Report on Neuropsychology of Visuo-Haptic Integration

- revised version -

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Abstract:

Patients with parietal cortex damage often have markedly impaired proprioception. Here we show that they are unable to match the proprioceptively-determined position of their affected arms with their unaffected arms. Vision of the arm whose position is to be matched greatly improves performance, showing that visual and proprioception can be combined. Even non-informative vision of the workspace improves matching performance.

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1 Executive Summary

Patients with parietal cortical damage are very impaired in matching the position of the affected limb with the unaffected limb when using proprioceptive cues alone. ‘Non-informative’ vision, that is vision of the workspace but not of the arm itself, improved accuracy of limb position matching. Vision of the limb whose position was to be matched improved accuracy. Thus visual information can be integrated with haptic cues to improve proprioception in patients with parietal cortical damage.

2 Introduction

We present two case studies of visuo-proprioceptive-guided arm movements in patients with parietal stroke. In the first case (WW), ‘non informative’ vision (that is, vision of the workspace but not of the limbs) improved position matching based on proprioception. In the second case (SB), visual information was shown to be useful in improving the accuracy of proprioception.

3 Position matching task and the role of non-informative vision

Background: A number of investigators, utilizing matching paradigms; in which participants are required to indicate the position of one hand, without vision, by pointing to it with the opposite hand, have indicated that the precision with which proprioception signals hand position is imperfect, and varies as a function of the location of the target hand in space (van Beers et al 1998). The cross modal modulation of sensory perception, including proprioception, by non-informative sensory input has been described in a number of contexts including: the effect of non-informative vision (NIV) on two point discrimination (Taylor-Clarke et al, 2002), the effect of proprioception on visual extinction (Di Pellegrino and Frassinetti, 2000), and the effect of NIV on reaction time to tactile stimuli (Tipper et al, 1998).

Aim: To quantify proprioceptive impairments using a matching paradigm in a patient with a right parietal lobe stroke, and to investigate the effects of non-informative visual input on proprioceptive acuity.

Patient details: patient WW had suffered a right parietal lobe stroke causing marked left-sided haptic perceptual loss, but no visual impairment.

Method: the patient was seated at a raised table under which his arms could be freely moved. On the underside of the table were affixed six targets and one start position, with which the patient’s midline was aligned (see figure 1, left panel). The distance of each target from the start position was such that each could easily be contacted without movement of the torso. Visual feedback of the movements of the proximal part of the impaired arm was prevented by a screen next to and above the impaired shoulder joint. A start position was marked on top of the table; aligned with the start position beneath the table on which the non-impaired index finger was positioned at the start of each trial, no other visual target cues were available on the table top. The position of both index fingers was tracked using an infrared motion tracking system (*Qualysis Proreflex)*. Reflective markers were attached to the centre of the nail on the dorsal aspects of left and right index fingers. Cameras were positioned above and below the table to track the movement of both arms. Movement was sampled at a rate of 200Hz.

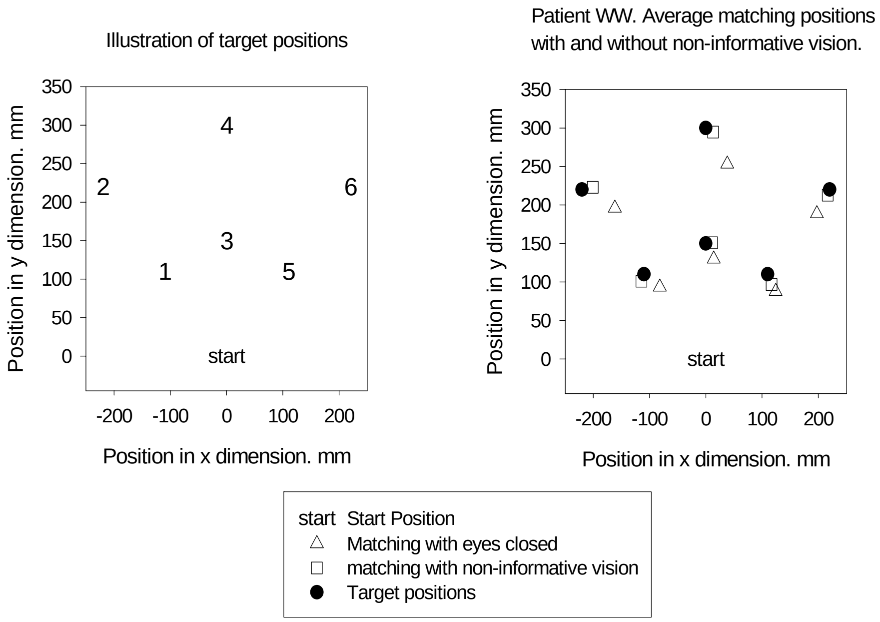

Figure 1. Proprioceptive matching with and without non-informative vision. The figure to the left illustrates the six target positions together with the start position. The figure to the right shows the average matching positions when patient WW attempted to place his non-impaired hand at the target location at which his impaired hand was being held.

On each trail the patient's impaired arm was moved by the experimenter to one of the target positions, whereupon the patient was instructed to place the index finger of their non-impaired arm at the felt location of the impaired arm using a single movement. This was done under two conditions; a no vision condition, in which the patient kept his eyes closed and a non-informative vision condition in which vision of the table surface above the impaired hand was allowed. Vision in this condition did not provide any information regarding target position. 16 trials per condition per target were performed.

