impaired limb as the proprioceptively-defined target ($F_{[1]} = 5.8$, $p < 0.05$).

Amplitude Error (AE)

Analyses of patient CT's AE scores revealed significant main effects of HAND ($F_{[1,31]} = 8.6, p < 0.01$) and CONDITION ($F_{[2,62]} = 27.7, p < 0.0001$). There was also a statistically significant HAND x CONDITION interaction effect ($F_{[2,62]} = 8.7, p < 0.001$). Relevant means are presented in Figure 7.3.2. Planned comparisons revealed that in the VV and VP

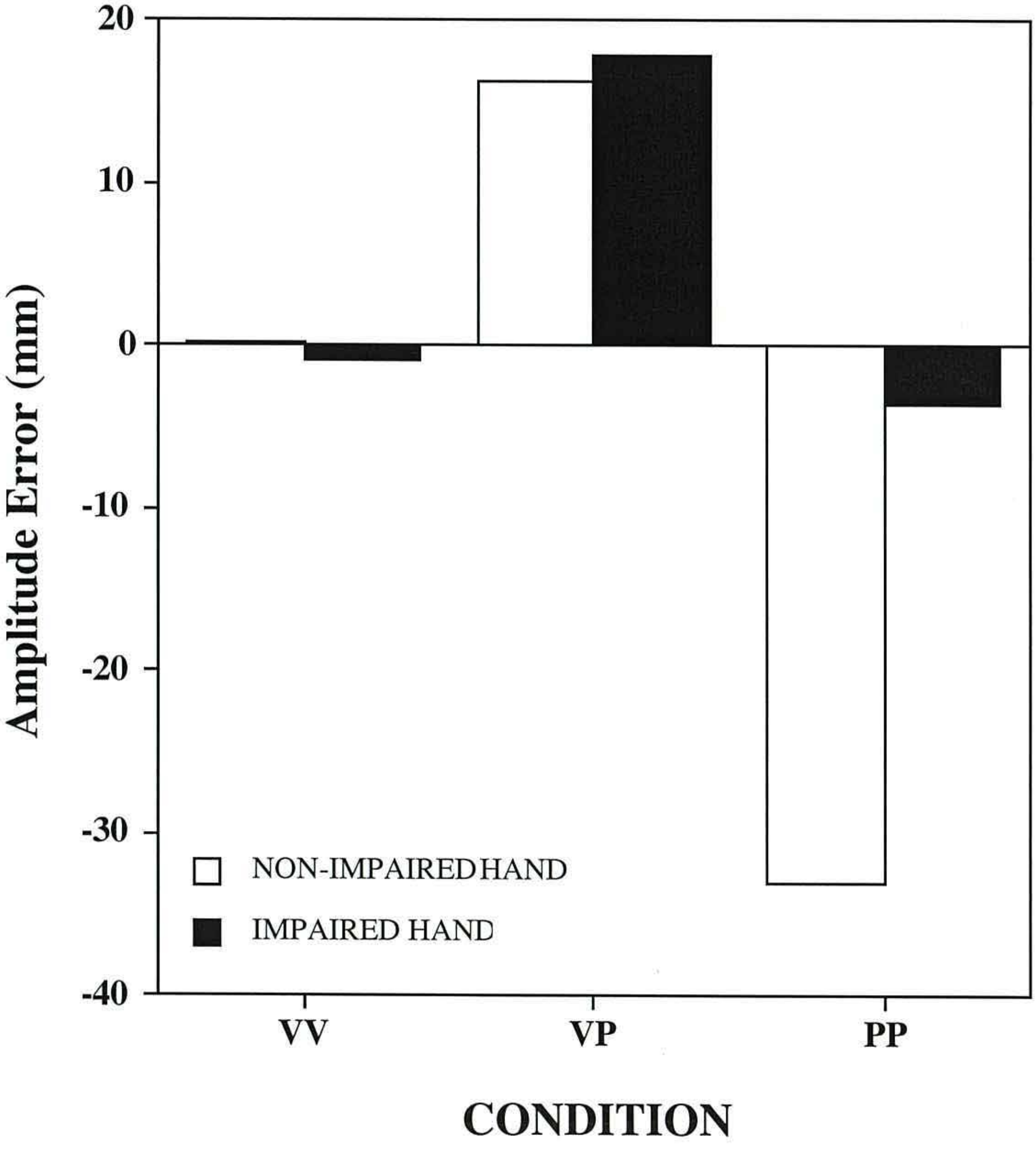

Figure 7.3.2: Mean amplitude error scores for Patient CT.

conditions, CT's AE scores for reaches executed using her non-impaired limb did not differ statistically from reaches executed using her impaired limb (minimum $F_{[1]} = 0.1$, $p > 0.7$). In contrast, during PP trials there was a significant difference in amplitude error between the limbs ($F_{[1]} = 26.2$, $p < 0.0001$). More importantly, these analyses revealed that CT's amplitude errors for reaches executed with her non-impaired limb (to targets defined proprioceptively by her impaired limb) decreased significantly on VP trials compared to PP trials ($F_{[1,31]} = 73.6$, $p < 0.0001$).

7.3.4 Discussion

Despite the passage of 12 months and some degree of recovery of function, patient CT shows a very similar pattern of deficits to those observed for Experiment 1. Specifically, when she reaches to a target location which is defined proprioceptively, amplitude errors for movements made using her non-impaired hand are consistently and substantially greater than for reaches made using her impaired hand. Furthermore, when reaching with her non-impaired limb to proprioceptively-defined targets, amplitude errors are substantially reduced if visual cues are available, in spite of the fact that such cues cannot possibly signal the spatial location of the target hand. Once again, this consistent and limb-dependent reduction in movement amplitude cannot be readily explained by an impairment in the ability to locate the target using visual cues or to execute an appropriate reaching movement using the non-impaired limb. Rather, the pattern of effects suggests that in the absence of visual cues, the felt position of the target hand is perceived to be closer to the body that it actually is.

It will have been noticed that CT exhibited an increased hypermetria in the VP condition in this experiment compared to

Experiment 1. Experiment 5, another retest on the basic paradigm, will show CT being slightly hypometric in this condition. Although CT's performance on the VP condition tended to vary on tests that were months apart, it is important to bear in mind that her performance was consistent within each experiment and in experiments conducted on the same day.

7.4 Experiment 4: The importance of viewing the workspace with, or without, vision of the reaching hand.

The results of Experiments 1-3 indicate that patient CT has a limb-specific impairment in movement accuracy when reaching with her non-impaired limb to targets defined by her impaired limb. This is substantially reduced when visual cues are available even though, in Experiments 1 and 3, such cues could not possibly signal the spatial position of the target hand directly. In Experiments 1 and 3 vision of the hand prior to, and during, movement onset was available, as was vision of the general workspace and any one, or a combination, of these factors might have served to improve reach accuracy: In this experiment we sought to investigate further the nature of the visual cues responsible for the increase in end-point accuracy observed in this patient during the VP trials. One possibility is that, perhaps because of the greater spatial acuity of the visual system relative to the proprioceptive system, viewing the moving hand relative to the felt position of the target hand - particularly during the later, 'homing in', stages of the reach - increases the end-point accuracy of the movement. If so, visual feedback of the hand may be particularly important. We removed visual feedback of the hand in Experiment 2, and found that reach performance still improved in the VP condition, but in this instance we also allowed vision of the target location. Another possibility is that viewing the static hand prior to movement onset may allow the proprioceptive map to be calibrated relative to the visual map, thereby producing an increase in movement accuracy (Desmurget et al., 1997b; Rossetti et al., 1994b). Finally, vision of the workspace behind which the target hand is located may serve to improve localization of the unseen limb. To test these ideas we examined how viewing the hand, or the workspace, prior to movement onset or during movement execution affected end-point accuracy in patient CT.

7.4.1 Case CT

Experiment 4 was conducted on the same day as Experiment 3 and there was no change in her clinical assessment between experimental sessions. Throughout the following analysis and discussion CT's right limb will be referred to as her impaired limb.

7.4.2 Procedure

The layout of the target positions in Experiment 4 was identical to that used in the experiments described in the previous chapter (see Figure 7.4.1 for details). The experimental procedures were broadly similar to those described above in relation to Experiments 1 and 3. A major procedural difference in this experiment, however, concerned how and when vision was occluded in the VP and PP conditions.

In the previous experiments, vision was occluded in the PP conditions by having subjects wear a blindfold. In the current study we wished to be able to occlude vision at movement onset, or, to provide vision only during movement execution. To achieve this, we had patient CT wear a pair of PLATO spectacles (Translucent Technologies Inc.) throughout the experiment. The use of these spectacles has been published previously (Jackson, Jones, Pritchard and Newport, 1997), but briefly, vision was occluded by means of liquid crystal (LCD) lenses worn over each eye. These lenses, which were normally transparent, were mounted within a pair of spectacle frames and were worn throughout the experiment by patient CT. Each lens could be rapidly (< 5 msecs) rendered opaque by a computer-controlled electrical trigger. It is important to note that occlusion did <u>not</u> lead to a significant decrease in levels of illumination reaching the eye.

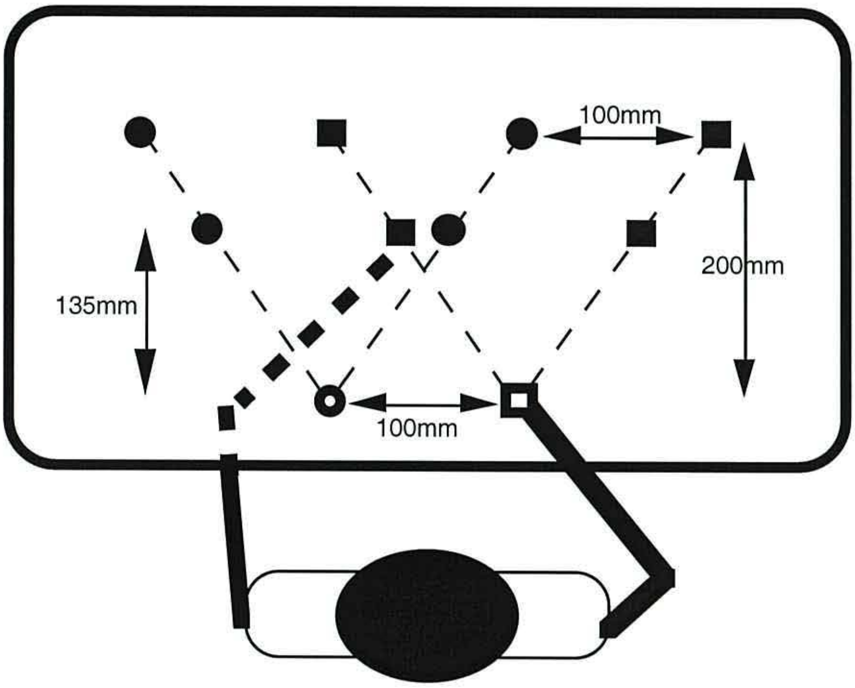

Figure 7.4.1: Overhead view of the experimental set-up. Reaches could begin from either an ipsilateral (open circle) or contralateral (open square) start position. Reaches from each start position were directed to one of four target locations associated with that start position and could be either contralateral or ipsilateral and two one of two distances (e.g. reaches starting from the open square could be directed to one of the four targets depicted by closed squares and from the open circle to targets depicted by closed circles).

