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Vertical and bisection bias in active touch

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Abstract. We investigated the conditions that underlie the vertical and bisection illusion in touch, in order to understand the basis of their similarity to visual illusions, and the means of reducing the biases in length perception by active touch. Movement, speed, and spatial reference cues were tested. Movements in scanning L-shapes in ipsilateral and contralateral (across the body midline) table-top space produced significant underestimation of the vertical line with the right hand, but not with the left hand. Right-handed scanning of L-shapes showed no significant bias when the vertical line in the figure was aligned to the body midline, suggesting that spatial cues were involved. The vertical line was overestimated in inverted T-shapes, but underestimated in rotated T-shapes, implicating line bisection. Holding scanning latencies constant reduced the vertical error for inverted T-shapes, but could not explain the bisection bias. Sectioning biases were predicted by the location of junctions on sectioned lines, showing that junction points act as misleading anchor cues for movement extents. The illusion was significantly reduced when reference information was added by instructing subjects to relate two-handed scanning of the figure to an external frame and to body-centred cues. It is argued that disparities in spatial reference (anchor) cues for movement extents are involved in vertical and bisection biases in active touch. The hypothesis that length illusions depend on disparities in spatial reference information can also account for the similarity of the tactile to the visual horizontal – vertical illusion.

1 Introduction

Overestimation of vertical compared to horizontal lines (horizontal – vertical illusion) was first reported in vision and was considered an optical illusion (eg Fick 1852). The illusion has also long been known to occur in active touch (eg Burtt 1917). But neither the basis of the tactual illusion, nor its similarity to the 'optical' illusion is well understood. The vertical bias in touch is most often attributed to radial (to and from the body) movements in scanning vertical lines, compared to tangential movements (along the front or side of the body) for horizontal lines (Cheng 1968; Collani 1979; Day and Wong 1971; Deregowski and Ellis 1972; Heller et al 1997). Two main explanations have been given for the difference. One is that radial movements are slower, and are therefore overestimated compared to tangential movements (Wong 1977). The other one is that radial movements involve the whole arm, and thus depend more on inputs from the shoulder joint, compared to kinaesthetic inputs mainly from the elbow joint (eg Heller et al 1997). However, L-shapes do not always elicit the bias in touch (eg Day and Avery 1970; Hatwell 1960), leading to the suggestion that touch is less susceptible to the length illusion, unless line bisection is involved (Hatwell 1960). But no explanation has yet been put forward why line bisection should produce an illusion in touch. In fact, line bisection does not always produce the tactual illusion either (eg Heller et al 1997). The present experiments were designed to test specific hypotheses that have been proposed to explain the tactual illusion.

Length biases in touch are important for understanding how the modalities function in perception, and for practical reasons. Both L-shapes and T-shapes represent junctions that are found in tactual maps. In order to reduce the errors that such configurations produce, it is necessary to investigate the conditions under which they occur. The informational conditions that underlie the tactual illusion are also important for the wider question of how the modalities relate to each other. There can be no doubt that there are wide differences between the inputs to touch and vision that are specific to the two modalities. How then can the undoubted differences in modality-specific inputs in touch and vision explain the equally undoubted similarities in illusions? The assumption that perception is amodal does not address the inherent paradox. Explanations have tended to concentrate either on input differences, which fail to account for the similarity to vision; or to invoke unspecified cognitive mediation, which does not explain why the illusion is difficult to eliminate. It is not proposed to test these assumptions against each other here. Instead, it is assumed that information can come from a variety of sources, but that these need to be specified in each case. The focus is therefore on the informational conditions that produce or reduce length biases in touch.

It has been suggested that the visual horizontal–vertical illusion involves not only an overestimation of vertical lines, but also a further overestimation of bisecting lines (Finger and Spelt 1947; Harris et al 1974; Künnapas 1955). That may also be the case in touch (Deregowski and Ellis 1972). The tactual illusion thus needs to be investigated with both L-shapes and T-shapes.

