SPECIAL SECTION

VISUAL AND TACTILE LENGTH MATCHING IN SPATIAL NEGLECT

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Abstract

Previous studies have shown that many patients with spatial neglect underestimate the horizontal extent of leftwardly located shapes (presented on screen or on paper) relative to rightwardly located shapes. This has been used to help explain their leftward biases in line bisection. In the present study we have tested patients with right hemisphere damage, either with or without neglect, on a comparable length matching task, but using 3-dimensional objects. The task was executed first visually without tactile contact, and second through touch without vision. In both sense modalities, we found that patients with neglect, but not those without, tended to underestimate leftward located objects relative to rightward located objects, differing significantly in this regard from healthy subjects. However these lateral biases were not as frequent or as pronounced as in previous studies using 2-D visual shapes. Despite the similar asymmetries in the two sense modalities, we found only a small correlation between them, and clear double dissociations were observed among our patients. We conclude that leftward length underestimation cannot be attributed to any one single cause. First it cannot be entirely due to impairments in the visual pathways, such as hemianopia and/or processing biases, since the disorder is also seen in the tactile modality. At the same time, however, length underestimation phenomena cannot be fully explained as a disruption of a supramodal central size processor, since they can occur in either vision or touch alone. Our data would fit best with a multiple-factor model in which some patients show leftward length underestimation for modality-specific reasons, while others do so due to a more high-level disruption of size judgements.

Key words: tactile, neglect, visual, size perception

Introduction

A number of recent studies have demonstrated that patients with unilateral spatial neglect show a tendency to underestimate the horizontal extent of the leftward of two shapes presented simultaneously side by side, either on a monitor screen (Milner and Harvey, 1995; Irving-Bell et al., 1999; Kerkhoff, 2000), or on paper (Milner et al., 1998). Typically a neglect patient will perceive two horizontal lines or rectangles as of equal length only when the leftward of the two is actually some 10%-15% longer than the one on the right. One way of understanding such leftward length underestimation in neglect patients is to posit a logarithmic distortion of their subjective space, whereby it is progressively more compressed in more leftward parts of space (Milner, 1987). According to this view, the space occupied by a line located to the left would literally appear shorter to a neglect patient than an identical one located on the right. The idea was originally intended as a way of understanding line bisection errors, but equally it could account for the length underestimation data seen in matching tasks.

In an independent approach to the question of perceptual distortion in neglect, Bisiach et al (1996, 2002) used the 'line extension' task (Ishiai et al., 1994), in which patients are asked to add an equal-length line to one they are shown, either by drawing leftwards or rightwards. Their data indicated that neglect patients tended to over-extend the line leftwards, in contrast to right-hemisphere damaged patients without neglect, who tended to show contralesional under-extension. They proposed that in neglect there might be a *progressive contralesional expansion* of the underlying medium representing space in the brain. According to this idea, a horizontal line lying on the left side would be mapped on to an expanded internal template, so that it would need to be made longer than one on the right side in order to be perceived as of equal length. At first sight, this leftward-expansion hypothesis looks to be at odds with the earlier proposal by Milner (1987) of a leftward *compression* of subjective space. However it is essentially just a different way of embodying the same idea – that leftward extents are perceived as shorter than rightward ones. Implicitly, Milner (1987) had suggested that the distortion came about during perceptual length processing within the visual pathway, whereas Bisiach et al. (1996) had located the distortion within the medium of length representation, i.e. at a higher representational level.

How might one decide between these two broad options in understanding the length distortion phenomenon? One way might be to investigate whether object length processed through a *non*-visual sense modality might also be subject to a similar perceptual distortion in neglect patients. If it is, then clearly an explanation like that of Milner (1987) that invokes a dysfunction restricted to the visual processing pathway could not account for the data. Either an analogous distortion would have to be presumed to occur separately within both perceptual systems, or alternatively the distortion could be located at a higher (multimodal or supramodal) representational level, such that it affected all afferent routes to that stage, as implied in the model of Bisiach et al. (1996). To choose between these two accounts, it would help to know whether the distortions observed in the two sense modalities were well intercorrelated across a sample of patients. If they were, then a supramodal disorder would provide the more plausible account. Otherwise separate unimodal disorders would gain in plausibility.