On trials without visual feedback (No VFB trials) the LCD lenses were rendered opaque when movement onset was detected (if they were not already opaque). In this case, the position of the index finger marker was continually sampled using miniBIRD (at a sampling rate of 86.1 Hz), and the onset of a movement was defined as that point at which the displacement of the marker exceeded a value of 15 mm (Euclidean distance) from its initial position. The delay between detection of movement onset and sending the digital output signal to trigger the LCD lenses was typically less than 1 ms. Note that this movement onset measure was used solely for the purpose of triggering the LCD lenses. For statistical analyses we continued to use the velocity-based measure (described above in relation to Experiment 1) for defining the movement onset for each trial. On trials with visual feedback (VFB trials) the lenses were rendered transparent upon movement onset (if they were not already transparent) and remained transparent throughout movement execution. On some trials vision was occluded prior to movement onset, by having the lenses become opaque at the start of the trial, and on other trials vision was allowed prior to movement onset, by having the lenses remain transparent at the start of the trial. Thus, the availability of vision prior to movement onset and during movement execution could be independently manipulated giving rise to the following six experimental conditions see also Figure 7.4.2):

1. **<u>No vision / No Visual Feedback</u>** <u>(No-Vis/No-VFB)</u> - in this condition the lenses remained occluded both prior to, and during, movement execution. This condition can thus be thought of as comparable to the PP condition used previously;

2. **<u>Vision (-hand) / No Visual Feedback</u>** <u>(V-H/No-VFB)</u> - in this condition the lenses remained transparent up until movement onset. While the subject was free to make eye and head movements, vision of the static

hand was prevented by placing a narrow matt black board over the hand at the level of the shoulder. This had the effect of allowing the subject to view the workspace while occluding the hand. It is important to note that the positioning of the occluding board in no way obstructed movement of the reaching limb;

3. **Vision (+hand) / No Visual Feedback** (V+H/No-VFB) - this condition is identical to condition 2 except for the fact that the hand was not occluded. The subject could thus view both the hand and the workspace simultaneously;

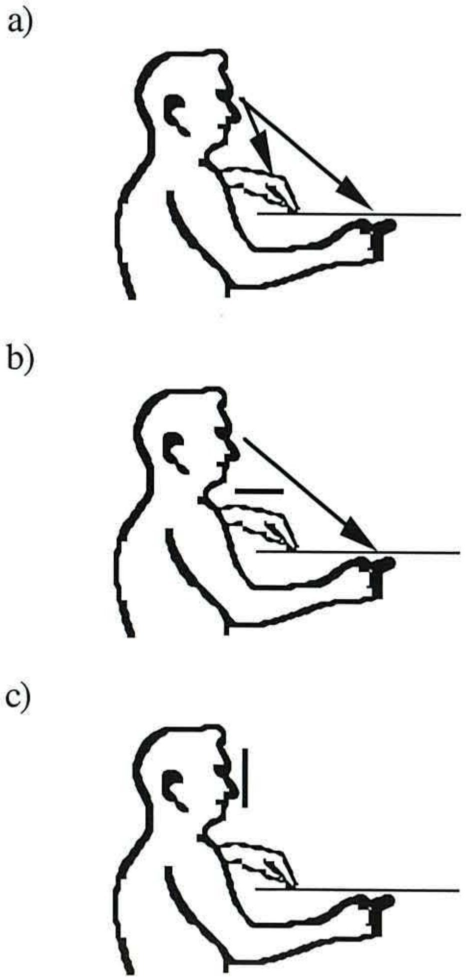

Figure 7.4.2: Initial view visual conditions for Experiment 4. Subjects could see either a) both the initial position of the hand and workspace, b) only the workspace or c) neither the workspace nor the hand. Visual feedback conditions allowed either vision or no vision upon movement onset.

4. **No vision / Visual Feedback** (No-Vis/VFB) - in this condition the lenses were occluded until to movement onset was detected. In this case, on-line visual cues were available to compensate for the absence of visual cues during the movement planning phase;

5. **Vision (-hand) / Visual Feedback** (V-H/VFB) - this condition is identical to condition 2 except that visual feedback was provided during movement execution. Thus, while vision of the hand and workspace are not simultaneously available during movement planning, the hand and workspace become jointly visible during movement execution;

6. **Vision (+hand) / Visual Feedback** (V+H/No-VFB) - in this condition vision of the hand and workspace is available both prior to movement onset, and during movement execution. This condition can thus be thought of as comparable to the VP condition used in experiments 1 and 3.

Because of the increased number of conditions used in Experiment 5 it was necessary to restrict data collection to reaches executed by patient CT using only her non-impaired limb. Reaches executed by CT using her impaired limb are, theoretically, of less importance than reaches executed using her non-impaired limb as they do not seem to impaired on this task. Thus in the current experiment, the key question to be addressed is whether the hypometria observed in the PP condition of previous experiments is substantially reduced when CT has vision of her static hand prior to movement onset, or, when vision of the static hand is provided during movement execution.

The six pointing conditions were blocked. The order of presentation being determined by a randomized ABCDEFFEDCBA design. The order of target presentation was also randomized within each condition. All other details of the design and procedure used were identical to those described for previous experiments.

7.4.3 Results

Data for patient CT were entered in separate 2 X 3 repeated-measures analyses of variance (ANOVA) for each dependent variable. Each ANOVA consisted of the following factors: FEEDBACK - whether or not visual feedback was available after movement onset (no visual feedback vs. visual feedback) and INITIAL VIEW - the type of visual information available prior to movement onset (no vision vs. vision available but vision of the static reaching hand occluded vs. vision available, including vision of the static hand). As in previous experiments, linear contrasts were used to evaluate planned comparisons between relevant means. The importance of viewing the static hand prior to movement onset can be assessed by holding visual feedback constant and comparing trials where vision of the hand is available with trials where vision of the hand is occluded (V+H/No-VFB vs. V-H/No-VFB). Similarly, the importance of viewing the work-space prior to movement onset can be assessed by holding visual feedback constant and comparing trials where vision of the work-space only is available with trials where vision of the work-space is occluded (V-H/No-VFB vs. No-Vis/No-VFB). The importance of viewing the reaching hand during movement execution can be obtained by comparing trials in which vision of the hand is available during movement execution or withdrawn at movement onset (V+H/VFB vs. V+H/No-VFB).

Direction Error (DE)

Analyses of patient CT's DE scores revealed no significant main effects of Feedback ($F_{[1,31]} < 1.0$, $p > 0.8$) or Initial view ($F_{[2,62]} < 1.0$, $p > 0.5$), and no statistically significant Feedback x Initial view interaction effect ($F_{[2,62]} = < 1.0$, $p > 0.1$). Relevant means and statistics for the planned comparisons are presented in Figure 7.4.3. F and Table 7.4.1.

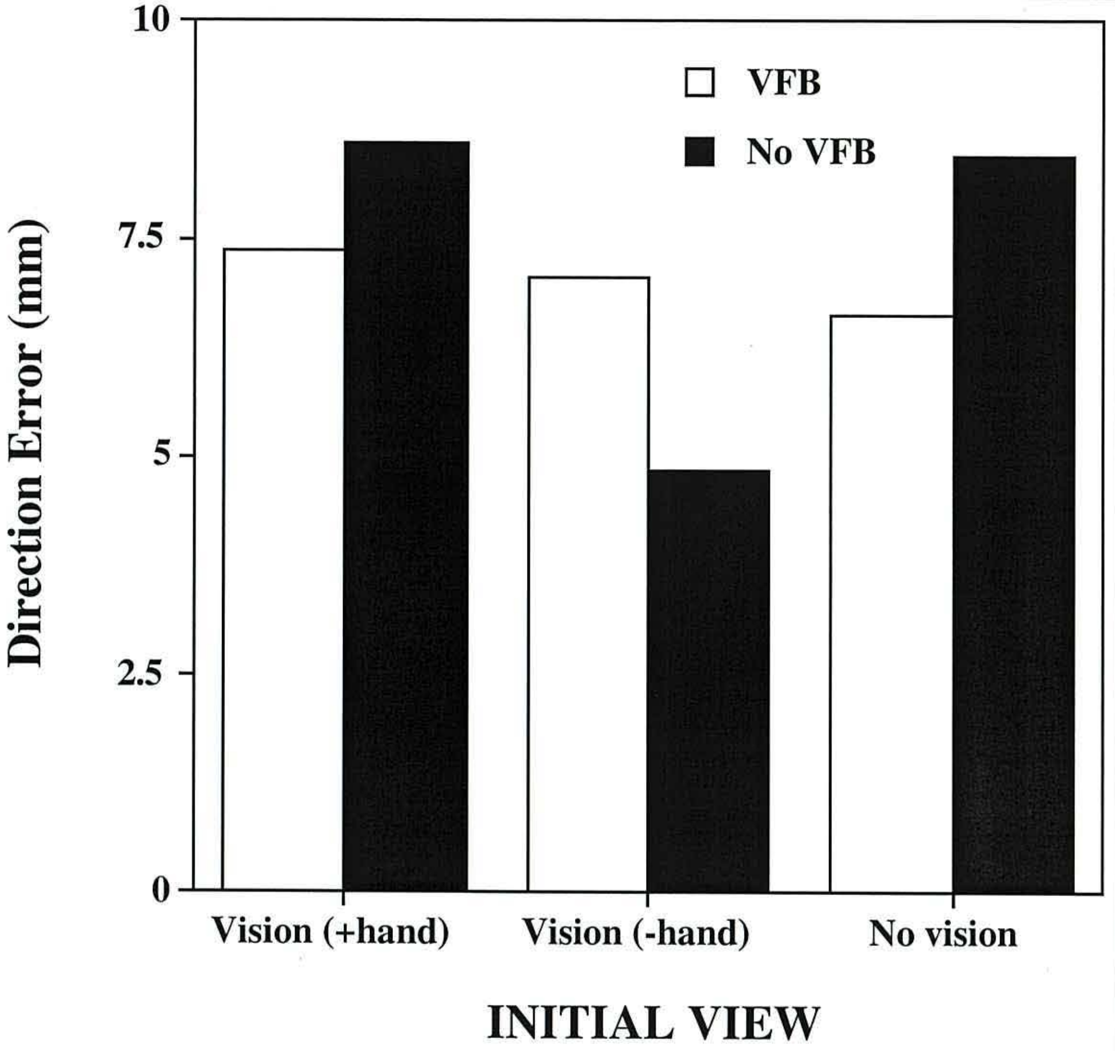

Figure 7.4.3: Mean direction error scores for Patient CT.