Active touch necessarily involves movement. The hypothesis that vertical overestimation depends on radial movements (Cheng 1968; Collani 1979; Day and Wong 1971; Deregowski and Ellis 1972) that involve the whole arm and inputs from shoulder (Heller et al 1997) is thus considered first. The explanation implicating movements of the whole arm and shoulder was based on findings showing significant overestimation of vertical lines in L-shapes when scanning with an elevated elbow, but no bias for very small stimuli, or when the arm was immobilised (Heller et al 1997). However, it is not clear that the explanation can account for all previous findings. It should be noted that all previous reports of vertical overestimation in L-shapes involved scanning with the outstretched arm at shoulder height and/or in conditions that changed the angular planes of presentation (Cheng 1968; Collani 1979; Deregowski and Ellis 1972; Wong 1977), or scanning with the elbow deliberately elevated (Heller et al 1997). Thus, vertical lines in L-shapes were not overestimated in the upright (frontoparallel) spatial plane (Day and Avery 1970). Scanning movements in the frontoparallel plane do not necessarily involve shoulder movements less. It is thus not clear that the movement hypothesis alone can account for the absence of vertical overestimation in that plane, compared with movements in the horizontal plane at shoulder height in which the illusion has been reported. Effects of stimulus size also need to be considered in that respect. The size of stimuli in touch determines not only the extent of scanning movements. Stimulus size also determines how the movements relate to the posture and body-centred cues that can provide current spatial reference anchors (Millar 1994). Spatial reference cues could thus also be involved.

In the first experiment we therefore tested whether movements involving the whole arm and shoulder are sufficient to explain vertical bias in touch. We argued that having to reach across to the opposite side (contralateral hemispace) in order to scan L-shapes involves the shoulder more for the horizontal than for the vertical line, than in scanning the figures on the same (ipsilateral) side. Once the reach across the midline has been accomplished, exploring the vertical line mainly involves the elbow joint, while scanning the horizontal line depends more on inputs from the whole arm and shoulder. Therefore, if the involvement of inputs from the shoulder is the only determinant of vertical overestimation, the overestimation should be reversed. An underestimation (negative vertical error) would thus be predicted. Furthermore, the negative error would be expected for reaching across the midline for both the right and left arm, in contrast to ipsilateral (same side) scanning with either arm. This predicts an effect of the contralateral versus the ipsilateral hemispace for either hand.

We used figures in the range of sizes for which vertical bias has been reported. Normal scanning movements that were comfortable to the subjects were used in all experiments. Subjects were seated at the table on which the figures were presented. The distance at which subjects find it natural and comfortable to explore raised line shapes on the table differs with their height and arm length. In all experiments, the distance of test shapes from the subject's body was therefore adjusted to the distance that was comfortable to the individual subject. The point was to allow the type of scanning of tactile figures with the forefinger that subjects would use naturally in everyday life to explore tactile stimuli.

2 Experiment 1

The hypothesis was that whole-arm and shoulder movements produce the illusion, and thus predicts a negative vertical error. The horizontal line in L-shapes in contralateral space involves the shoulder more in exploratory scanning. The vertical line requires only an initial reach. After that, vertical scanning of the vertical line depends more on elbow-joint movements. Figures placed in ipsilateral space do not involve the shoulder to the same extent for lateral scanning, and should therefore be less likely to elicit the illusion. The left hemispace for the right hand and the right hemispace for the left hand should thus show the illusion, while less or no illusion would be found for the left hand in left hemispace and for the right hand in right hemispace, thus producing an interaction between hands and hemispaces.

2.1 *Method*

2.1.1 *Design.* A factorial Hands (left/right) × Gender × Hemispaces (left/right) × Comparison Lengths (5) × Runs (5) design (repeated measures on the last three factors) was used with a psychophysical adjustment task. Subjects scanned the standard and comparison lines in a shape with the forefinger. The task was to adjust the length of the comparison line by moving the scanning finder along (or beyond) the comparison line to the length subjects deemed equal to the standard line in the stimulus figure.