We therefore devised a matching task that could be used either visually (without manual contact) or tactually (with eyes closed), and have tested a number of right-hemisphere damaged patients either with or without neglect. As well as providing information that might help us to understand the locus of the length distortion effect in neglect, a demonstration of tactile length distortion might also provide an indicator as to the role played by visual field defects in determining the visual effect. Recent research indicates that the biases seen both in visual length matching (Ferber and Karnath, 2001) and in the line-extension task (Doricchi and Angelelli, 1999) are strongly associated with posterior lesions and with the presence of visual field defects. The location of the lesions, however, rather than the field defects, might be the primary cause of the perceptual underestimation. This interpretation would be strengthened by the occurrence of tactile length underestimation, which clearly could not be explained by a visual field defect. We have already published a case report of one patient (D.L.) with left-hemisphere damage and rightward neglect (Pritchard et al., 2001), in which we observed a significant rightward length underestimation on both the visual and tactile versions of the present matching task. That coupling, however, is clearly interpretable in many different ways, and the present more broadly-based study is intended to provide more definitive data on tactile length underestimation and its relationship to visual length perception.

Our use of a tactile task to study neglect is not entirely novel. Indeed, much of the pioneering work on tactile neglect was performed by Ennio De Renzi and his colleagues. De Renzi et al. (1970) required unilaterally brain-damaged patients to search for a marble in a four-armed tactile maze. Right brain-damaged patients with hemianopia proved to be least likely to locate contralesional targets within the 90 second time-limit. Since this group also made left-sided omissions on a visually-guided search task, the tactile omissions were interpreted as evidence of tactile neglect, analogous to visual, with both reflecting the same supramodal disorder of spatial awareness. Another study from De Renzi's group, using a different exploratory task, found similar results (Gentilini et al., 1989). However, in the same year, Barbieri and De Renzi (1989) reported tactile neglect in individual left and right brain damaged patients, but no systematic association with visual neglect, leading them to reject their earlier hypothesis of a supramodal impairment. This conclusion was bolstered by a careful multiple single-case analysis of Gentilini et al.'s (1989) data, which revealed that visual and tactile neglect were in fact doubly dissociated amongst the right brain-damaged patients tested (Cubelli et al., 1991). Several subsequent studies have also found double dissociations between visual and tactile neglect (e.g. Vallar et al., 1991; Beschin et al., 1996), arguing against a supramodal spatial impairment in neglect.

All of these studies defined tactile neglect as an ipsilesional bias of spatial exploration under blindfolded conditions. This broad symptom might be better described as "haptic" or "manual exploratory" neglect, since it crucially emphasizes motor factors. [Indeed, blindfold exploratory tasks have been adopted by other authors as direct measures of directional hypometria (Daffner et al., 1990; Liu et al., 1992).] In the present study, however, the focus is on the *perception* of space through touch, rather than on spatial exploration, a distinction emphasized by De Renzi in his celebrated book (1982). Previous studies have attempted to address this issue using tactile rod bisection, but have failed to find any evidence for tactile bisection biases amongst visual neglect patients (Fujii et al., 1991; Hjaltason et al., 1993; McIntosh, 1999; Chokron et al., 2002). This failure may be due to the ease with which simple counting or timing strategies can be applied during manual exploration to solve the rod bisection task. A task designed to prevent such strategies, in which the patient has to locate the centre of a haptically explored circle, has proved more sensitive to rightward biases in neglect (McIntosh 1999; McIntosh et al., 2002b). This result may indicate that there is a spatial distortion in tactile perception analogous to that seen in vision. However, the haptic circle-centring task still involves a manual response, so the contribution of motor biases to the performance of neglect patients cannot be excluded (McIntosh et al., 2002b). In the present study, by contrast, the motor demands for stimulus exploration and response are minimal, and this should allow for a less ambiguous assessment of tactile length perception in neglect patients.

Unfortunately, as the results of the present study well illustrate, even visual size misperception is by no means universal in neglect patients, and this is especially true when 3-dimensional objects are used. We have previously reported this difference in a recent study with somewhat different aims (McIntosh et al., 2002a). The reason why solid objects should elicit less perceptual abnormality in neglect is unclear at the present time. Nonetheless, the aims of the present study could not be achieved without the use of such solid objects.