Results: Figure 1 (right panel) shows that with NIV patient WW was able to more accurately indicate the position of his unseen impaired arm. When the straight line distance between the actual target position and matching positions for the two conditions was analyzed using a 2 way ANOVA (Target, Visual condition) a significant effect for both target (F=(5, 180) 12.40 $P < .001$) and NIV (F=(1,180) 97.14 $P < .001$) was revealed. Figure 2 shows the errors for each target. Figure 2a illustrates matching error for the two conditions. However, when each matching position was defined in terms of its direction and extent relative to the start position, no effect of NIV on direction was found (F=(1,190) .412 P = .522) while movement extent was significantly larger in the NIV condition (F=(1,190) 7.332 $P <.005$). Figure 2b illustrates directional errors while Figure 2c illustrates amplitude errors.

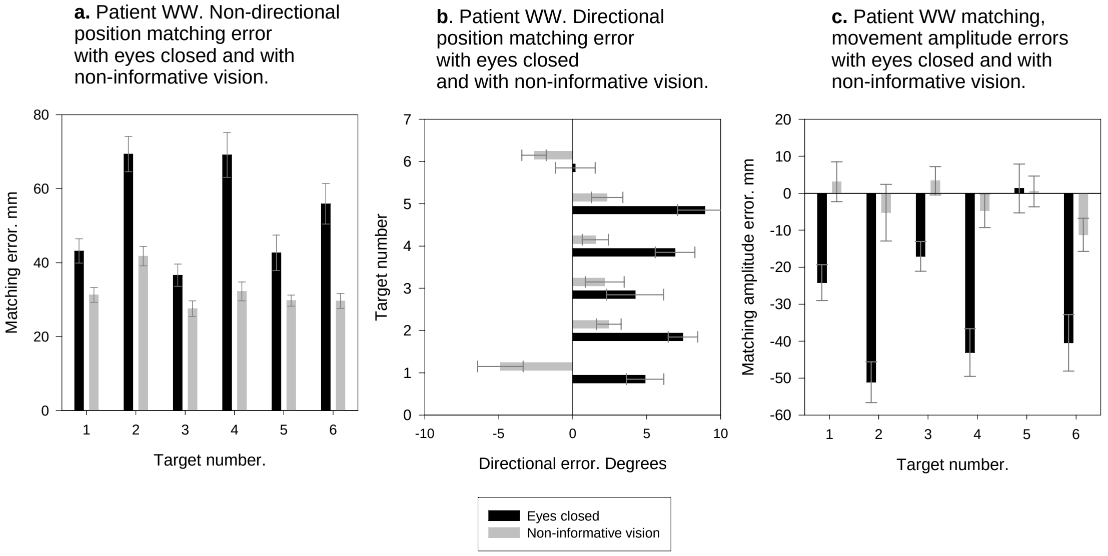

Figure 2. Magnitude of errors made by WW for each target position

When Patient WW reached to match the position of his unseen impaired hand he was significantly more accurate with non-informative vision of the surface below which his impaired hand was positioned (P < .001) (Figure 2a). When matching movements were decomposed into direction and extent, no effect on directional error was found (P = .522) (figure 2b, negative error indicates average matching directions were to the left of each target while positive error indicates directions to the right). In contrast, movement extent was significantly larger in the NIV condition (figure 2c, negative error indicates under reaching, while positive error indicates overreaching) (P <.005).

Conclusion: Non-informative vision can improve proprioceptive acuity following parietal stroke. In the case of patient WW improvement can be attributed to an increase in the amplitude of movements made by the non-impaired hand to match position of the non-impaired hand, while movement direction was unaffected.

4 Proprioceptive localization and visual/ proprioceptive integration

Introduction

Proprioception is the process by which the central nervous system [CNS] derives a percept of body orientation and motion, which is not dependent on visual or other sensory input. Intramuscular receptors, particularly muscle spindles, provide the CNS with the neural signals relating to muscle length and its rate of change, on which this sense is based; although joint and cutaneous afferents have also been implicated at least with regard to movement of the fingers. Normal movements are characterized by complex sequences of muscle length change and joint rotation, typically involving multiple joints. In these circumstances, information from multiple sources must be integrated within the CNS to provide an overall sense of limb position. The coordinate system in which arm/hand position is coded has been the subject of much debate. While some have suggested a intrinsic, proprioceptive coordinate system centered on the shoulder joint (Helms Tillery, et al, 1991), others have posited that hand position, derived from proprioceptive input, may be transformed into an extrinsic, spatial reference frame, similar to that suggested for the visual modality (Baud-Bovy and Viviani, 1998),

The ability to localize the hand in space, using proprioceptive cues, has been studied using matching paradigms. Typically, a participant’s arm is passively moved so that the index finger can be used to define a location in space without vision. Subsequent reaching movements, made by the location-defining arm, after it has been returned to a start point, or by the opposite arm, are made to match the proprioceptivly defined location. Reaching to positions in space encoded proprioceptively in this way has been compared with reaching to visually encoded targets and to targets encoded simultaneously by proprioception and vision. The performance of neurologically normal participants making repeated attempts to localize targets using the methods described above, have, in most instances, been quantified in two ways. Constant errors represent the distance between a target and the average movement endpoint, while variable errors refer to the spread of movement endpoints around the mean constant error. While constant errors are thought to represent the spatial biases associated with modality specific target coding (Haggard et al, 2000), variable errors have been used as a metric for localization precision (Van Beers, 1996).