2.1.2 *Subjects.* Twenty right-handed graduate and undergraduate volunteers were recruited. Right-handed people constitute the majority of the population and have usually been tested in studies of this kind. Handedness was determined by self-description (majority of relevant tasks performed with the right hand). The interest in the present study was not in handedness, but in the relation between reaching and hemispace. Subjects were allocated, on the basis of availability as practicable, to using the right dominant hand (three male, seven female) and to using the left non-dominant hand (six male, four female) for scanning. At the request of a referee, Gender was assessed and reported routinely as a factor in the analyses of all the experiments reported here, but was found to have no significant main effects.

2.1.3 *Materials.* The shapes were highly tangible raised lines, embossed professionally(1) on transparent plastic sheets (25 cm × 30 cm) by machine, or by stylus on a rubber underlay (Sewell Raised Line Drawing Kit). The raised lines were darkened from the reverse side. Highly contrasting green adhesive mats kept them in place on the table. Ruler markings on transparent plastic were used to read off adjustment errors.

Each L-shape consisted of 8 cm vertical standard lines and one of five horizontal comparison lengths (7 cm, 7.5 cm, 8 cm, 8.5 cm, and 9 cm), averaging to 8 cm. Test sheets contained two L-shapes, one in left and one in right hemispace. The left and right figures, respectively, started and ended at 11 cm from the middle of the sheet. The horizontal lines were at 4 cm from the bottom of the test sheet.

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(1) We are greatly indebted to the late Dr Hinton and Mrs R Hinton for valuable help in producing the embossed materials professionally.

2.1.4 *Procedures.* In all experiments, subjects were blindfolded and informed of the task prior to trials. Figures were always presented on the flat (table-top) plane. The subject was seated at the table, at a distance that was comfortable to the individual for scanning with unrestricted body position and movements chosen by the subject. The distance of the test sheet from the subject's body for comfortable scanning without movement restriction varied (from 20 to 30 cm) with subject's arm length.

The experimenter placed the subject's index finger at the start of standard (scanned first) lines of test figures and told him/her the direction in which to move. The appropriate index finger was used to explore the figures without touching the surrounding space. The other hand rested in the subject's lap. Subjects (in all experiments) found it easier to explore the stimuli without fixing their elbows on the table, although they could have done so if they had wished.

The figure on the left of the test sheets was explored first. On completion of the task for the figure on the left, the experimenter guided the subject's index finger to the top of the vertical standard of the figure on the right. The right/left placements of the five standard/comparison L-shapes on test sheets was counterbalanced over 25 trials and subjects.

2.1.5 *Scoring.* Final finger positions on comparison lengths were scored as algebraic (constant) errors in adjusting horizontal comparison lengths to equal the vertical standard. Adjustments which lengthen the horizontal comparison line more than warranted by their actual length relative to the vertical standard indicate vertical overestimation (positive vertical errors). Undershooting errors show that vertical standards are underestimated (negative vertical errors).

2.2 *Results and discussion*

Mean constant errors, showing the points of subjective equality (PSEs) which indicate the presence of the illusion are graphed in figure 1 separately for the right and left hands in left and right hemispaces. Contrary to prediction from the hypothesis, the Hands (left/right) × Gender × Hemispaces (left/right) × Comparison Lengths (5) × Runs (5) ANOVA on constant errors showed no significant interaction between Hands and Hemispaces (ipsilateral/contralateral) ($F > 1$). Instead, Comparison Lengths were highly significant ($F_{4,72} = 44.9$, $p < 0.000$), and interacted significantly with Hands ($F_{4,72} = 5.06$, $p < 0.001$) and with Hemispaces ($F_{4,72} = 2.71$, $p < 0.036$). Neither Gender nor Runs showed significant effects or interactions.