Materials and Methods

Subjects

Forty-three right brain-damaged subjects, and ten healthy age-matched controls (mean age 68.8, SD 8.8 years) were tested. Twenty-one of the patients were recruited and tested in Milan, whilst the remaining patients and control subjects were tested in the UK. Because the study specifically concerned length distortion effects rather than more generalized aspects of neglect, we used an operational definition of neglect based on line bisection performance. Right brain-damaged patients making a mean rightward bisection error of more than 10% of the line's half-length were included in the neglect group (RBDN+, n = 27; mean age 67.3, SD 9.9; median days post-stroke 39, range 719), while the remaining patients were assigned to the non-neglect group (RBDN–, n = 16; mean age 64.1, SD 10.6; median days post-stroke 60.5, range 870).

Standard Tests

Bisection. Subjects bisected ten black horizontal lines presented individually and centrally on white sheets of A4 paper directly in front of the body midline. For subjects tested in Italy, the lines were each 18 cm long. Those tested in the UK bisected lines of 15 cm. To standardize the scores obtained, bisection errors were expressed as a percentage of stimulus half length.

Line cancellation. Line cancellation performance was tested using arrays based on those described by Albert (1973).

Landmark-V. A modified version of Milner et al.'s (1993) Landmark task, introduced by Bisiach et al. (1998), was administered to each subject (except for one patient in the neglect group). A series of 180-mm long horizontal lines was presented, each made up of two segments, one black and the other red. The segment on the left was 30, 60, 75, 85, 90, 95, 105, 120 or 150 mm long. Each stimulus was presented once per block in a pseudo-random order. Each subject performed twelve blocks of trials. In alternating blocks, the black segment was on the left or was on the right. In the first three and the last three blocks, the subject was asked to name the colour of the longer segment. In the middle six blocks, the subject was asked to name the colour of the shorter segment. Performance was scored in two ways. The perceptual bias index (PB) is the percentage of trials in which the subject indicates that the segment on the left is shorter, or the segment on the right longer. The response bias index (RB) is the percentage of trials in which the subject responds by indicating the segment on the right, regardless of the discrimination asked of them. Full details of the Landmark-V task can be found in Bisiach et al. (1998).

Tactile and Visual Length Matching

In the experimental task, subjects made relative length judgements about the horizontal extent of solid rectangular objects which were either inspected visually, or explored tactually whilst blindfolded. Four rectangular grey plastic objects were used. All objects were 1.0 cm high and 1.0 cm wide, and were fitted with pins to fix them in position on a 30 cm square board made of the same grey plastic. The board was placed directly in front of the subject's body midline. On each trial, two objects were presented, centred 15 cm from the edge of the board on the subject's side and displaced 7.5 cm to the left and right of the midline. For visual discriminations, subjects were allowed unlimited viewing time. For tactile judgements, they were blindfolded and their right index finger placed on a starting position equidistant from the two objects. The objects had to be explored using the index finger only, but they could be explored in any order and as many times as desired. The objects were relatively short (4.0 cm maximum length) making it unlikely that patients would fail to explore their full extent. Any exploratory failure would certainly have been obvious in the tactile task, but was never observed in practice.

On every trial a standard stimulus (4.0 cm in horizontal length) was presented in one of the stimulus positions. Four blocks of 24 trials were performed, with each block preceded by eight initial practice trials. Within each block of trials the standard stimulus was paired with a smaller stimulus on the left (3.5, 3.0, 2.5 cm long) on six occasions, and with a smaller stimulus on the right on six occasions. On the remaining 12 trials identical standard stimuli were presented on both sides of the board ('critical' trials). Stimulus order was randomized within each block of trials. Stimulus modality was blocked in an ABBA design beginning with visual presentation. Within these four blocks, the judgement required ("which is shorter" or "which is longer") was blocked in an AABB design beginning with "shorter" judgements. For each task, the dependent measure was the number of trials with identical stimulus pairings (i.e. critical trials) in which the subject indicated that the leftward stimulus was shorter (or the rightward longer).

Results

Standard Tasks

A summary of the results on bisection, line cancellation and Landmark-V is given in Table 1.

TABLE I

	Controls (n = 10)	RBDN- (n = 16)	RBDN+ (n = 27)
Line bisection	– 1.90	– 2.05	+ 31.14
(% of half length)	(3.28)	(8.89)	(20.91)
Line cancellation	0.00	3.38	14.33
(targets omitted)	(0.00)	(7.58)	(13.34)
Landmark-V	51.00	52.98	62.57*
(perceptual bias)	(3.62)	(8.24)	(11.00)
Landmark-V	50.39	49.59	54.81*
(response bias)	(2.52)	(3.38)	(11.49)
Visual size matching	10.70	12.25	14.81
("Left is smaller" from 24)	(6.33)	(5.13)	(5.94)
Tactile size matching	10.70	12.56	14.63
("Left is smaller" from 24)	(3.80)	(4.87)	(4.95)

Mean scores with standard deviations in brackets for each subject group on each task. *Landmark-V data were missing for one patient in the RBDN+ group.