Haggard et al (2000) investigated variable and constant errors using a matching paradigm, where participants were asked to reach towards nine targets arranged symmetrically across a planar surface in front of them. Reaching movements were made below the table, while target position was defined either by vision, proprioception (the participants non-reaching hand was placed on each target location without vision), or both vision and proprioception (the participants non-reaching hand was placed and simultaneously seen at each target location). Variable error was largest when targets were defined by proprioception only, while localization was most precise for targets defined simultaneously by proprioception and vision. Furthermore, in a similar paradigm, Van Beers et al (1996) demonstrated that the observed reduction in variability during bimodal visual-proprioceptive matching is of a larger magnitude than would be predicted by combining the observed variable errors associated with unimodal visual and proprioceptive performance. They propose that this results from an integration of vision and proprioception to allow more precise mapping of targets in space.

In common with the magnitude of variable error, the direction in which variability is largest, for a given end-point distribution is also influenced by the modalities used to code target location (Van Beers et al, 1998). Van Beers et al (1998) asked subjects to reach to targets defined either by vision or proprioception, ellipses were constructed to characterize movement end point distributions. Taking the shoulder joint of the arm defining target location as the origin, proprioceptive matching was most precise in the radial direction and most variable in the azimuth. Taking a cyclopean eye as the visual origin, the opposite was true for targets encoded by vision. Moreover, for proprioceptive matching, targets closer to the subject were localized more accurately with greater precision than more distant ones.

Distributions of constant error, associated with visual, proprioceptive and visual-proprioceptive position matching, have been described by Haggard et al, (2000). During visual matching subjects tended to overreach each target. The magnitude of over reaching was greatest for targets closest to the midline. Alternatively, for proprioceptively defined targets, constant errors were bias towards the direction of the shoulder of the arm defining each position, and were rotated around the midline. This rotation was in an anticlockwise direction for targets defined by the left hand and in a clockwise direction for the right hand. The symmetrical pattern of constant errors, when matching locations defined by the left compared with the right hand, as distinct from visual matching errors is a finding that has been replicated extensively (e.g., van Beers et al, 1998). These findings have been used to support the idea of a coordinate system, centered on the shoulder joint being used to represent arm/hand position in space (Haggard et al, 2000). This assertion is supported by the observation that in circumstances where subjects are required to indicate the remembered spatial location of their hand, when its position is coded proprioceptivly; accuracy was reduced when they were forced to match its location using vision (Helms Tillery et al, 1991; 1994). According to the authors, the decrement in performance could be accounted for by the assumption that the location of the hand was not transformed into an extrinsic spatial frame of reference, but instead remained intrinsic and limb based. Conversely, Baud-Bovy and Viviani, (1998) observed comparable, constant and variable errors when the remembered, proprioceptivly coded, location of the right hand was matched with the left or right hands; the absence of idiosyncratic constant errors for left and right limb matching, being claimed as evidence for a common extrinsic coordinate system. It is important to not however that the magnitude of constant errors was larger in this study, 76-156mm, compared with Haggard et al, (2000) in which errors ranged between 5 and 30mm. One explanation, both for the larger error constant errors and the absence of left right bias seen in Baud-Bovy and Viviani (1998) is the fact that participants reached towards remembered spatial locations, while in Haggard et al, (2000), targets were coded by online input. Therefore, it may be possible for arm/hand location to be encoded in either intrinsic or extrinsic coordinate systems, with the former giving rise to more accurate representations.

Given that when online input is used to reach towards visual or proprioceptive targets, different patterns of constant error are observed, the question has arisen as to how the nervous system integrates, and so resolves this disparity when both vision and proprioception simultaneously define spatial locations. Van Beers et al (1999), in addressing this question observed that constant errors for reaching movements made to targets defined by vision and proprioception simultaneously, do not as might be expected fall on a straight line between unimodal proprioceptive and visual constant error locations. Instead, combined visual/proprioceptive constant errors result from a direction dependent weighting of unimodal visual and proprioceptive input, the weighting and therefore the constant error position being dependent on the relative precision of the unimodal input. Further support for visual proprioceptive integration based on a precision dependent weighting of unimodal information is provided by Van Beers et al (2002) who used an adaptation paradigm in which discrepancies between the visual and proprioceptive locations of targets presented simultaneously to vision and proprioception were created. Discrepancies were either in the radial direction, where proprioception is most precise, or in the azimuth, where vision shows the greatest precision (Van Beers et al, 1998). The authors predicted that during post adaptation unimodal matching; if visual proprioceptive integration is weighted in relation to the relative unimodal precision of vision and proprioception, adaptation to positional discrepancies should be smallest for the direction in which unimodal precision is greatest. This was indeed shown to be the case, with less adaptation for vision in the azimuth relative to proprioception, while the opposite was true for the radial direction.

In summary, previous research has shown that when normal subjects reach to targets in space, the size and direction of constant errors are dependent upon the modality or modalities used to code a particular target location. The precision of end point distributions, centered on constant error locations, is dependent on the modality or modalities used to define the location; combined visual/proprioceptive endpoints showing the greatest precision. Moreover, the directional precision of unimodal visual and proprioceptive endpoints show roughly opposite distributions, with proprioception being most precise in the radial direction relative to the shoulder joint of the arm used to define the particular location. In addition, evidence exists to support the idea that during visual/proprioceptive integration, unimodal visual and proprioception inputs will be weighted as a function of their relative precision across space. Finally, evidence exists, which supports the notion that hand position can be coded both in shoulder centered intrinsic and extrinsic spatial coordinate systems.

In view of the work outlined above, it is surprising that little can be found in the literature concerning the effects of proprioceptive impairments, as a consequence of CNS lesions, on constant and variable errors during reaching to spatial locations defined by a proprioceptivly impaired arm. Similarly, no studies, so far as we are aware, have examined the performance of such patients while attempting to integrate, presumably noisy, proprioceptive input, with unimpaired vision. Given that up to 50% of the post stroke population are said to exhibit impaired proprioception and somatosensory deficits have been negatively linked with rehabilitation outcome, attempts to elucidate the nature of such impairments, and their interaction with intact modalities seem justified.