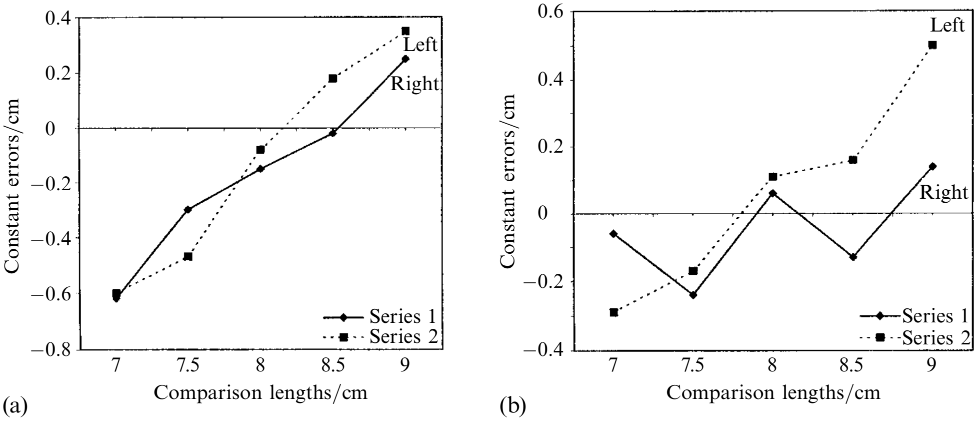

Figure 1. Mean constant (signed) errors in adjusting horizontal comparison lengths to vertical standard lines in L figures, showing interactions of the range of five stimulus lengths (standard 8 cm) with right hemispace (Series 1) and left hemispace (Series 2) locations for the right hand (a), and for the left hand (b).

The interactions found above were analysed further by separate ANOVAs for Hands and Hemispaces. Simple effects showed that Comparison Length was significant for the right hand ($F_{4,36} = 40.97$, $p < 0.000$) in both right and left hemispaces (figure 1a). The left hand ANOVA also showed a significant effect of Comparison Lengths ($F_{4,36} = 12.38$, $p < 0.000$), but this interacted significantly with Hemispaces ($F_{4,36} = 2.88$, $p < 0.036$). Simple effects (figure 1b) on this interaction showed that, for the left hand, Comparison Lengths were significant in left hemispace ($p < 0.000$), but the simple effect of Comparison Lengths was not significant for that hand in right hemispace ($p = 0.09$). Cognate results were found for effects calculated on the basis of hemispaces. Thus, Comparison Lengths were significant for left hemispace for both hands ($F_{4,72} = 31.69$, $p < 0.000$). For right hemispace, Comparison Lengths were significant ($F_{4,72} = 10.1$, $p < 0.000$), but interacted significantly with Hands ($F_{4,72} = 4.49$, $p < 0.003$), showing no significant effect of Comparison Lengths for the left hand in right hemispace. The results on simple effects thus show that the interactions of Hands and Hemispaces with Comparison Lengths in the main ANOVA were due to the left hand in right hemispace.

Stimulus range (context) effects are commonly found with psychophysical methods (Gescheider 1997; Poulton 1979), but differences have not previously been implicated in length illusions in touch. The finding that the left hand was not affected by comparison lengths in right hemispace suggests a possible link with greater involvement of spatial (right hemisphere) processing for the left hand (Heller et al 1993; Kumar 1977; Milner and Taylor 1972).

The PSE, which is the indicator for magnitude of the illusion, did not differ significantly from zero in either hemispace for the left hand, consistent with that interpretation. By contrast, though percentages of error were low (2.13% and 1.63%), the PSE for the right hand was significantly negative for scanning on the same side (−0.17 cm, $t = -3.41$, $p < 0.008$), as well as for scanning on the opposite side (−0.13 cm, $t = -3.60$, $p < 0.006$).