Table 7.4.1: F statistics and p values for the planned comparisons with respect to direction error.

Effect of...	Comparison	Statistic
viewing the static hand prior to movement onset	V+H/No-VFB vs. V-H/No-VFB	$F_{[1]} = 2.5$, $p > 0.1$
viewing the work-space prior to movement	V-H/No-VFB vs. No-Vis/No-VFB	$F_{[1]} < 2.3$, $p > 0.1$
viewing the reaching hand during movement execution	V+H/VFB vs. V+H/No-VFB)	$F_{[1]} = 0.3$, $p > 0.6$

Amplitude Error (AE)

Analyses of patient CT's AE scores revealed significant main effects of FEEDBACK ($F_{[1,31]} = 13.1$, $p < 0.001$) and INITIAL VIEW ($F_{[2,62]} = 43.2$, $p < 0.0001$). There was not a significant FEEDBACK x INITIAL VIEW interaction ($F_{[2,62]} = 2.7$, $p > 0.05$). Relevant means are presented in Figure 7.4.4. F statistics and p values for the planned comparisons are given in Table 7.4.2.

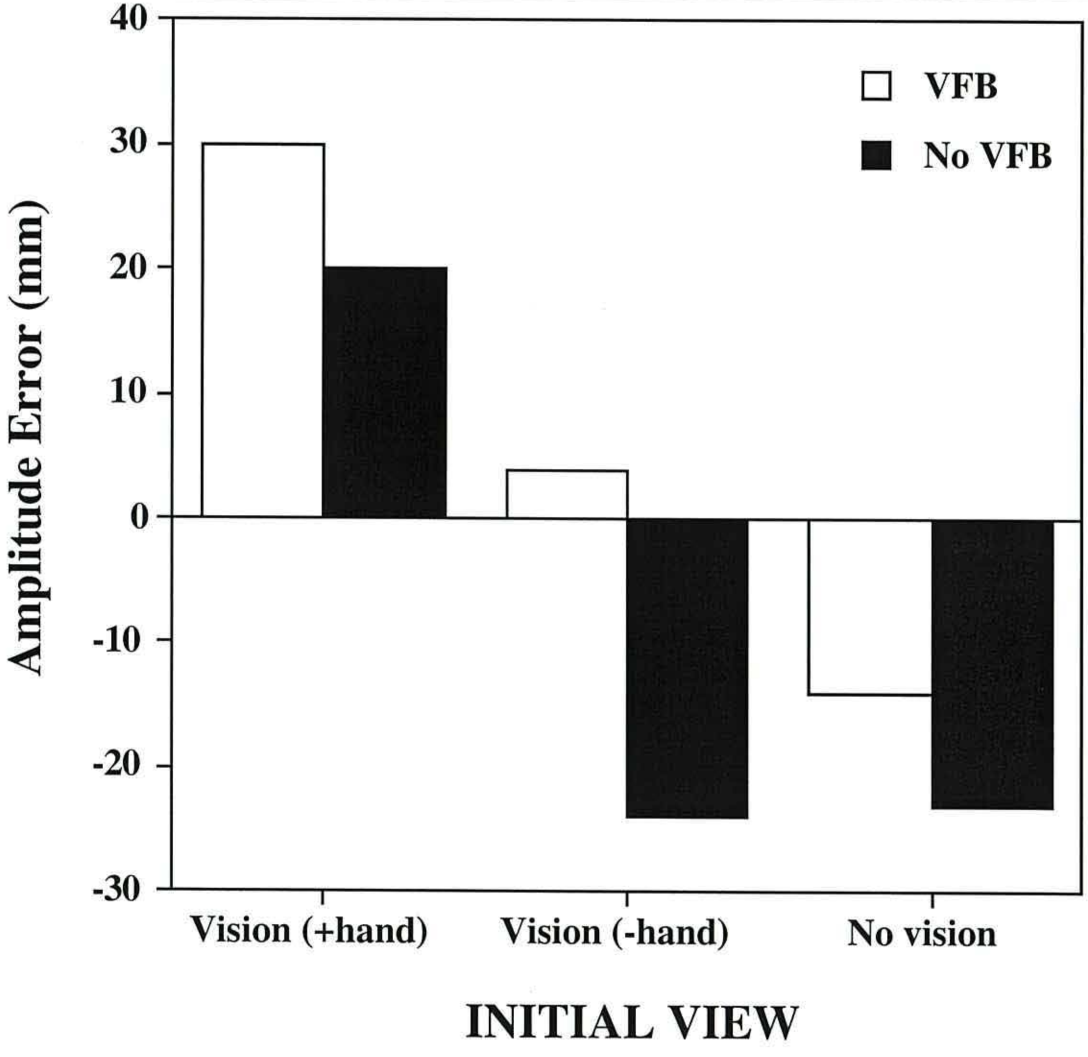

Figure 7.4.4: Mean amplitude error scores for Patient CT.

Table 7.4.2: F statistics and p values for the planned comparisons with respect to amplitude error.

Effect of...	Comparison	Statistic
viewing the static hand prior to movement onset	V+H/No-VFB vs. V-H/No-VFB	$F_{[1]} = 48.2$, $p < 0.0001$
viewing the work-space prior to movement	V-H/No-VFB vs. No-Vis/No-VFB	$F_{[1]} < 0.1$, $p > 0.8$
viewing the reaching hand during movement execution	V+H/VFB vs. V+H/No-VFB	$F_{[1]} = 2.7$, $p > 0.1$

7.4.5 Discussion

Inspection of Figure 7.4.4 indicates that CT still made similar hypometric reaches to those in the equivalent PP condition in Experiment 3 when deprived of vision both prior to, and during, movement execution (No-Vis/No-VFB condition). CT's reaches were hypermetric, however, when vision of the workspace and reaching limb were available throughout. This hypermetria was also observed in the equivalent VP condition in Experiment 3, though to a slightly lesser extent. It must be remembered that normal subjects also have a tendency to overshoot the target distance when reaching to proprioceptively-defined targets (see subject IJ in this chapter and the discussion of the 'overlap' effect in Chapter 2).

Having a view of only the workspace prior to movement onset (V-H/No-VFB vs. No-Vis/No-VFB) did not significantly improve accuracy. It is interesting to compare this result with that of Neggers and Bekkering (1999) who examined the accuracy of reaches directed towards visual and somatosensory targets located on the knee. They found a slight improvement in pointing accuracy when subjects made both eye and hand movements towards the proprioceptively-defined targets (in the dark) compared to movements of the hand when fixation was straight ahead. No direct statistical comparison of these two conditions was performed, however, and it is not clear whether this 'slight' improvement was significant or not.

As was noted above, it has been suggested that viewing the static hand prior to movement onset may increase movement accuracy (Desmurget et al, 1997b; Rossetti et al. 1994b). To test this, we compared trials in which both the hand and workspace could be seen with those in which only the workspace could be seen (V+H/No-VFB vs. V-H/No-VFB). The analyses showed that vision of the hand prior to movement onset had a large and significant effect on movement accuracy. The planned comparisons indicated that when no visual feedback was available, vision of the workspace without vision of the initial hand position produced reaches which were as hypometric as when vision of neither workspace nor hand were available. Providing vision of both the initial hand position and the workspace together, however, produced reaches equal to those when complete vision was available throughout. In other words, an initial view of both the hand and the workspace appears to be necessary in order to completely ameliorate CT's hypometric reaching when indicating the position of a proprioceptively-defined target. It made no difference, in this case, whether visual feedback of the limb after movement onset was provided or not (V+H/VFB vs. V+H/No-VFB) which indicates that seeing the hand and workspace simultaneously during movement execution is not enough to compensate for a restricted view during movement planning.

These findings suggest that patient CT produces markedly hypometric reaches only when she is deprived of visual cues which include vision of her initial limb position and the workspace behind which the target is located. However, this conclusion is based largely on comparisons of reaches in which the workspace and the hand can be seen against reaches in which the workspace, but not the hand can be seen. In no condition is there an initial view of the hand, but not the workspace (the direct equivalent of the Desmurget et al. (1997b) study set-up). If there is no difference between being able to see the hand but not the workspace and being able to see the hand as well as the workspace then the assumption made by Desmurget et al. (1997b), that vision of the initial hand position alone is crucial and that vision does not help localize the position of the unseen target hand, may be valid. If there is a difference between these two conditions, however, then this may indicate that vision can serve to localize the position of the target hand - even though it cannot be seen directly. Experiment 6 was performed in pursuit of this hypothesis. This experiment will be described after a further retest of Patient CT, the results of which are given in Experiment 5.

7.5 Experiment 5: 16 month retest.

Experiments 6 and 7 were completed 16 months after CT's initial examination and 4 months after Experiments 3 and 4. Accordingly, in Experiment 5, CT was retested on the basic paradigm - this time on the new target lay-out. At this stage of testing we were primarily interested in CT's performance when using her non-impaired limb to indicate the felt position of her impaired limb.

7.5.1 Case CT

CT continued to show signs of gradual improvement and, at her own insistence, still received weekly physiotherapy sixteen months after her initial admission to hospital. At the time of testing CT continued to show some evidence of somatosensory loss in her right upper limb, although it was less severe than on previous examinations. Specifically, she consistently failed to discriminate between single and double (simultaneous) punctate stimuli applied to her right hand and forearm, and continued to experience difficulty picking up small objects if she was prevented from viewing her hand. In addition, CT continued to report the presence of a constant 'pins and needles' sensation in her right hand and arm. In contrast to 16 months previous, CT could detect, and correctly identify, the direction of rotations applied to the joints of the fingers of her right hand, and her right wrist, elbow, and shoulder (4/4 for each). In addition, without vision she could detect and correctly localize when the fingers, hand, and forearm of her right limb were touched by the experimenter (4/4 for each). She also exhibited somaesthetic transfer across the hands (4/4), and no longer experienced difficulties mirroring passively imposed postures of her impaired limb using her non-impaired limb (4/4). this latter improvement was most likely due to her recent physiotherapy. Throughout the following analysis and discussion CT's right limb will be referred to as her impaired limb.

7.5.2 Procedure

The procedure and apparatus were identical to those used in Experiment 1 with two notable exceptions: a) only the left (unaffected) hand was tested as a reaching hand as this was the most theoretically interesting arrangement and it also helped to reduce fatigue in the patient and b) the new target lay-out, as used in Experiments 4, was employed.