The aim of this report is to use a matching paradigm to investigate the performance of a patient with central proprioceptive impairments and normal vision, when asked to localize his impaired arm, without informative vision. Unimodal proprioceptive localization will be compared to unimodal visual and bimodal visual/proprioceptive position matching. In this way, impaired proprioceptive and normal visual performance will be compared, together with performance under conditions were vision and proprioception would normally be integrated (Van Beers et al, 1996). Constant errors in both movement direction and amplitude will be described; together with the variability of movement endpoints centered on constant error locations.

Methods

Subject

Patient SB had left parietal and temporal lesions. Clinical examination revealed relatively preserved motor functions, normal vision, but extensive somatosensory impairments. We were unable to find suitable control participants in the age range of patient SB (84). We therefore selected two controls that were as close to this age as possible, mean age 73. All the controls participants were right handed. All participants gave their informed consent prior to the onset of the investigation.

Procedure

The participants were seated facing a table, raised to allow free movement of their arms beneath it. Six numbered targets were fixed onto the table surface; together with a visual start position on the tabletop and a tactile mark indicating an identical start position below the table. Figure 3 shows the arrangement of targets on the table surface viewed from above. The start position was visible on the table surface, and replicated below the table by a tactile mark. Targets were not replicated below the table surface. Targets T1, 2 and 3 were in the left hemispace, and T3, 4 and 5 were in the right hemispace.

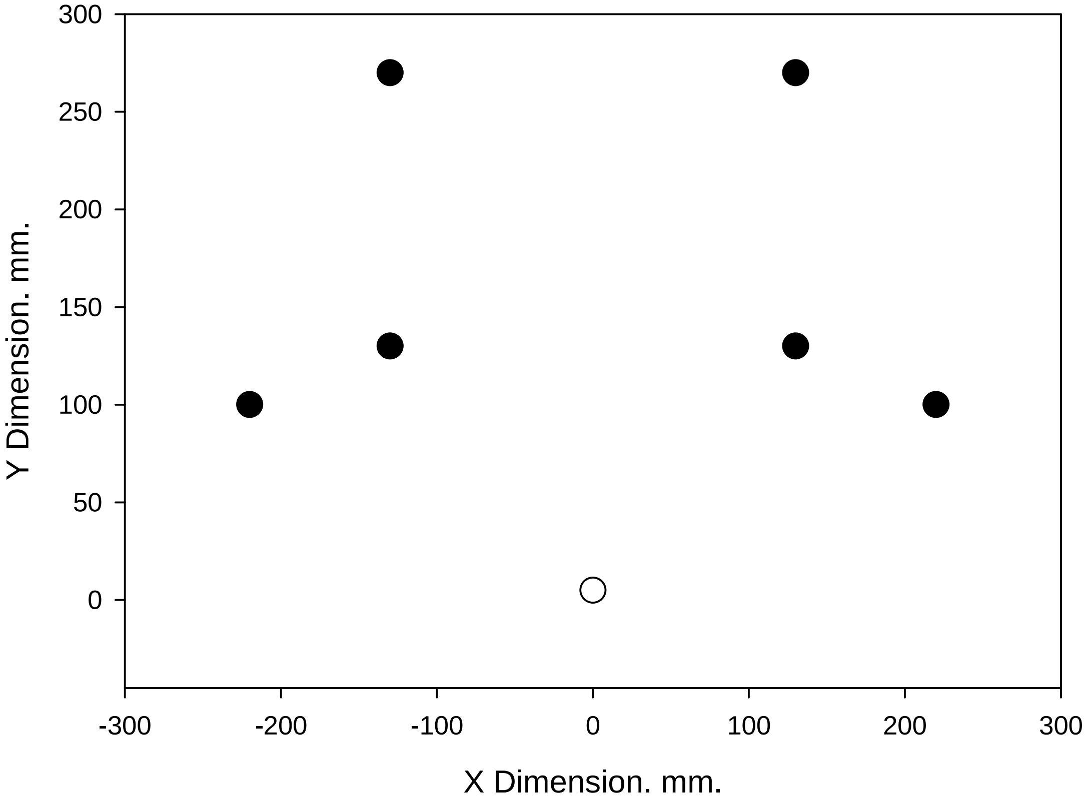

Figure 3 Target positions (filled circles) and start position (empty circle)

The targets were arranged to extend across a large range of space in both hemifields, while still within the reaching limits of both arms. Each trial began with the index finger of the non-impaired hand contacting the start position below the table. The basic procedure on each trial involved participants reaching with one arm below the table, using a single movement, to move the index finger tip from the start position to contact one of the target locations which was being defined by proprioception of the opposite arm positioned on the table top (P), vision (V), or simultaneously by vision proprioception (VP). In the V condition, the experimenter simply called out a target number and the participant was required to reach and contact the underside of the table at a location, which corresponded to the visual target on the table top. Vision of the target was allowed throughout the trial, while vision of the arm below the table was prevented by the table itself, and by a shield, which was positioned above shoulder and extended below their chin. In the P condition, a larger shield extending above both shoulder joints, below the chin and roughly half way across the table surface prevented vision of both arms and target locations. On these trials, the participants were instructed to close their eyes while the experimenter passively moved the arm above the table to place the index finger tip on one of the targets. The participant kept their eyes closed in order to prevent visual cues from the experimenter positioning the arm influencing performance. Once the experimenter had placed the finger accurately, the participant was instructed to keep their finger still by pressing it down onto the table surface, open their eyes, and match its location as for visual trials. VP trials were identical to P trials except that the larger shield used in the P condition was replaced with the shield used in the visual condition, which prevented vision of the non-impaired limb below the table. The key difference in this condition was that vision of the arm positioned at a target location on the table top was allowed, thus providing visual and proprioceptive input to guide the unseen limb below the table to the target location. In the P and VP conditions, the impaired arm defined target locations above the table, and the non-impaired arm matched it below.