The negative vertical (PSE) bias for right-hand scanning is consistent with predictions for movements involving the whole arm and shoulder more in horizontal scanning (see earlier). But the results are not compatible with the hypothesis that the greater involvement of gross arm movements is the only factor in the illusion. The findings implicate spatial cues. Locating L-shapes to the left or right of the body midline seems to interfere with spatial coding of scanning movements by reference to the body midline, and does so more for the right than for the left hand.

The next experiment was designed to test the spatial hypothesis more directly. The hypothesis that the vertical bias in touch depends on the relation of movements to body-centred reference cues predicts that aligning the vertical line of L-shapes with the body midline eliminates the vertical bias also for right-hand scanning.

3 Experiment 2

The spatial-cue hypothesis predicts that L-shapes produce no significant vertical bias in right-hand scanning, if the vertical line is aligned with the body midline. The L-shape was also compared with an inverted T-shape of the same size and alignment to test for bisection effects.

3.1 *Method*

3.1.1 *Design.* A Shape (L/T) × Gender × Comparison Lengths (5) × Runs (5) design (repeated measures on the last two factors), was used with the adjustment task, as before.

3.1.2 *Subjects.* Twenty right-handed fifth-form volunteers (mean age, 14.0 years) from local secondary schools were allocated randomly to the L-shape (nine female, one male) and to the inverted T-shape (five female, five male) conditions.

3.1.3 *Materials.* The L-shape and the inverted T-shape were produced by precisely the same methods as before. Both shapes had vertical (8 cm) standards and the same five horizontal comparison lengths (averaging to 8 cm), as before. Each test sheet contained one figure. The vertical line in each figure was in the middle of the test sheets, and these were aligned with the subject's body midline.

3.1.4 *Procedures.* All procedures and conditions were the same as before. Only the right index finger was used. To ensure scanning the whole horizontal comparison line in inverted T-shapes, subjects were told to move the finger down, then to the left to the start of the horizontal line, before scanning the horizontal line from left to right. The vertical lines of figures were aligned to the body midline of the subject for each run.

3.2 *Results and discussion*

Mean constant errors together with standard errors are graphed in figure 2. The ANOVA on constant errors showed significant main effects of Shapes, ie L versus T ($F_{1,18} = 36.99$, $p < 0.000$) and of Comparison Lengths ($F_{4,72} = 26.89$, $p < 0.000$). Further analysis of the result showed that the vertical bias was significantly positive for the inverted T-shape (PSE = +0.55 cm, $t_9 = 7.69$, $p < 0.000$ from zero error). Consistent with the prediction, no significant bias was found for the L-shape. The PSE for the L-shape (−0.06 cm) did not differ significantly from zero ($p < 0.25$). Effects of Gender and Runs produced no significant results.

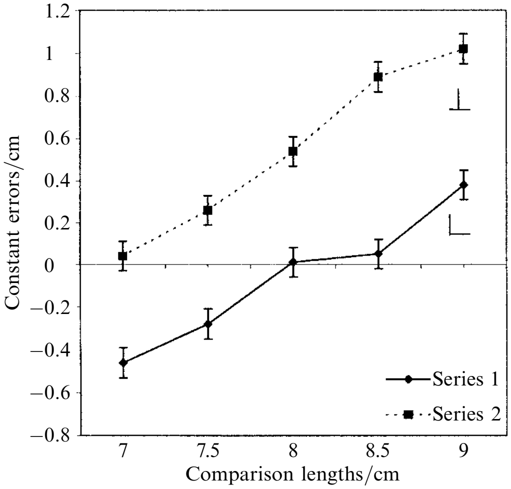

Figure 2. Mean constant errors and standard error bars for L-shapes and inverted T-shapes A, showing the PSEs when the vertical lines of the shapes were aligned to the subject's body midline.

The finding that right-handed scanning produced no bias when vertical lines in L-shapes are aligned with the subject's body midline is important. It suggests that hand movements which relate consistently to body-centred reference cues are less liable to illusory length bias.

The findings of experiments 1 and 2 suggest that spatial information, as well as movement information is involved in the vertical bias for L-shapes in touch. The results are considered further in section 8.