Since the patient groups were defined in terms of line bisection errors, these data were not analysed statistically. The line cancellation task was performed without omissions by all control subjects and the majority of RBDN- patients, whilst the majority of RBDN+ patients made omissions indicative of left neglect. A Kruskal-Wallis one-way ANOVA found a highly significant effect of subject group [χ^2 (2) = 17.94, $p < 0.001$]. On the Landmark-V task, there was a highly significant effect of group on the PB index [F (2, 51) = 8.34, $p < 0.001$], with the RBDN+ patients differing reliably from the RBDN- patients ($p < 0.01$) and the healthy controls ($p < 0.005$). On the RB measure the three groups did not differ significantly [Kruskal-Wallis one-way ANOVA: χ^2 (2) = 2.60, P = 0.27].

Matching Biases in the Visual and Tactile Tasks

The data on visual and tactile length-matching asymmetries are also presented in Table I, as the mean number of 'left-smaller' judgements made by each group in each stimulus modality on the 24 'critical trials'. A repeated measures ANOVA was performed with modality (visual, tactile) as a within-subjects factor, and subject group (Control, RBDN-, RBDN+) as a between-subjects factor. The main effect of subject group was significant [F (2, 50) = 3.82, $p < 0.05$]. There was no significant effect of modality or significant interaction term. Post-hoc assessment of the subject group effect by Bonferroni t-tests found a reliable difference only for the comparison between the RBDN+ group and healthy controls ($p < 0.05$).

For each group and for each modality of length matching, a one-sample t-test was carried out to assess whether mean group performance differed from chance performance. Significant deviations from chance were seen only in the RBDN+ group, where it was present in both sense modalities [visual task: t (26) = 2.46, $p < 0.05$; tactile task: t (26) = 2.76, $p < 0.05$].

Despite these group effects, only 14 of our 43 patients showed a bias score of 18 or more ($p < 0.05$ on binomial test) on the visual task, and only 12 showed this on the tactile task. Of these patients showing a significant bias, only seven did so on both tasks. Furthermore, two healthy controls showed a similar bias on the visual task, and one on the tactile task, though none showed a significant bias on both. Reflecting further the large individual differences within the groups, five patients and three healthy controls showed a reverse bias on one or both tasks.

Dissociations between Visual and Tactile Length Distortion

A scattergram of visual against tactile length-matching biases for all patients and controls is shown as Figure 1. To detect evidence of dissociated performances between visual and tactile length-matching tasks, single-case analyses were carried out, based on the analytical methods employed by Cubelli et al. (1991).

Abnormal left-sided underestimation on each task was defined as a score exceeding the maximum obtained by any control subject on that task. These cut-offs are shown as broken lines in Figure 1, where it can be seen that four patients (upper right) showed left-sided underestimation in both tasks (three of these patients were members of the RBDN+ group, and one was a RBDN– patient). Seven patients (lower right) showed left-sided underestimation in the visual but not in the tactile task (six RBDN+, one RBDN–), and three patients (upper left) showed left-sided underestimation in the tactile task only (two RBDN+, one RBDN–).

These patterns are suggestive of a double dissociation between length underestimation in the visual and tactile modalities. To address this possibility in a different way, the difference between the scores obtained on the two tasks was computed for each subject. Dissociated performance was identified in any patient with a difference score that exceeded the maximum difference score of healthy controls. Nine such cases were found (shown as triangles in Figure 1). Three of these cases of dissociation had left-sided length underestimation in