7.5.3 Results

Data for CT's unaffected hand were entered in a 1 x 3 ANOVA with CONDITION (VV vs. VP vs. PP) as the single factor. Planned comparisons identical to those in Experiment 1 were used to determine that the differences in performance observed in Experiment 1 were still manifest.

Direction Error

Analysis of CT's direction error scores revealed a significant main effect of CONDITION ($F_{[2,62]} = 11.7$, $p < 0.0001$). The result of the planned comparisons was that VV and VP scores were not significantly

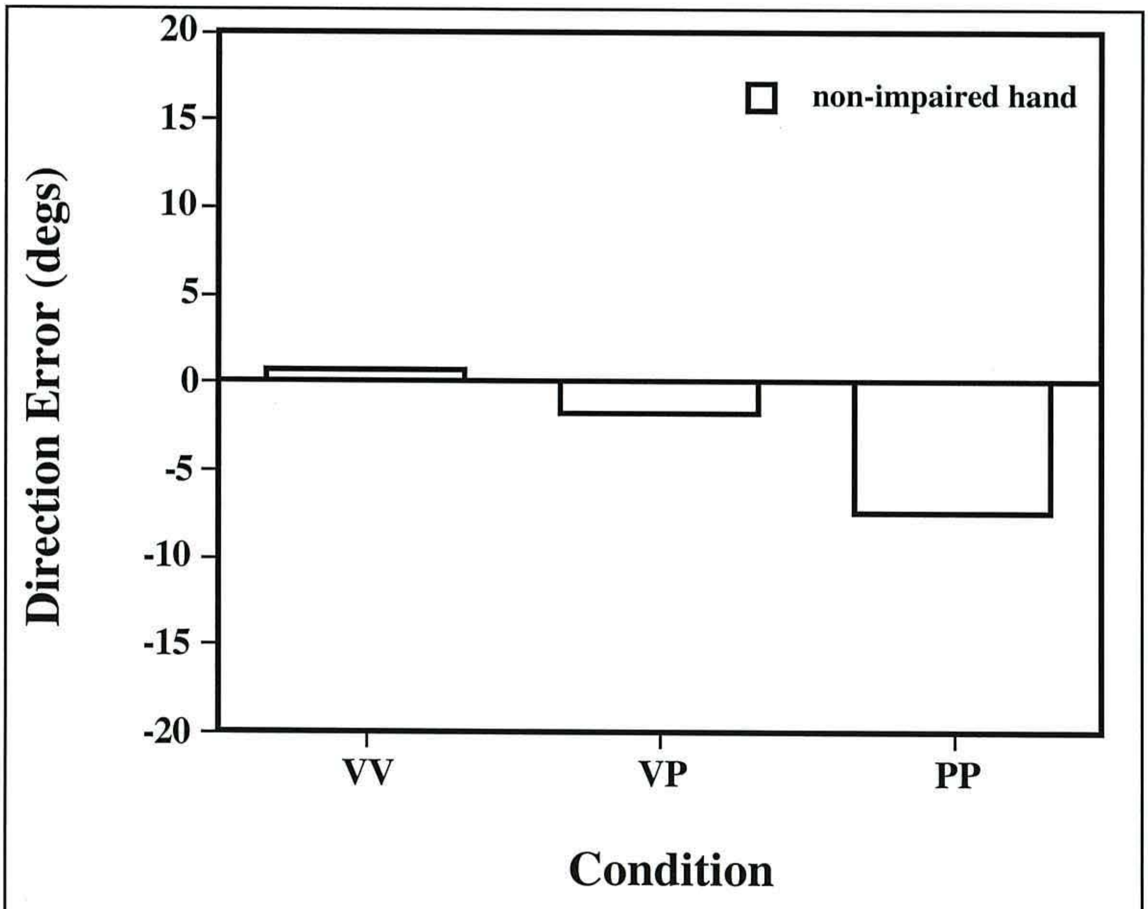

Figure 7.5.1: Mean direction error scores for Patient CT reaching with her non-impaired hand.

different ($F_{[1]} = 2.1$, $p > 0.1$). PP scores, in contrast, veered significantly anti-clockwise when compared to both VV ($F_{[1]} = 22.2$, $p < 0.0001$) and VP scores ($F_{[1]} = 10.6$, $p < 0.005$). Relevant means are given in Figure 7.5.1.

Amplitude Error

Analysis of CT's amplitude error scores revealed a significant main effect of CONDITION ($F_{[2,62]} = 42.0$, $p < 0.0001$). The result of the planned comparisons was that VP reaches were more hypometric than VV reaches ($F_{[1]} = 16.3$, $p < 0.001$) and PP reaches were significantly more

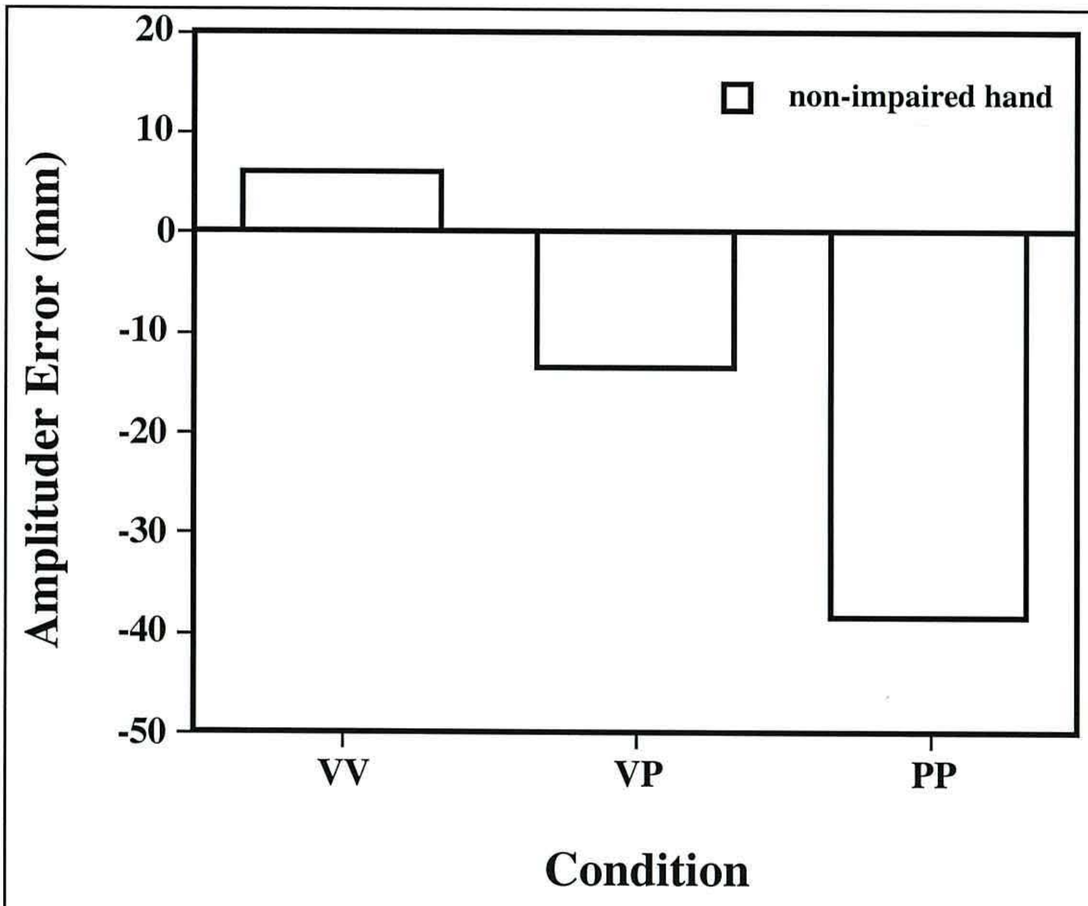

Figure 7.5.2: Mean amplitude error scores for Patient CT reaching with her non-impaired hand.

hypometric than both VP ($F_{[1]} = 83.6$ $p < 0.0001$) and VV reaches ($F_{[1]} = 26.0$, $p < 0.0001$). Relevant means are given in Figure 7.5.2.

7.5.4 Discussion

The results observed in this experiment broadly match those revealed by CT's initial examination 16 months previously in Experiment 1. When reaching to the felt location of her affected hand with unaffected hand without vision she displayed anti-clockwise end-point errors which also fall considerably short of the target. This continued underestimation of the felt position of her affected hand persists despite slow, but gradual improvement in her overall condition as clinically assessed prior to testing. When vision of the workspace and reaching hand was made available (VP condition) her reaching errors were substantially ameliorated as they have been throughout the period of examination. CT was still completely unimpaired when reaching to visually-defined targets placed in the same locations as the proprioceptively-defined targets. It will be noted that in this session she is slightly hypometric when reaching in the VP condition. This is contrary to her performance in the equivalent condition four months previously. Despite this variability between testing sessions, however, she always remained consistent within testing sessions as can be seen in the two experiments which follow, both of which were performed on the same day as this experiment.

7.6 Experiment 6: The importance of concomitant vision of the workspace.

The results of Experiment 4 strongly suggested that concurrent vision of the limb and the area of workspace adjacent to the unseen target was crucial for reach accuracy. Evidence for this came from a comparison between reaches made when vision of the both workspace and hand was available and reaches made when only the workspace could be seen. It was observed that occlusion of the initial position of the reaching hand led to hypometric reaches by patient CT. It is conceivable, however, that it is only vision of the hand, not vision of the hand and workspace together, that is important for reach accuracy and that having vision of the workspace does not significantly improve localization of the unseen target limb. To test this hypothesis we tested CT on a further variation of the VP proprioceptive pointing task in which vision of the initial position of the hand was allowed but vision of the workspace was not.

We have already demonstrated that seeing the hand and workspace simultaneously during movement execution is not enough to compensate for a restricted view during movement planning. We hypothesized that it may be necessary for CT to be able to see the hand and workspace simultaneously in order to accurately plan VP reaches. If this is the case we still do not know whether CT must see the hand and workspace during movement planning, or whether a view of the hand and workspace which is recent enough to eliminate proprioceptive drift of the target limb once it had been accurately localized would be sufficient. According to Goodale et al. (1994) the dorsal action system operates in real time and does not possess mechanisms capable of storing visuomotor coordinates for more than a few milliseconds. To determine whether it was necessary for CT to see the hand and workspace during movement planning we added a third condition to this experiment in which vision of the reaching hand and workspace was available during the placement of the target hand, but was removed immediately prior to receiving the signal to move - i.e. immediately prior to movement planning.

7.6.1 Case CT

Testing took place on the same day as Experiment 5 and there was no change in her clinical condition. Throughout the following analysis and discussion CT's right limb will be referred to as her impaired limb.