The experiments that follow were designed to examine conditions under which bisection effects occur. Hatwell (1960) suggested that vertical lines in touch are overestimated, because they bisect horizontal lines, not because they are vertical. We tested the hypothesis by comparing inverted T-shapes, in which vertical lines bisect horizontals, with rotated T-shapes in which the vertical is the bisected line.

4 Experiment 3

The previous experiment implicates bisection effects, since T-shapes produced a positive vertical bias in conditions in which L-shapes showed no bias. The 'strong' prediction about bisection effects (Hatwell 1960) is that vertical lines are overestimated when they bisect horizontal lines, but not when they are bisected by horizontal lines.

Standards are scanned before comparison stimuli in methods of adjustment. A second aim was, therefore, to assess a possible memory component. That has not been tested directly so far. There is evidence (Pepper and Herman 1970) that short-term memory for movement extents tends to 'shrink' with delay. The hypothesis predicts that vertical standards (scanned first) 'shrink' in memory, and are thus overestimated less than vertical lines that are scanned last as comparison lengths.

4.1 *Method*

The main hypothesis predicts that vertical lines in T-shapes are overestimated when they constitute the bisecting line, but are underestimated when they are the bisected line. The subsidiary hypothesis predicts that vertical lines are overestimated less as standards (scanned first) than as comparison (scanned second) lengths.

4.1.1 *Design.* Shapes × Gender × Comparison Lengths (5) × Runs (5) designs (repeated measures on the last two factors) were used with the method of adjustment as before.

4.1.2 *Subjects.* In addition to the ten subjects tested on inverted T-shapes with vertical standards (from now called shapes A) in experiment 2, equal numbers of thirty right-handed volunteers (seventeen male, thirteen female; mean age 14.0 years), from local high schools, were allocated randomly (determined by the availability of volunteers at different times) to tests of shapes B, C, and D.

4.1.3 *Materials.* The shapes were produced precisely as described earlier. Inverted T-shapes A had vertical standards (scanned first) that bisected the horizontal comparison lengths. Inverted T-shapes B had vertical comparison lengths (scanned second) that bisected horizontal standards. In clockwise (90°) rotated T-shapes C the vertical comparison lengths (scanned second) were bisected by horizontal standards. In anti-clockwise (90°) rotated T-shapes D, the vertical standards were bisected by horizontal comparison lengths. All shapes had the same (8 cm) standards and five comparison lengths as before. The vertical line of all shapes was in the middle of the test sheet and aligned with the subject's body midline.

4.1.4 *Procedures and conditions.* All procedures and conditions were the same as for shape A in experiment 2, with the following exceptions. For shape B, scanning directions were reversed. Scanning started at the left end of horizontal standards. Subjects were asked to move the index finger to the end of that line, before moving back to the junction and up the vertical (sagittal/midtransverse plane) line. For shape C, subjects started scanning at the left end of the horizontal standard, and moved to the start of the vertical comparison line before going up to scan the total vertical length from the top to the end. For shape D, scanning started at the top of the vertical standard, moved down to scan the whole length and then back to the start of horizontal comparison lengths, then from left to right along the comparison line.

4.1.5 *Scoring.* Constant (algebraic) errors in adjusting comparison lengths to the standard lines were scored, as before, relative to the vertical lines. Inverted T-shapes A and rotated T-shapes D had vertical standards. The positive and negative signs of comparison errors thus indicate, respectively, overestimation or underestimation of vertical lines. Inverted T-shapes B and rotated T-shapes C had horizontal standards. To show vertical overestimation or underestimation relative to other figures, errors were also scored relative to the vertical lines. The sign of comparison errors relative to the horizontal standards in shapes B and C were consequently reversed for statistical analyses. In all analyses, positively signed errors thus show overestimation of the vertical line, and negative errors show underestimation of the vertical line in the figure.