Twelve trials for each target in each condition were performed. Although the order of target presentation in each condition was arranged to be unpredictable, while ensuring the same target was not presented consecutively; trials from different conditions could not. This was because the nature of target presentation was self evident from the experimental setup. Therefore, the twelve trials in each condition were split into three blocks of four and presented in the following order: P, V, VP; V, VP, P; VP, P, V, to control for practice effects. Because the participants had viewed the target locations after the second block of trials, it may have been possible on subsequent proprioceptive trials, if for the patients there were large discrepancies between the felt position of the unseen hand and the remembered visual target locations; that they may have ignored the felt proprioceptive positions and instead matched the remembered visual ones. In an attempt to prevent this, all participants were told that some of the target locations used in the proprioceptive condition were different from other conditions (although they were identical), and a show was made of a second set of identical targets, which the participants never saw, being placed on the tabletop prior to proprioceptive trial blocks. Furthermore, it was emphasized that in the proprioceptive condition, attention should be paid to matching the position of the unseen impaired hand and not remembered visual locations.

The locations of the fingertips of each hand were recorded using an optoelectric motion tracking system (*Qualysis)*. Reflective markers were attached to the dorsal aspect of the tip of each index finger and movement was sampled at a rate of 200Hz.

Results

It will be recalled that for two of the control participants the right arm was positioned at each target location in the P and VP conditions. Results from these controls, were compared with those from patient SB who showed a proprioceptive impairment affecting the right arm. This was necessary, given the symmetrical pattern of constant errors observed when the left and right hands are used to encode target locations in the neurologically normal (Haggard et al, 2000).

We analyzed two components of constant error (see figure 4). These were constant movement amplitude error and constant movement directional error. Amplitude error was derived by calculating the straight line distance from x and y coordinates, between the start location and each target, and subtracting this value, for each target, from the straight line distance between the start and endpoints of each matching movement. Thus, twelve amplitude errors were derived for each target. Negative errors, represent under reaching while positive errors represent over reaching. These were then averaged to give the mean amplitude error for each target in each condition. In a similar way, directional errors were derived by calculating the direction of each target relative to the start point in x and y coordinates, and transforming the Cartesian coordinates into degrees. The edge of the planar reaching surface closest to the start point and to the extreme right was defined as 0 degrees, while the extreme left was defined as 180 degrees, see figure 4. The direction of each matching movement to each target was subtracted from the actual direction. In this way, negative directional errors indicated movements made to the right of the actual target direction, while positive errors were to the left. As for amplitude errors, mean directional errors were calculated for each target, in each condition.

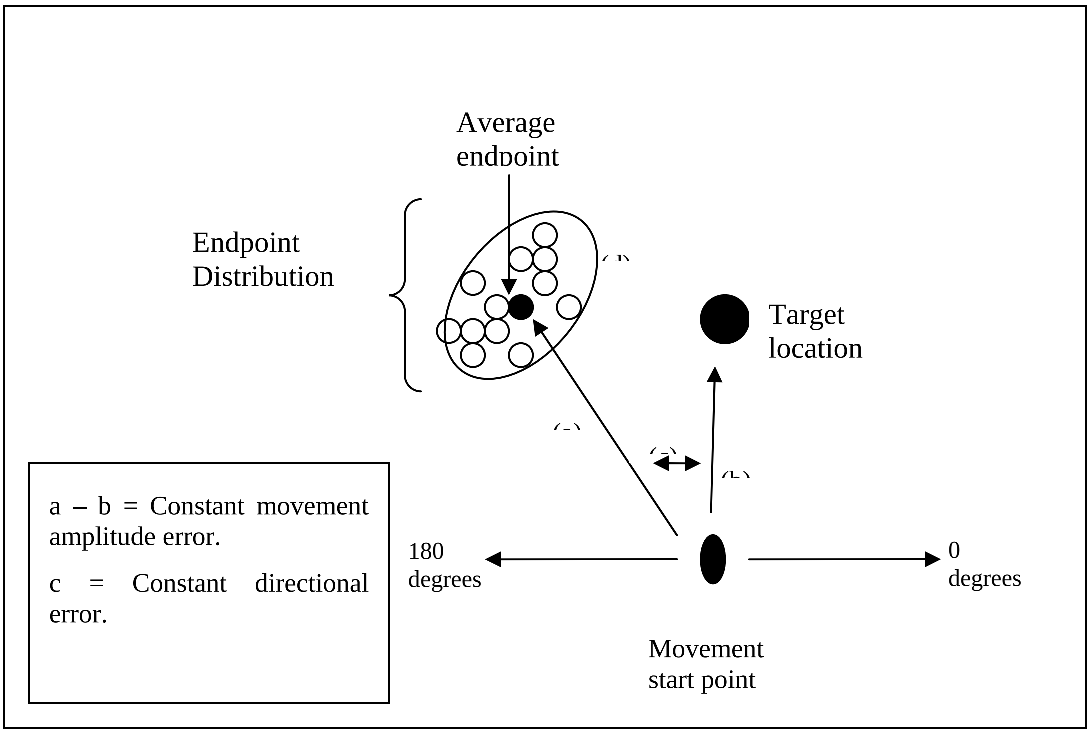

Figure 4. Schematic to illustrate constant and variable errors used to quantify matching performance.