7.6.2 Procedure

The experimental set-up was broadly identical to that used in the previous experiment, the only differences being changes in the procedures associated with the different visual conditions. LCD goggles were worn throughout the experiment and could be rendered opaque either before, or after, movement onset. The experiment consisted of three different versions of the VP condition as follows:

i. VP condition - this consisted of the standard VP condition in which the subject could view both the reaching hand and the work surface prior to, and after, movement onset.

ii. VP(delay) condition - in this condition subjects were able to simultaneously view the static reaching hand and the workspace throughout the period prior to the arrival of the auditory 'Go' signal. At the same time as this signal was given, vision was occluded to both eyes using the PLATO spectacles. In this way, on each trial, subjects had simultaneous vision of the static reaching hand and the workspace in the vicinity of the target hand, but not during movement planning or movement execution.

iii. VP(hand only) condition - a matt black board was placed across the workspace at shoulder height such that the hand could be viewed in its initial start position, but the rest of the workspace was occluded (see Figure 7.6.1). An auditory beep signalled the start of the trial and vision to both eyes was occluded by the LCD goggles upon movement onset.

7.6.3 Results

Data for each dependent variable were entered in a 1 x 3 analysis of variance (ANOVA) with the single factor CONDITION (VP vs. VP(delay) vs. VP(hand only)). Planned comparisons were employed to assess a) the effects of introducing a delay (VP vs. VP(delay)) and b) the effects of being able to see the initial position of the hand, but NOT the area of workspace in which the target was located (VP vs. VP(hand only)).

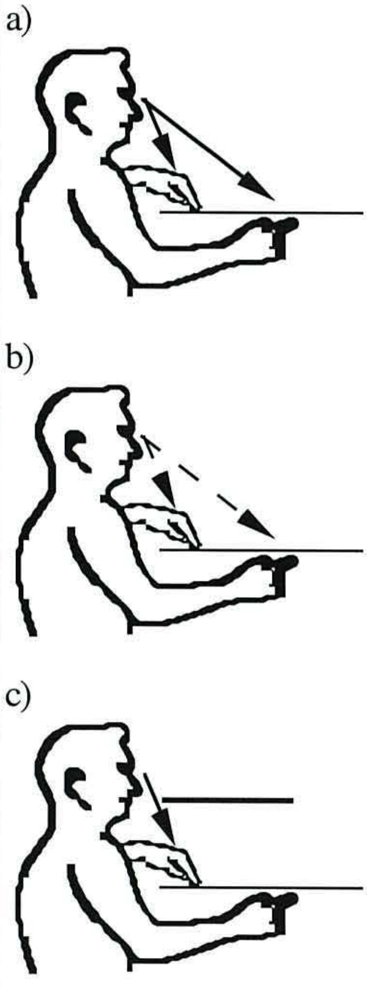

Figure 7.6.1: Side-on view of the experimental set-up. a) VP condition: Unrestricted vision of reaching hand and workspace before and during movement; b) VP(delay) condition: Unrestricted vision of reaching hand and workspace removed prior to movement onset and c) VP(hand only) condition: A matt black wooden board across the reaching area at chin height allowed vision of the initial hand position (arrowed), but not vision of the workspace beneath which the target hand was located.

Direction Error

There was no main effect of CONDITION ($F_{[2,62]} < 1.0$, $p > 0.9$) and the planned comparisons revealed no significant differences either (minimum: $F_{[1]} < 1.0$, $p > 0.8$). Relevant means are given in Figure 7.6.2.

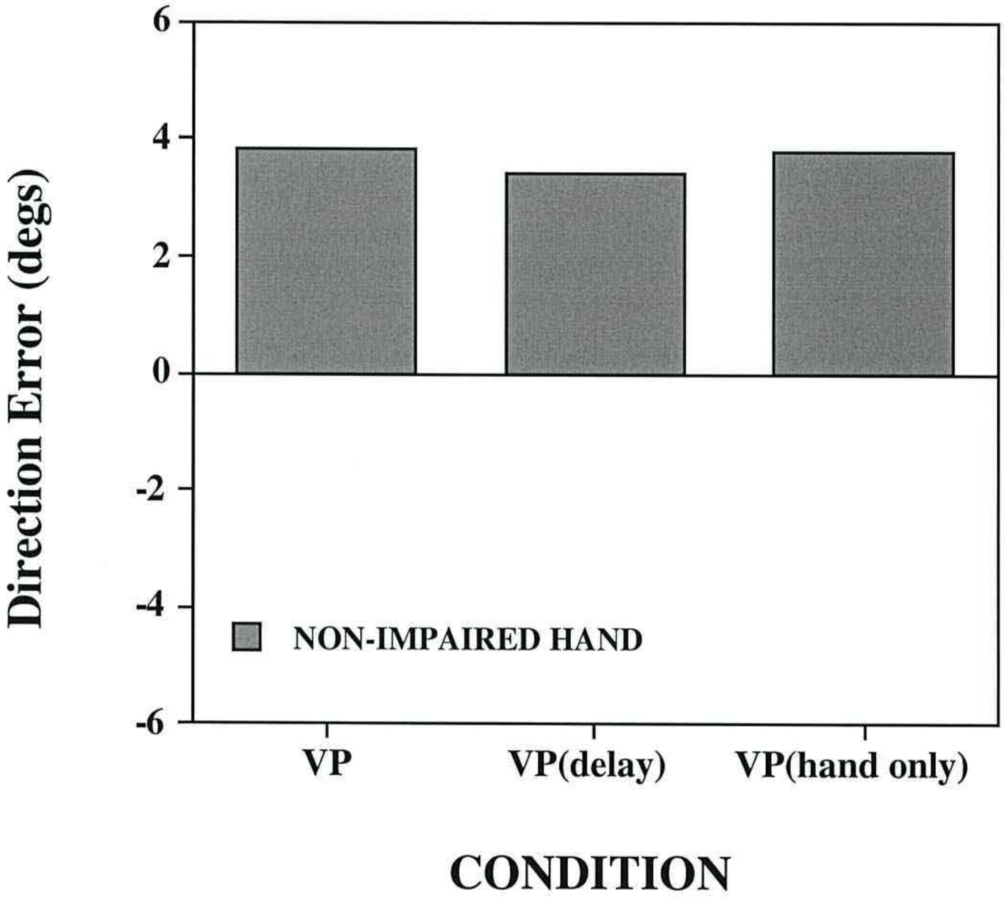

Figure 7.6.2: Mean direction error scores for Patient CT reaching with her non-impaired hand.

Amplitude Error

Analysis of amplitude error scores revealed a main effect of CONDITION ($F_{[2,62]} = 16.4$, $p < 0.0001$). Planned comparisons revealed that there was no difference between the VP and VP(delay) conditions ($F_{[1]} < 1.0$, $p > 0.7$). In contrast, there was a significant difference between the VP and VP(hand only) conditions ($F_{[1]} = 23.2$, $p > 0.0001$) with reaches in the VP(hand only) condition being substantially less accurate and more hypometric than those in the VP condition. Relevant means are given in Figure 7.6.3.

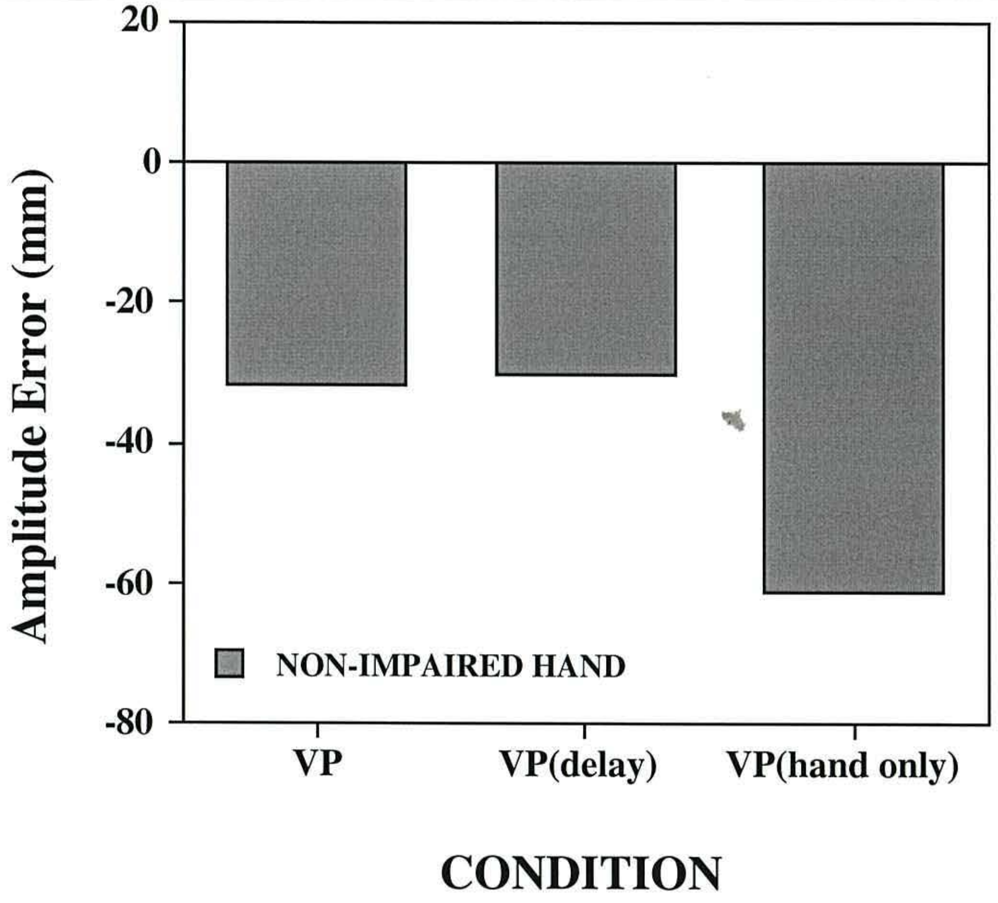

Figure 7.6.3: Mean amplitude error scores for Patient CT reaching with her non-impaired hand.

7.6.4 Discussion

In 1997 Desmurget et al. determined that pointing accuracy in normal subjects was better when the initial position of the hand (but not the workspace) could be seen compared to when neither the hand nor workspace could be seen. They concluded from this that what was crucial for accurate movement planning was having vision of the initial hand position, not, as others have argued, having simultaneous vision of the hand and target. Their theories were based on the rules that apply to reaching towards visual targets, however, and they neglected the possibility that other mechanisms might be at work when the target is a proprioceptive one. The results of the current experiment are clear: when CT was allowed vision of both the workspace and her reaching hand simultaneously, her performance was much better than when she could only see the initial position of her hand. The results of this study, therefore, extend the findings of Desmurget et al. (1997b) by showing that a) simultaneous vision of the adjacent workspace improves proprioceptive localization of the unseen contralateral hand and b) vision of the initial hand position alone is not sufficient for accurate movement planning on this type of task. The results of the current experiment, taken in conjunction with the results of the Experiment 4, confirm that CT is severely hypometric when deprived of vision of the initial position of the hand (VP-H), vision of the workspace (VP/H-W), or both (PP/No-VFB and PP/VFB).