4.2 *Results and discussion*

The mean constant errors (PSEs) and their standard errors for shapes A, B, C, and D are shown in figure 3. The PSE for adjusting horizontal comparison length to the bisecting vertical standard in inverted T-shapes A was significantly positive ($+0.55$ cm, $t = 7.67$, $p < 0.001$). It was significantly positive also for the bisecting vertical comparison lengths in inverted T-shapes B ($+0.71$ cm, $t = 6.21$, $p < 0.001$). By contrast, the PSE for the bisected vertical standard in rotated T-shapes D was significantly negative (-0.26 cm, $t_9 = -2.55$, $p < 0.031$), and the PSE for the bisected vertical comparison lengths in rotated T-shapes C was also significantly negative (-0.62 cm, $t_9 = 5.38$, $p < 0.000$). The findings are consistent with the bisection hypothesis.

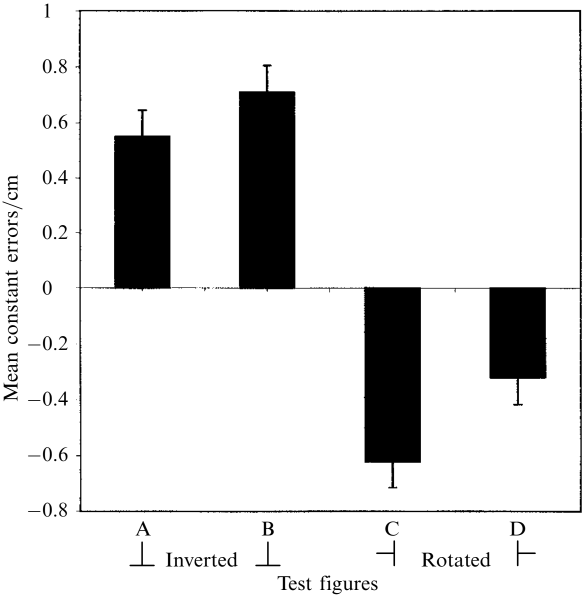

Figure 3. The PSE (mean constant errors from zero and standard error bars) scored relative to the vertical lines in inverted T-shapes A (vertical standard, scanned first, bisects horizontal comparison lines), inverted T-shapes B (vertical comparison lines, scanned second, bisect horizontal standards), and for rotated T-shapes C (vertical comparison lines, scanned second, bisected by horizontal standards), and rotated T-shapes D (vertical standards, scanned first, bisected by horizontal comparison lines).

The second hypothesis, that length biases also involve short-term memory 'decay', predicts that vertical standards (scanned first) are overestimated less than comparison lengths (scanned last). The difference in positive vertical bias, between inverted T-shapes A with vertical standards and inverted T-shapes B with vertical comparison lines, was in the predicted direction, but not significant. The predicted attenuation of the negative bias for rotated T-shapes D with vertical standards, compared to rotated T-shapes C with vertical comparison (scanned last) lines was significant in the predicted direction, in the relevant ANOVA ($F_{1,18} = 4.51$, $p < 0.048$). The finding suggests that a memory 'decay' component must be assumed in length bias in active touch. But it was not sufficient to explain the difference in bias between inverted and rotated T-shapes.

The relevant Shape × Comparison Lengths ANOVA on constant errors showed a highly significant difference between inverted T-shapes A, in which vertical standards bisect horizontals, and rotated T-shapes D in which the vertical standard is the bisected line ($F_{1,18} = 72.54$, $p < 0.000$). Comparison Lengths were significant ($F_{4,72} = 7.68$, $p < 0.000$), and interacted significantly with Shapes ($F_{4,72} = 2.86$, $p < 0.029$). The simple effect of Comparison Lengths was not significant for shapes D, and the significant effect was therefore due to shapes A.