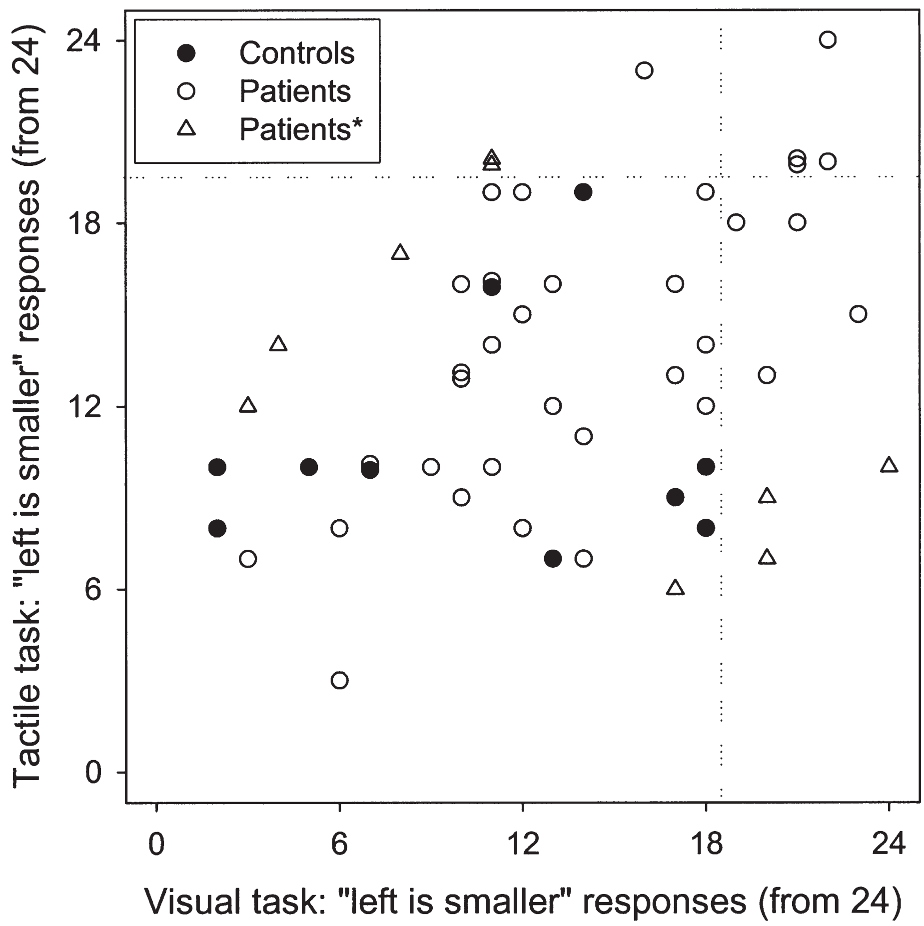

Fig. 1 – *A plot showing the relationship across patients and controls between the lateral biases observed in the visual and tactile size matching tasks. The axes indicate the mean frequency with which either the leftward of two objects is judged smaller or the rightward one is judged larger. Filled symbols represent healthy control subjects, while open symbols represent brain-damaged patients. Open triangles (patients*) represent patients whose difference score between the visual and tactile measures exceeds that of any healthy control.*

the visual but not the tactile task (all were RBDN+), two showed left-sided underestimation in the tactile but not the visual task (one RBDN+, one RBDN-) and one patient (RBDN+) scored within normal limits on the visual task but showed evidence of *right-sided* underestimation on the tactile task. Additionally, three patients (all RBDN+) obtained difference scores indicating a dissociated performance pattern, despite scoring within normal limits on both length-matching tasks. Taken together, these patterns strongly support the view that length distortions in the visual and tactile modalities are doubly dissociable.

Correlational analyses

Because some measures (line bisection, line cancellation and Landmark-V RB) were distributed non-normally, Spearman correlations were computed between all of the tasks used. Since there was no reliable difference between the two RBD patient groups in terms of their length-matching

TABLE II

	Line bisection	Line cancellation	Landmark-V (PB)	Landmark-V (RB)	Visual size matching
Line cancellation	0.52**				
Landmark-V (PB)	0.66**	0.26			
Landmark-V (RB)	0.21	0.29	– 0.12		
Visual size matching	0.39**	0.23	0.24	0.20	
Tactile size matching	0.19	0.01	0.11	0.26	0.31*

Spearman's correlations between the different tasks for the 43 right brain-damaged patients (*p < 0.05; **p < 0.01). Landmark-V data were missing for one patient.

performance, the correlational analyses were conducted across all of the patients tested. The results are presented in Table II. A significant correlation was found between the visual and tactile matching biases ($p < 0.05$), and between the visual matching bias and mean line bisection errors ($p < 0.01$). In addition, line bisection errors correlated well with the line cancellation task ($p < 0.01$) and the Landmark-V PB index ($p < 0.01$).