It is important to remember that in this experiment vision of the workspace in the VP-H condition was occluded by a matt black board positioned at shoulder height. This board was identical in surface structure to the board used to occlude vision of the target finger (i.e. the workspace under which the target finger was positioned). The VP(hand only) condition in this experiment and the V+H/NoVFB condition in Experiment 4 were essentially identical in that vision was allowed until movement onset except, that is, for the height of the occluding board (see Figure 7.6.4). When the board was at shoulder level in the current experiment (VP(hand only)) performance was impaired in comparison to the VP condition whereas when the board was just above hand height in Experiment 4 (V+H/NoVFB) performance was not impaired. In the current experiment performance was also poorer in the VP(hand only) condition, in which the occluding board was high, than in the VP(delay) condition in which, for the initial view, the occluding board was low. It seems that being able to see the area of workspace directly adjacent to the target hand improves localization of that target hand whereas receiving exactly the same amount of visual information, but of a workspace that is not adjacent to the target hand does not. Why should this be? The retina receives the same information in both conditions, yet one improves localization of the hand and the other does not. An answer to this question might be found in the electrophysiology literature. Graziano and Gross (1998) described neurons in the ventral premotor area of the monkey brain which respond to both tactile and visual stimuli. Furthermore, for these bimodal cells, the visual receptive field extends from the

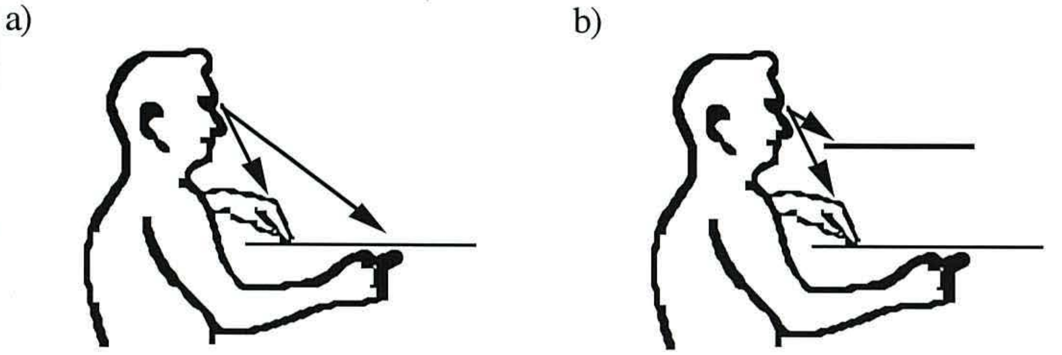

Figure 7.6.4: The retinal information regarding the location of the proprioceptively-defined target is essentially the same for the V+H/NoVFB condition from Experiment 4 (a) and the VP(hand only) condition in this experiment (b). The only physical difference between the two is the height of the featureless matt black board which obscures vision of the target area.

approximate region of the tactile receptive field into the immediately adjacent space (see Figure 7.6.5). The visual receptive field of these bimodal cells remains anchored to the region of the tactile receptive field so that for bimodal cells with a tactile receptive field on the arm, the visual receptive field moves with the arm when it is placed in different locations regardless of eye position. Graziano extended this work in 1999 by examining the relative contribution of vision and proprioception to the response patterns of cells in the premotor cortex just ventral to the spur of the arcuate sulcus where a high proportion of cells have bimodal properties with both tactile response fields on the arm and visual response fields near the arm. Graziano tested the responses of bimodal cells to a visual stimulus moving close to arm of the monkey which could be either covered or uncovered. In a separate set of trials neuronal responses were

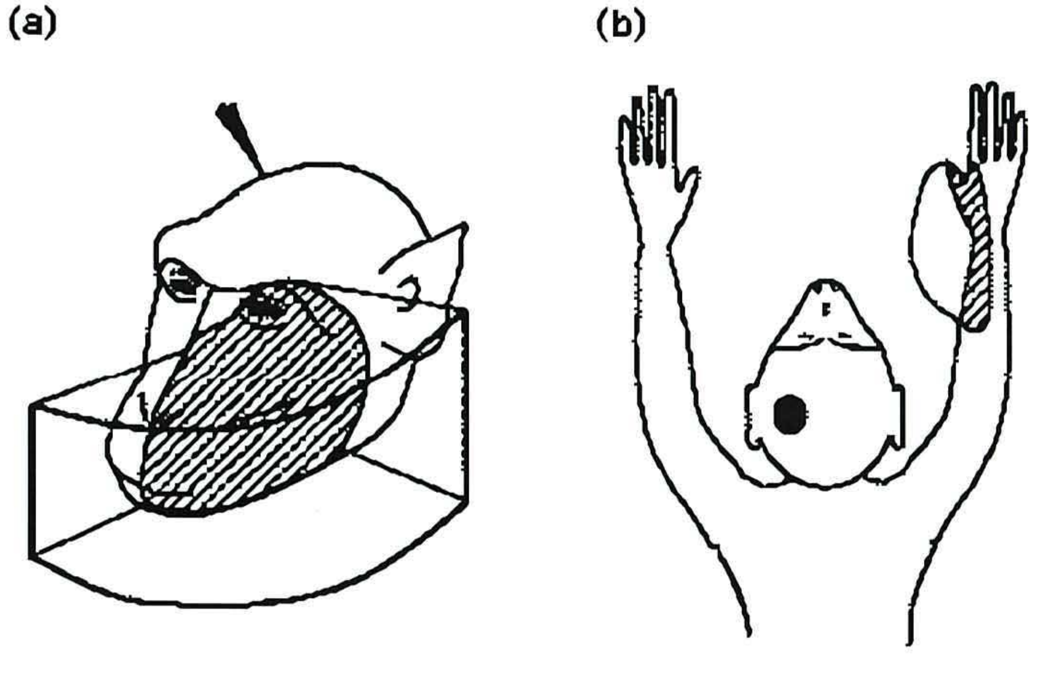

Figure 7.6.5: Tactile receptive field (shaded area) and associated visual receptive field (boxed) for a) the face and b) the hand. Electrode sites are also marked. Adapted from Graziano and Gross (1998).

measured when a stuffed monkey arm was placed above the monkey's covered arm. Note that the stuffed arm could be positioned independently of the real arm and thus conflict with the real arm position to give an indication of the contribution of vision alone. When the arm was uncovered and could be seen (i.e. visual and proprioceptive information was available) they replicated their earlier finding that the visual receptive field (RF) moved with the arm. When the arm was covered (so that only proprioceptive information was available) the visual RF still moved with the arm, but the neuronal response was not so great as when vision was available. Thus, proprioceptive information alone was enough to influence the visual receptive field response of bimodal neurons. These neurons were also influenced by the sight of the fake (stuffed) arm. The visual RF moved with, and in the same direction as, the fake arm, even when the position of the fake arm did not correspond with the stationary position of the real arm. Further analysis indicated that there was a range of neurons in the premotor area: some influenced primarily by visual information about the monkey's own arm (and sight of the stuffed arm) while others were primarily influenced by proprioceptive input (and therefore not influenced by the stuffed arm). Perhaps the most interesting aspect of this analysis, however, was the discovery of two neurons with what Graziano called an especially intriguing property. The visual receptive field for these neurons moved with the arm, but moved the most when the arm was hidden from view and movement of the visual RF was reduced when the arm was visible.

CT's premotor cortex remained intact following her stroke. Neurons similar to those found in the monkey premotor cortex may be responsible for the improvement in CT's performance when she can see the workspace adjacent to her hand, even though she cannot see the hand directly. Graziano (1999) found two cells for which the visual receptive field for the arm moved even when the arm itself could not be seen. Perhaps the CNS, simply by looking at the surface of the table under which the arm is hidden, receives information regarding the proximity of visual input and arm position. Such cells, if they are indeed similar to those found in the monkey, should be responsive regardless of eye position, however, and it should not matter whether CT is looking directly towards her unseen hand or not, though if CT's proprioceptive map of space is distorted, as we suggest, then it may require hand position and eye fixation to be coincident before accurate calibration of the unseen limb position can take place. This raises a further issue: although the workspace adjacent to the target could be seen in the VP condition, this does not necessarily mean that CT was actually looking at that area. To address this issue (of being able to see the area of workspace adjacent to the target and of actually looking at that area) we will manipulate CT's point of fixation in the VP condition in the next experiment .

CT's performance in the VP(delay) condition was almost identical to that in the basic VP condition. This once again demonstrates that vision of the moving hand is not necessary for accurate performance on this task. Goodale et al. (1994) assert that the dorsal action system operates in real time and, as such, does not possess mechanisms capable of storing visuomotor coordinates for more than a few milliseconds. Rather, motor plans are computed de novo, as and when needed. CT was able to accurately plan movements in the VP(delay) condition, even though vision of the reaching hand and workspace were removed before the 'Go' signal sounded. If her reach was planned afresh after hearing the signal to move and the loss of vision, using only the proprioceptive information available to her, CT's reaches should have been more hypometric than they were. That they were not suggests one of two possibilities. Either CT was constantly updating her motor plan in anticipation of the 'Go' signal and the delay between loss of vision and that signal was so short that the motor plan was still 'live' and available for movement execution, or she used a visual trace of where she had identified the target to be and guided her reach from memory. Although the board occluding vision of the target hand was featureless, painted surfaces still have a certain texture and visual information such as gaze angle and vergence would still have been available for memory-guided movement planning. The use of vision in this way is important as it raises the possibility that although the target could not be seen directly, CT was still using visual information in order to guide her reach and, as a result, a certain amount of within-modality planning may have taken place. Access to within-modality visual cues for movement planning will be discussed further in the next section.

7.7 Experiment 7: The importance of concomitant gaze angle information.

We suggested after the previous Experiment that localization of the unseen target finger may have been improved in the VP condition because CT was able to view the area of workspace adjacent to the target hand in relation to the initial position of the reaching hand. It was not known in any of the previous experiments, however, whether the subject was indeed looking towards the felt position of the hand or not. In order to test whether it was necessary for CT to look towards her unseen hand directly we retested CT on another variation of the VP condition of the existing proprioceptive pointing paradigm. In this variation we manipulated whether CT looked directly at where she felt her target hand to be, or at a fixation point which did not coincide with any of the target locations. We also tested the conclusions of the previous experiments, that CT needed to see the target area in relation to the static reaching hand by occluding vision of the initial hand position on a subset of trials.

7.7.1 Case CT

CT was tested on the same day as Experiments 5 and 6 and there was no change in her clinical condition. Throughout the following analysis and discussion CT's right limb will be referred to as her impaired limb.