A combined analysis of amplitude and directional errors was undertaken using multivariate analysis of variance (MANOVA). Factors were condition (V, P, and VP), target (1 to 6) and participant (Patient vs controls). This was followed by analyses using univariate ANOVA where significant MANOVA effects were revealed.

When the coordinates of patient SB's matching movements were plotted for the three conditions, it was seen that he made large errors in the P condition, Figure 5. This was true both in comparison to his own performance in the V and VP conditions, and compared with control data Figure 6. When performance was decomposed into amplitude and direction components as described above Figure 7, it can be seen that errors for SB can largely be attributed to directional errors, for which SB was bias in judging the location of his impaired hand to the right of its actual location. Controls' data are shown in Figure 8. All multivariate tests revealed significant main effects for condition ($P < 0.001$), target ($P<0.01$) and participant ($P < 0.001$), together with significant interactions between condition and participant ($P < .005$), and condition and target ($P < 0.01$). To discriminate between directional and amplitude errors, ANOVA's were performed, with factors identical to the MANOVA analysis. For directional errors, a significant main effect for participant ($F (1, 18) = 131.07$; $P < 0.001$) was found, indicating that Patient SB's performance was significantly different from that of controls. Furthermore, significant effects were found for both condition ($F (2, 18) = 67.84$; $P< 0.001$), and target ($F (5, 18) = 8.04$; $P < 0.001$). Importantly, a significant interaction between condition and participant ($F (2, 18) = 27.64$; $P <0.001$) was found. This accounts for the observation that Patient SB's directional errors were largely confined to the P condition, Figure 5. Moreover, significant interactions were found between condition and target ($F (5, 18) = 5.73$; $P < 0.01$), target and participant ($F (5, 18) = 5.06$; $P < 0.01$), together with a three way interaction between condition, target and participant ($F (10, 18) = 3.95$; $P < 0.01$). The latter three way interaction is of particular significance, and can be accounted for by the observation that for target 6, SB's directional error had returned to a level that was comparable to that of the control participants Figure 7.

An ANOVA performed for amplitude errors showed no significant main effects or interactions ($P > 0.30$), indicating that although Patient SB showed a large rightward bias in matching movements in the P condition, he was able to match the movement amplitudes used to position his impaired arm at each target.

Summary

SB was able to reach quite accurately to a visual target, but showed large errors in reaching to a proprioceptively defined target. The key condition is the VP one, in which vision of the arm positioned at a target location on the table top was allowed. SB's performance in the VP condition was good, demonstrating that he was able to integrate informative visual and proprioceptive information.