Discussion

We have found evidence among a group of 27 patients with spatial neglect of a tendency towards length underestimation in both the visual and tactile sense modalities. This extends previous findings in two ways: first by showing that visual effects reported previously with 2-dimensional stimulus presentations (on a screen or on paper) can be replicated when solid objects are used; and second by showing for the first time a comparable length estimation phenomenon in the tactile modality. These conclusions, however, have to be tempered in several ways. Using the binomial test as a criterion, only 11 of our neglect patients showed a statistically significant length underestimation effect in the visual task, and 10 in the tactile task. Several neglect patients showed no bias, or even a tendency to show converse effects, indicating at the very least an instability of performance. As noted in the Introduction, there remains an unexplained reduction in perceptual distortion in neglect patients in the visual modality when 2-dimensional shapes are replaced by 3-dimensional ones. We are currently exploring different possible reasons for this difference. Furthermore, some of our non-neglect patients showed an apparent tendency for neglect-like length underestimation as well. (This finding may have been partly due to the unreliability of our measures, since even some healthy controls showed significantly biased scores, with three showing apparently leftward and three apparently rightward biases). Finally, since our neglect patients were selected, as is usual, by the use of a *visual* test, it is possible that some patients suffering from tactile, but not visual, neglect might have been wrongly placed in the RBDN- group.

We raised in the Introduction the question of whether the leftward length underestimation phenomenon in neglect might have a visual or a higher-level (supramodal) locus. The data seem to suggest both. The neglect group's tendency towards leftward underestimation in the tactile modality presents a phenomenon that cannot possibly be explained either by the presence of visual field defects or by a bias in the visual perceptual system. Either it has to be explained by a supramodal distortion effect or by a separate modality-specific effect within the tactile perceptual system. The possibility of a supramodal distortion, as had been implicitly suggested by Bisiach et al. (1996), is supported by the fact that there was a significant correlation, albeit a small one, between the tactile and visual length biases in our data. But the possibility that a supramodal deficit could be the *sole* cause of length distortions is excluded by the clear suggestion of a double dissociation between visual and tactile biases in the present data. It seems clear that the tactile length underestimation shown by patients with no visual deficit cannot be due to a supramodal disorder, nor indeed one derived from a mutilated visual representation, as proposed by De Renzi and colleagues (1970). In other words, the existence of such patients suggests that 'true tactile neglect' may exist, contrary to the argument of Gentilini et al. (1989). Indeed we cannot exclude the possibility that *all* of the visual and tactile biases we have recorded in our patients are modality-specific. That is, it is conceivable that even where biases are present in both sense modalities, they could be separately determined.

We have sought evidence bearing on this question by looking for an association of unimodal and bimodal length distortion effects with different lesion locations. CT reports were available for 39 of the 43 patients tested, 16 of whom showed statistically significant leftward length underestimation (binomial test) in at least one modality. These relatively small numbers preclude statistical analysis, but we may note two interesting trends in the anatomical data available. First, there was an increased incidence of parietal (63%) and temporal lobe (44%) involvement in those patients showing leftward length distortion, as compared with those not showing it (57% parietal and 30% temporal involvement). Second, this was particularly true among those patients showing *bimodal* leftward length distortion: all six such patients had parietal lobe damage and in four of these cases the temporal lobe was also affected. Of the ten patients with unimodal distortion, the parietal or temporal lobes were affected in only four and three cases respectively. These patterns are difficult to interpret unambiguously, given that the bimodal patients tended to have larger lesions than the unimodal patients. However it would be consistent with the idea that bimodal distortions tend to result from damage at a higher representational level than unimodal distortions. It is possible that in these patients a genuinely supramodal mechanism was disrupted, while in those with damage elsewhere, or with less complete temporo-parietal damage, a disruption of modality-specific mechanisms was more likely to be the cause of their leftward length distortion.

Recent eye-movement data (Dijkerman et al., 2003; Milner and McIntosh, 2002) indicate that the visual length matching bias is multiply determined, and that different patients are likely to show it for different reasons. A failure to compensate for visual field defects may be sufficient for the phenomenon, but neither sensory deficits nor oculomotor abnormalities are necessary factors (see also Harvey et al., 2003). Indeed, we even observed one patient in whom leftward length underestimation was clearly the result of a high-level response bias, based perhaps on an under-valuation of all things contralesional. We suggest that a similar multiplicity of causal mechanisms may provoke tactile as well as visual length misjudgements. Where there is a disorder at the representational level, or a high-level response bias, perceptual judgements would typically be biased in both sense modalities. A disorder at a lower perceptual level might cause a bias restricted to a single sensory modality.

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