7.7.2 Procedure

The target positions were identical to those previously described in Experiments 4-6. The procedure was identical to that adopted in previous VP conditions with two exceptions, firstly that subjects were instructed where to fixate and secondly, a narrow matt black board was placed across the workspace at shoulder height to occlude vision of the initial position of the reaching hand on a subset of trials. In all there were three conditions:

i. VP/target in which the subject was instructed to look at the table top in the position where she felt her unseen target finger to be;

ii. VP/centre in which the subject was instructed to fixate a small peg placed along her midline and 10 cm beyond the farthest target throughout the entire block.

iii VP/centre-hand which was identical to VP/centre except that vision of the initial hand position was occluded. The subject was not allowed to look at her hand in its initial start position between trials.

7.7.3 Results

Data for each dependent measure were entered in a 1 x 3 ANOVA with the single factor CONDITION (VP/target vs. VP/centre vs. VP/centre-hand). Planned comparisons (VP/target vs. VP/centre; VP/target vs. VP/centre-hand; VP/centre and VP/centre-hand) between means were also conducted in order to assess the effects of visual cues on accuracy.

Direction Error

Analysis of CT's direction error scores did not reveal a significant main effect of CONDITION ($F_{[1]} = 2.4$, $p > 0.1$). Planned comparisons, however, revealed that although there was not a significant difference between VP/target and VP/centre trials or between VP/target and VP/centre-hand trials, there was a significant difference between VP/centre

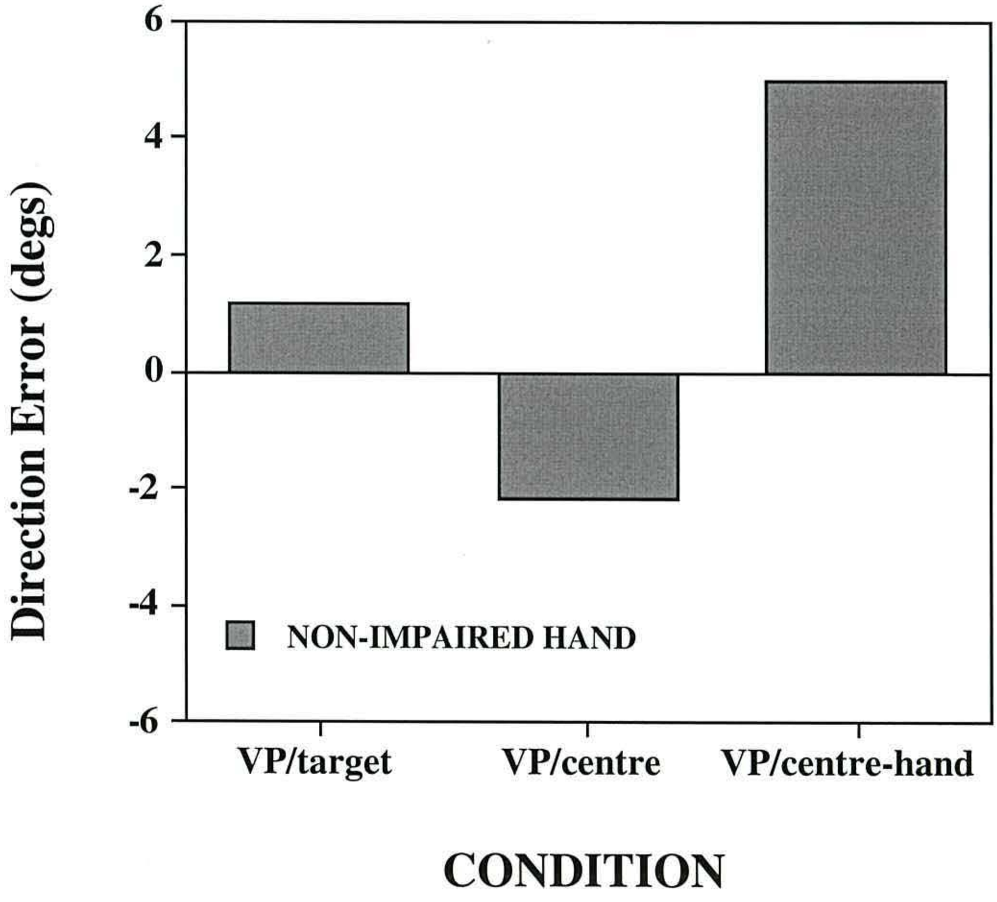

Figure 7.7.1: Mean direction error scores for Patient CT reaching with her non-impaired hand.

and VP/centre-hand trials - the former veering clockwise and the latter anti-clockwise. Relevant means are given in Figure 7.7.1.

Amplitude Error

Analysis of CT's amplitude errors revealed a significant main effect of CONDITION ($F_{[2,62]} = 18.0$, $p < 0.0001$). Planned comparisons revealed that VP/centre reaches were more hypometric than VP/target reaches ($F_{[1]} = 12.0$, $p = 0.001$) and that VP/centre-hand reaches were more hypometric than both VP/target ($F_{[1]} = 35.8$, $p < 0.0001$) and VP/centre ($F_{[1]} = 6.3$, $p < 0.05$) reaches. Relevant means are given in Figure 7.7.2.

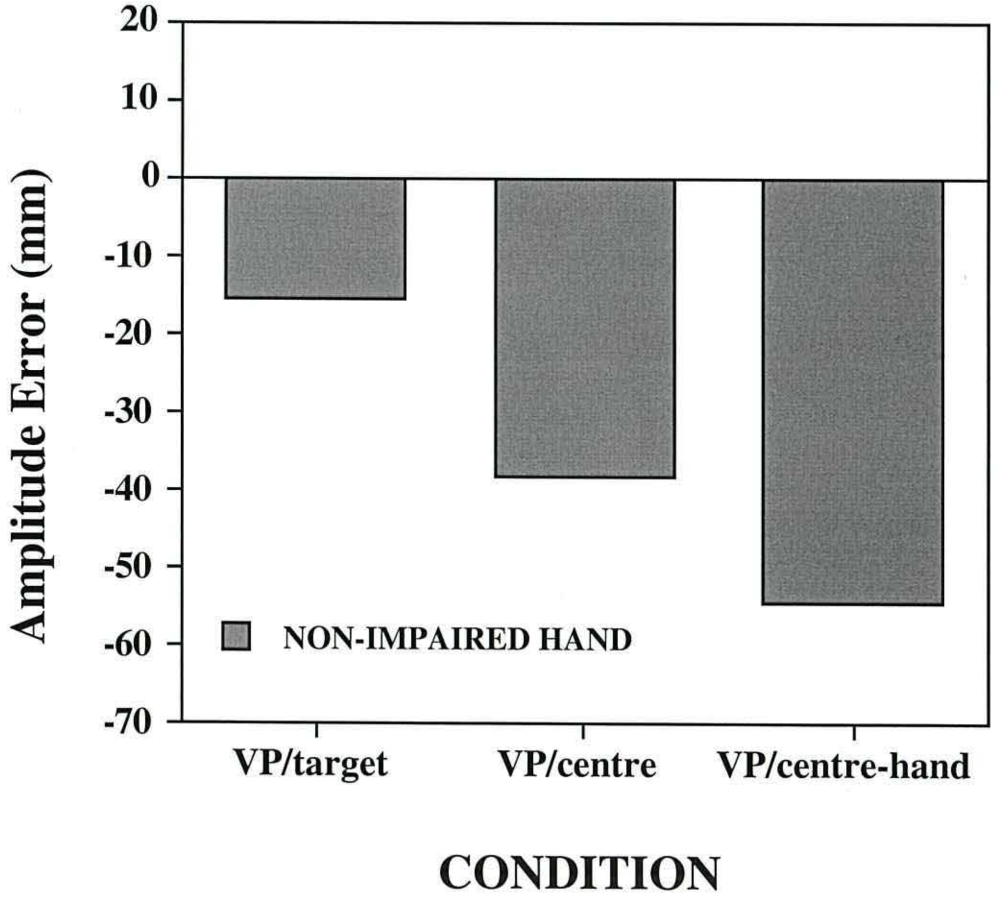

Figure 7.7.2: Mean amplitude error scores for Patient CT reaching with her non-impaired hand.

7.7.4 Discussion

The results of Experiment 7 appear to support the supposition made in Experiment 6, that, for CT, looking at the area of workspace immediately above the target finger improves the proprioceptive localization of that finger. When CT was required to foveate away from the workspace adjacent to her hand (even though it could still be seen in peripheral vision) her performance deteriorated significantly. While performing this task and required to foveate away from the target area CT would occasionally make no movement at all. On these occasions she would shake her head with disappointment and say, "I can't see it, I can't see where my hand is." When asked to explain her comments she would say that when she was not allowed to look towards her hand she only had a vague idea of where it was, but she could not tell exactly where it was. If she was allowed to look towards her hand she said that she could 'see' where was. CT was not delusional and was not under the impression that she could ever actually see her hand through the wooden work surface. It suggests that there is some mechanism by which the concomitance of vision and proprioception not only enhances proprioception, but also tells the CNS when the two are in the same place, even though information from the two modalities are separated by a physical barrier. Perhaps, as discussed in the previous experiment, there is an enhancement of firing in bimodal cells for stimuli occuring in areas for which the visual and tactile receptive fields are in close proximity. The stimulus in the current experiment could be either proprioceptive (the sensation of the finger tip on the target location) or visual (a particular area of foveated workspace). The question arises, however, of how does CT know where to look in order that her vision and proprioception might coincide? If she were to look where she felt her hand to be she would be looking in the wrong place (i.e. too close to her body). As Graziano (1999) pointed out, the types of bimodal cells that have visual receptive fields (RF's) which move with the arm are not restricted to the hand. There are other bimodal cells that appear to have the same properties for the forearm and upper arm. Thus, if CT's initial eye movement is too far towards her own body it might activate the response of bimodal cells with visual/tactile RF's for the upper arm. In this way the CNS might be able to direct the angle of gaze up the arm until the bimodal cells for the hand are activated.

Another explanation for CT's improved performance in the VP condition might be found in the selective attention literature. Proprioceptive orienting has been found to facilitate reaction times in tactile stimulus detection tasks (e.g. Tipper et al., (1998); Pierson et al., (1991); Honoré et al., (1989)). Could orienting the head and eyes towards the unseen hand improve localisation of that hand, perhaps by somehow 'boosting' the somatosensory signals for that hand? It seems unlikely, however, that proprioceptive orienting is sufficient on its own to cause such an improvement in CT's VP performance. CT's head and eye movements were not restricted in two conditions in which proprioceptive orienting was possible, but in which her performance was still very poor. The VP(hand only) condition in experiment 6 and the No-Vis/No-VFB and V-H/No-VFB conditions in experiment 4 all allowed proprioceptive orienting to take place, yet in all cases CT's reaching accuracy was not improved relative to the full VP condition. Thus it seems that vision of the initial hand position as well as vision of the workspace immediately adjacent to the target hand are both necessary conditions for accurate localisation of the unseen impaired target limb, but neither is sufficient on its own.