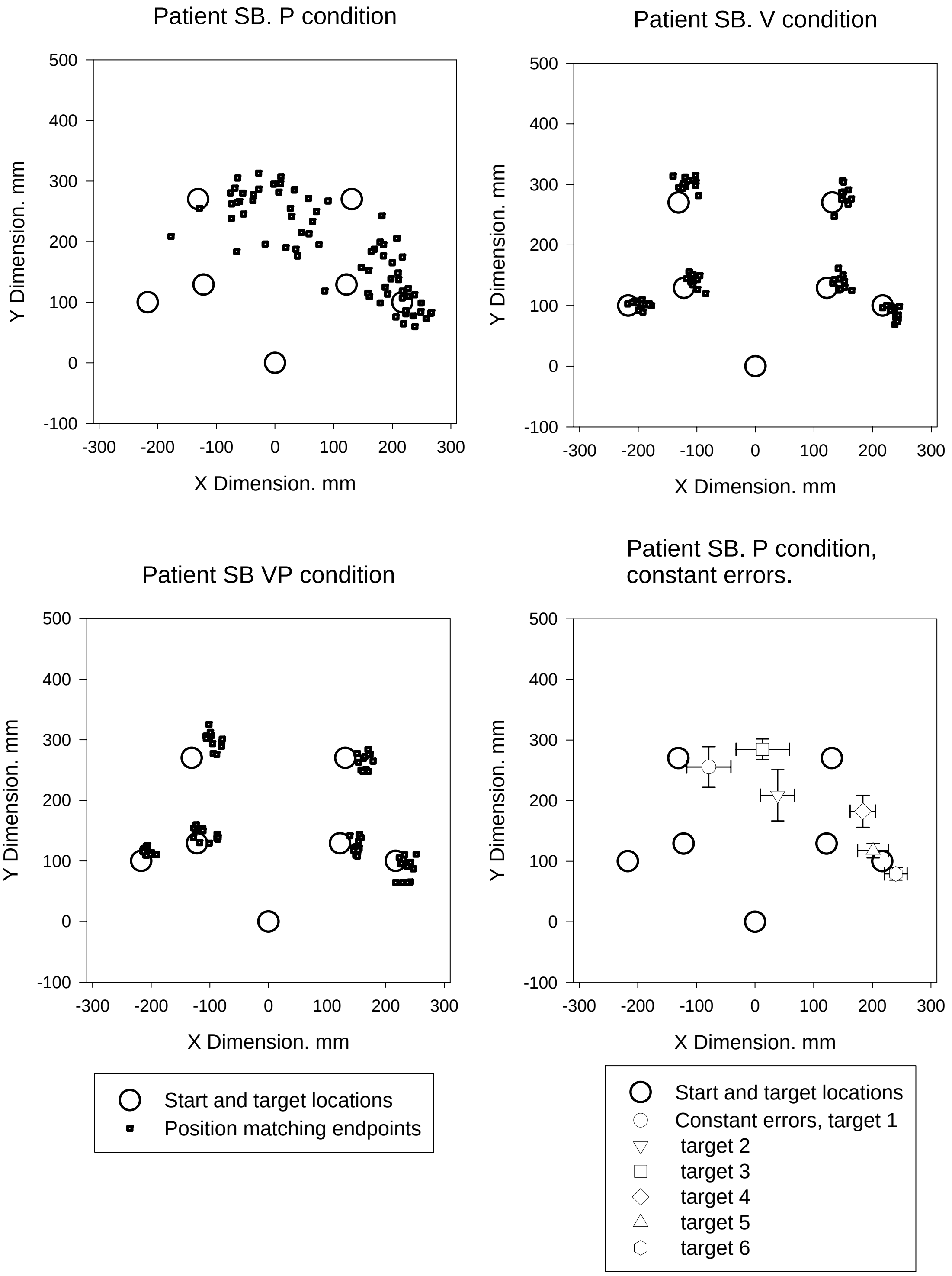

Figure 5 Distribution of errors made by SB in each condition

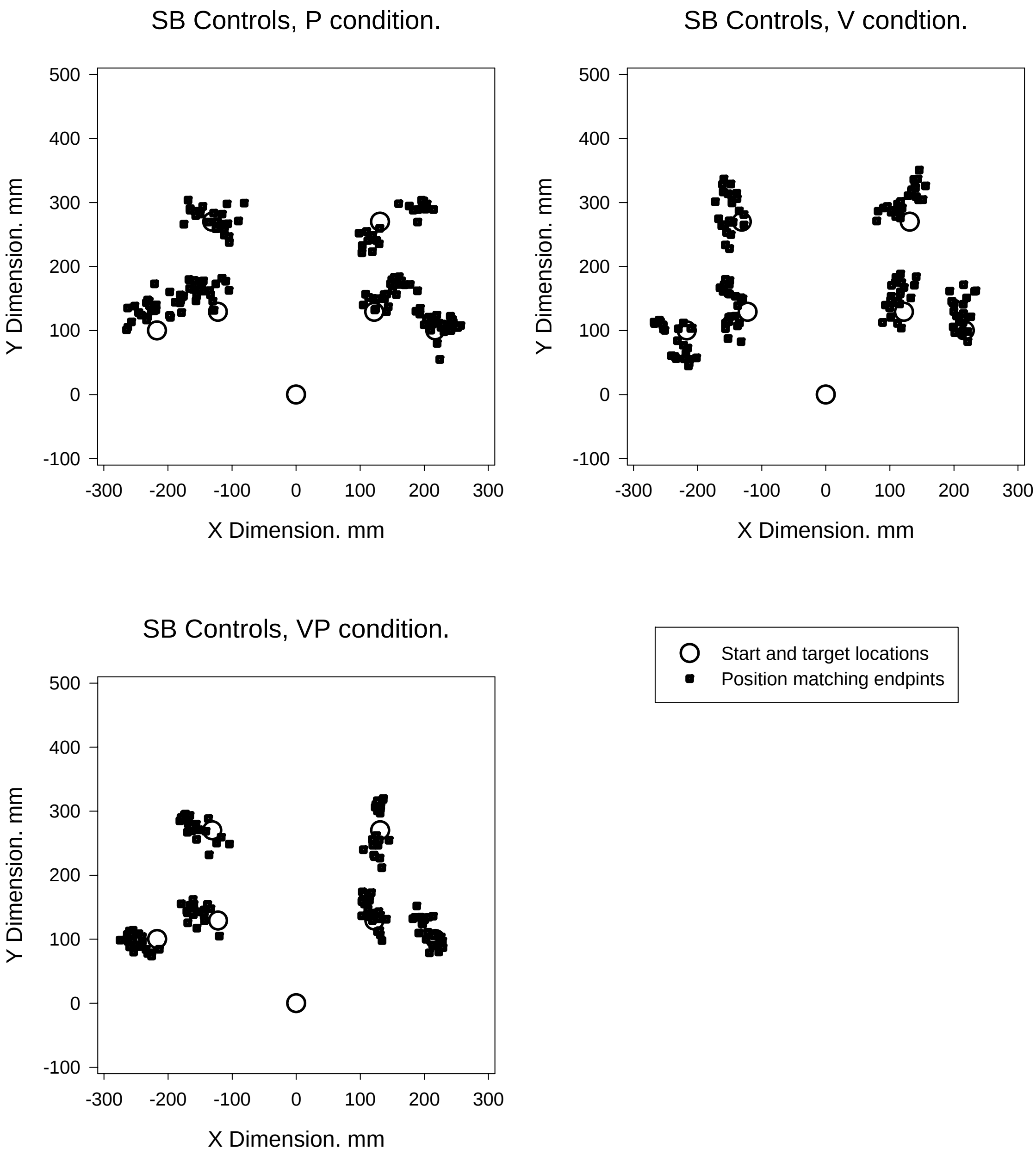

Figure 6 Distribution of errors made by control subjects in each condition

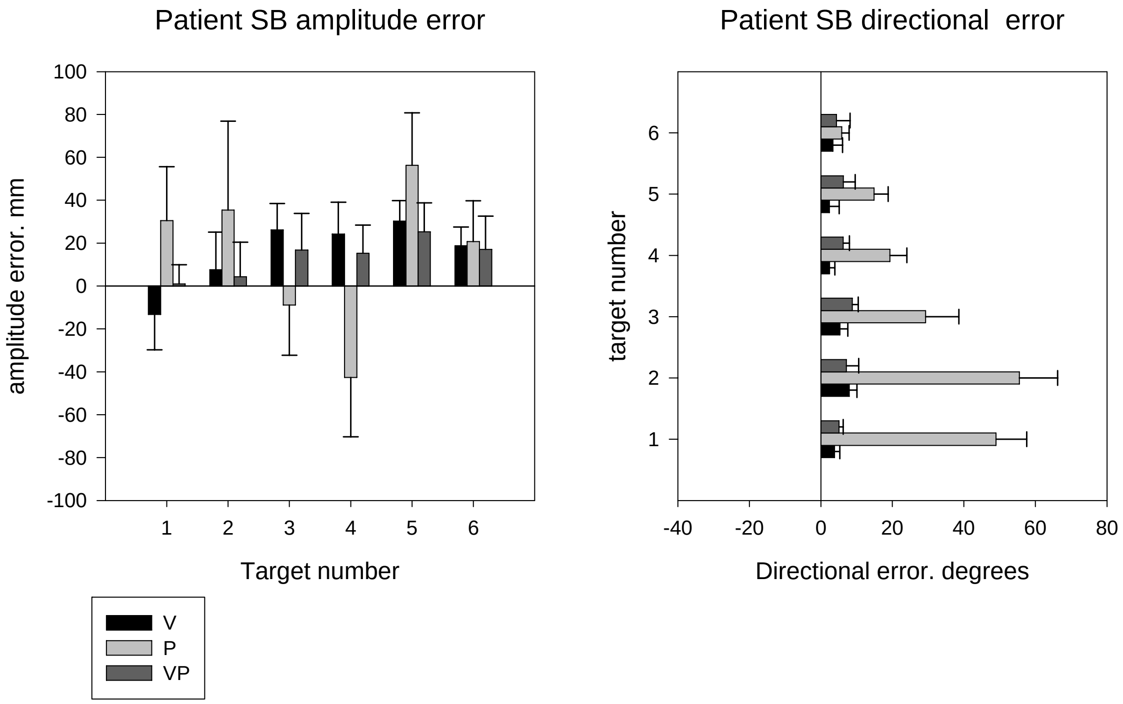

Figure 7 Amplitude and direction errors for SB for each target

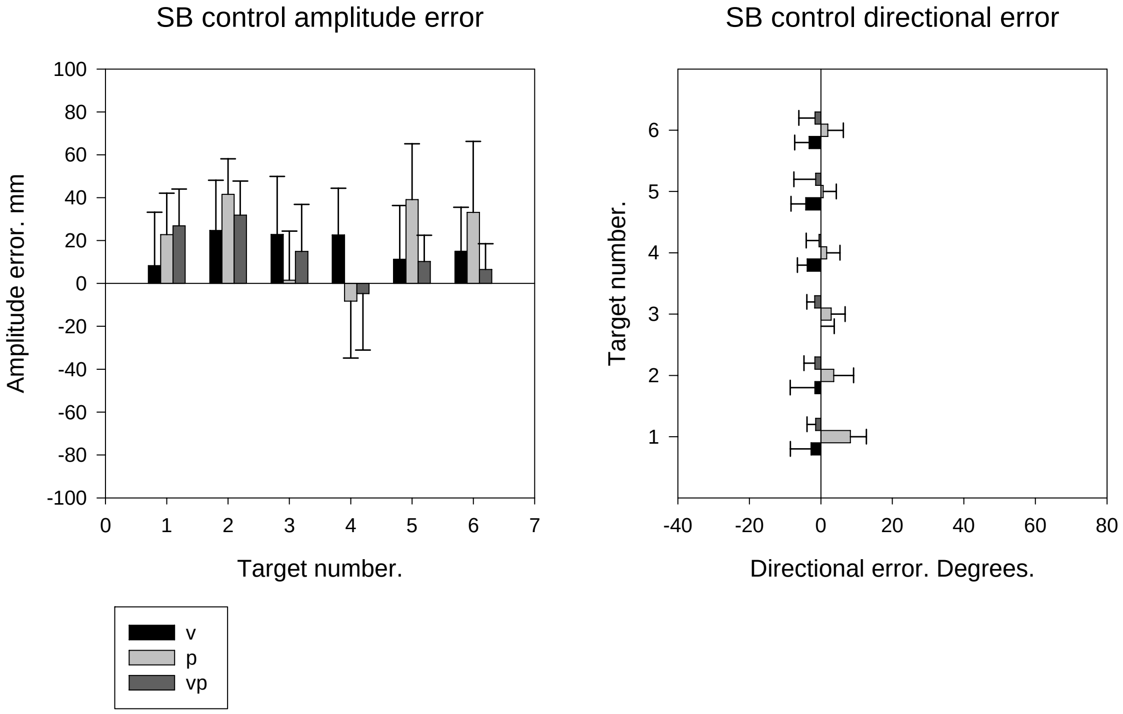

Figure 8 Amplitude and direction errors for control subjcets for each target

5 Conclusions

Multiple sources of information potentially inform us about the position of our body parts in space. The proprioceptive system combines signals from muscle, joint and cutaneous receptors to give neurologically intact subjects a fairly accurate felt position of, for example, the position of the arm. Direct vision of the arm also provides us with an estimate of the arm's position. We combine these two sources of information to generate a unitary percept of the arm's position.

Patients with parietal cortical damage often exhibit proprioceptive impairments that can be quite disabling. We have described a case in whom 'non-informative' vision helped to improve the accuracy of his proprioceptive estimates of arm position. In the second case vision of the arm whose position was to be matched improved the accuracy of matching, thus demonstrating that he could successfully combine visual and proprioceptive information.

It is of interest that even vision of the workspace alone (and not of the arm itself) improves limb position matching accuracy. These findings may have implications for rehabilitation strategies.

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