The VP/centre-hand trials in this experiment also demonstrate, again, that vision of the moving hand does not compensate for not seeing the hand in its initial resting position. These results support earlier suggestions that the hand and workspace must be seen simultaneously during the planning stage of the movement in order to benefit reaching accuracy. This brings us back to the conclusions of Desmurget et al. (1997b). They reported that having an initial view of the hand improved reach accuracy by the visual calibration of the felt position of the reaching hand and not because the hand and target could be seen within the same modality. Although the results presented in this chapter confirm that an initial view of the hand is indeed essential for accurate movement planning, our findings do not necessarily rule out the hypothesis that there is an advantage for within-modality planning. In our experiments both the initial position of the static hand and the target area of workspace can be seen and, furthermore, the area of workspace behind which the target is located can be signalled by gaze angle and vergence information. Thus, both hand and target information are available to the visual system simultaneously and as such reaches may be encoded within the same modality.

Summary and Conclusions

Summary

All of the experiments described in this body of work have been based upon variations of a single paradigm in which subjects were required to point to targets located within the workspace. Within each experiment the targets were always in the same place with the only difference between conditions being the type of sensory information available about those target locations. The initial experiment, using a group of healthy control subjects, resulted in a clear difference in the way reaches were performed between the VV condition, in which visual information about both the reaching hand and the target was available, and the PP condition, in which only proprioceptive information about both the reaching hand and the target (the non-reaching hand) was available. End-point errors were rotated about the target shoulder and the shape of hand paths was radically altered when subjects were forced to rely solely upon proprioception. We interpreted this as evidence for a shift in the frame of reference that was being used to plan reaches under the different visual and proprioceptive conditions. Furthermore, there was also evidence to suggest that vision of the area in which a proprioceptively-defined target was located could serve to improve the proprioceptive localization of that target despite the fact that it could not be seen directly: end-point errors were larger in the PP condition than in the VP condition (in which the reaching hand could be seen, but the proprioceptive target could not as it was occluded by the workspace).

This initial experiment raised the question of how visual and proprioceptive information are integrated when formulating a motor plan which requires the use of both. In order to investigate this further, subsequent chapters were devoted to examination of the same basic proprioceptive pointing paradigm, using patients or healthy normal subjects, in which either the visual or proprioceptive system was disrupted. The first of these experiments studied a small group of individuals suffering from spatial neglect. Reaches executed by all three patients (to identical target positions) were significantly more curved when made to visually-defined targets (VV) than to proprioceptively-defined targets (PP). These findings indicated that, in accordance with recent neuropsychological and anatomical findings, reaches made to proprioceptively-defined and visually-defined targets were being planned within different frames of reference and that abnormal hand paths in neglect must result from an impairment in the visual representation of space used to plan visually-guided reaches. Furthermore, the results revealed that the curvature of reaches to VP targets appeared to be between the extreme curvature of VV reaches and the more normal curvature of PP reaches. Differences in curvature between VV, VP and PP reaches was also observed in normal subjects and we suggested that the sensorimotor integration involved in movement planning entails a weighting of visual and proprioceptive information depending on the goodness of the source.

The finding that a pathological visual disturbance led to abnormal visually-guided reaching, but not abnormal proprioceptively-guided reaching, provided the motivation to examine the effect of optical prisms on reaching behaviour in normal subjects using the same basic paradigm. In the first of two prism chapters we investigated the mechanisms involved in prism adaptation and how they related to the large changes in observed end-point accuracy on our proprioceptive pointing task. The results of this experiment added weight to the idea that there are a number of autonomous spatial maps associated with different body parts and that they can be linked together in various ways depending on task demands. We also suggested that the change in end-point errors was largely dependent upon the weighting given to visual and proprioceptive cues. We argued that a purely proprioceptively-based coordinate system was being used for the conditions in which the subjects were blindfolded and that during the VP conditions the frame of reference was shifted to one which made use of what little visual information was available. Proprioceptive information, we argued, was not discarded in this case, but the weight given to it was reduced. In the VV conditions, when even more visual information was available, the weighting given to proprioception was reduced still further.

In the second prism chapter we investigated the effects of prism adaptation and the adaptation aftereffect on the curvature of reaching movements in normal subjects. We observed that after a short period spent adapting to rightward displacing prisms, healthy subjects exhibited increased hand path curvature during reaches executed under visual guidance, but not during reaches executed to proprioceptively-defined targets without vision. We also demonstrated that the direction of hand path curvature differed whether reaches were executed while wearing prisms or after the prisms had been removed. We noted that this pattern of effects is consistent with the increase in hand path curvature seen during visually-guided movements in patients with neglect. These findings provided support for the view that the origin of some aspects of neglect may lie in the impairment of mechanisms responsible for normal patterns of intersensory coordination.

In the next two chapters we examined the other side of the coin by testing a series of patients whose visual processes were intact, but whose somatosensory processes were impaired. In the first of these chapters we described the performance of three patients, all of whom presented with similar unilateral somatosensory impairments. Although the three patients were neuropsychologically heterogeneous there was a commonality in their performance. All were relatively unimpaired when reaching to visually-defined targets, whether reaching with their affected or unaffected limb. Without any visual cues available, and pointing to proprioceptively-defined targets, the end-point accuracy of all three patients was severely affected consistent with a compressed and/or rotated representation of somatosensory space. Allowing vision of the workspace and the reaching limb clearly improved performance over the no-vision condition in two of the three cases. For each patient we proposed hypotheses as to the underlying basis of their sensorimotor impairment. Overall, it again appeared that the representation of space for each hand was different and that the weighting of vision and proprioception altered the manner of reaching in each condition.

Throughout the various studies both patient groups and the control subjects had shown an improvement in performance on the VP condition compared to performance on the PP condition. In the final chapter we presented the case study of another unilaterally impaired patient who we tested over a number of sessions. Although this patient, CT, was tested many times over a long period, during which her clinical signs improved, she, like all the others, consistently performed better in VP trials compared to PP trials and we sought to determine why this might be. Possible sources of information available to improve VP performance included vision of the static reaching limb prior to movement onset, vision of the moving limb after movement onset and vision of the workspace. We firstly removed vision of the moving limb by asking CT to point to targets with her reaching hand beneath the workspace so that it was occluded in flight. Although her accuracy was not diminished by removing vision of the moving limb we felt that this result may have been clouded by the fact that the proprioceptive target in this case could also be seen. In the next manipulation we systematically varied whether we allowed vision of a) the initial position of the reaching hand, b) the workspace behind which the proprioceptive target was located and c) the reaching hand after movement onset. The results showed that CT required a view of both the reaching hand and the workspace before movement onset in order to reach accurately to a proprioceptively-defined target. Seeing the hand and workspace after movement onset was not enough to compensate for a restricted view during movement planning. However, this conclusion was based on comparisons of reaches in which the workspace and the hand could be seen against reaches in which the workspace but not the hand could be seen. In no condition is there an initial view of the hand, but not the workspace. It was possible that CT required only vision of the hand, not vision of the hand and workspace together, in order to reach accurately and that having vision of the workspace does not significantly improve localization of the unseen target limb. To test this hypothesis we examined CT on a further variation of the VP proprioceptive pointing task in which vision of the initial position of the hand was allowed but a direct view of the workspace was not. CT was impaired on this condition despite the fact that neither proprioceptive nor retinal visual information had changed. We hypothesized that CT needed to be able to see the area of workspace immediately adjacent to her target hand in relation to her reaching hand in order to reach accurately. The final experiment explicitly tested this hypothesis by manipulating CT's gaze and by manipulating peripheral vision of the reaching hand. CT was impaired when she was not allowed to look at where she felt her hand to be and further impaired when vision of the reaching hand was also denied. We suggested that bimodal neurons, similar to those found in the monkey, which fire maximally when visual and tactile fields coincide, might be responsible for

CT's improved proprioceptive localization of the unseen hand when she was able to look at where she felt it to be.

Conclusions

The main general conclusions that can be drawn from these studies are threefold: firstly, that each part of the body has its own representation of space in the brain; secondly, that motor plans are formulated by weighting whatever sensory information is available; and thirdly, that concomitant vision can serve to improve proprioceptive localization of an unseen hand.

The two hands, when placed together as in prayer, are mirror-symmetric, but it is impossible to place them, one on top of the other, so that they lie in exactly the same orientation. Furthermore, if the trunk remains stationary, it is not possible for each hand to reach into all the areas that the other can. In addition, each hand has its own motor and somatosensory cortical areas. It makes intuitive sense, therefore, that each hand might have its own representation of space in the brain. The brain is big and can afford the space. It also makes sense that the legs, trunk, head and eyes also have spatial representations which are distinct from the hands and from each other. The outcome of our proprioceptive pointing paradigm seems to support this idea and evidence from the unilaterally impaired patients with somatosensory loss, in particular, demonstrated this point. Reaches which were identical in all other respects were performed differently depending upon which hand was the target. The representation of space for one hand was distorted, whereas the other was not.

The act of reaching out for something requires that sensory information about ourselves and our environment is integrated so that a motor plan can be formulated and an action executed. Many diverse theories and models have been proposed to account for the way in which this might be done. In a perfect world the CNS will derive all possible sensory information from the hand, shoulder, trunk, neck and eyes in order to formulate a well practised motor plan. The world is rarely perfect, however, and different situations require different motor plans. The CNS must make use of whatever resources it can and put them together in the most efficient way in the time available. Our results suggested that the CNS does this by giving each source of information a different weighting. The neglect and prism studies demonstrated this point clearly. When more weight was given to impaired visual information the end product reaches reflected that impairment more than when less weight was given to visual input and more weight was given to unimpaired proprioceptive input.

It is well known that being able to see the hand can serve to calibrate the felt position of that hand, but what has not been realised until now is that vision could serve to calibrate the felt position of the hand even when it cannot be seen directly. Looking at the felt position of the hand, occluded behind a thin wooden board, improved the accuracy of pointing to that hand in all our subjects, patients and normals alike. We suggested that the concomitance of vision and proprioception not only enhanced proprioception, but also told the CNS when the two were in the same place. This was most aptly demonstrated by a unilaterally impaired patient, CT, who was unable to point to her unseen hand unless she was looking directly at it. Although she could not see the hand, she could see where it was. Thus, it seems that being able to see can improve what we feel, even when what we feel cannot be seen.

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"...unputdownable..."

Roger Newport

"...not exactly Raymond Chandler..."

Prof. Stephen Jackson