The ANOVA comparing inverted T-shape B, in which vertical comparison lengths were the bisecting lines, with rotated T-shape C in which the vertical comparison lengths were the bisected lines, showed significant effects of Shape ($F_{1,18} = 68.71$, $p < 0.000$), and of Comparison Lengths ($F_{4,72} = 3.74$, $p < 0.008$), which also interacted significantly with Shape ($F_{4,72} = 6.09$, $p < 0.000$). Simple effects showed that the Comparison Lengths effect was significant only for the inverted T-shape B, and was not significant for the rotated T-shape C. Figure 4 shows the constant errors for the simple effects of the interactions, signed relative to the respective vertical and horizontal standards of the figures.

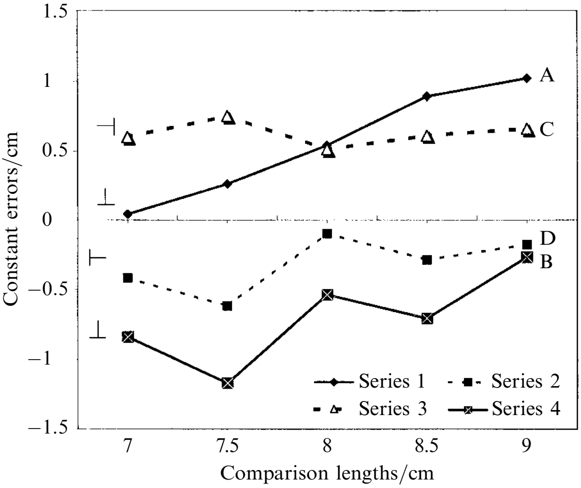

Figure 4. The interactions of the range of comparison lengths with inverted and rotated T-shapes. Mean constant errors, here scored with signs relative to the respective vertical or horizontal standards for Series 1: inverted T-shapes A (vertical standard, bisects horizontal comparison lines); Series 2: rotated T-shapes D (vertical standard, bisected by horizontal comparison lines); Series 3: rotated T-shapes C (horizontal standard, bisects vertical comparison lines); and Series 4: inverted T-shapes B (horizontal standard, bisected by vertical comparison lines).

The evidence thus supports the hypothesis that line bisection is a major factor in the haptic length bias. It also suggests that it is not the only factor. The memory component (see earlier) was relatively minor. But the difference in stimulus range effects between inverted and rotated T-shapes implicates differences in shape and/or orientation cues between the two types of figure, in addition to effects of bisection.

The residual vertical bias is demonstrated by calculating differences in constant error. The ‘strong bisection’ hypothesis predicts that the positive vertical bias for bisecting lines and the negative vertical bias for bisected lines cancel out. That was not the case. Thus the 6.88% positive vertical bias for shape A (vertical line scanned first), and the 8.88% positive vertical bias for shape B (vertical line scanned second) was not eliminated by the −3.25% negative vertical bias for shape D and the −7.75% for shape C (vertical line scanned first and second, respectively). An average residual 2% positive vertical bias remains when memory effects are averaged out in adding positive and negative bisection effects. Calculations based on constant errors relative to the respective vertical and horizontal standards produced the same result. An earlier finding (Tedford and Tudor 1969), although based only on type A and D shapes, is also consistent.

The residual vertical bias between inverted and rotated shapes, in conjunction with the finding that stimulus range effects differed significantly between rotated and inverted T-shapes, suggest that shape and/or orientation cues are involved. Nevertheless, the question remains whether either the main bisection factor or the additional residual vertical bias should be explained by differences in speed between vertical and horizontal movements (Wong 1977).

5 Experiment 4

The experiment was designed to test the movement-time hypothesis, that vertical lines are overestimated because they take longer to scan than horizontals (Wong 1977). Inverted T-shapes were used to probe the residual vertical error further. The latency hypothesis is that vertical lines are overestimated because they require radial movements that are slower than tangential movements for horizontal lines. Though no vertical bias was found when L-shapes were aligned with the body midline, that alone does not rule out the possibility that latency differences between radial/vertical and tangential/horizontal scanning affect residual vertical errors in inverted T-shapes.

The suggestion that slower movements are overestimated makes good sense. However, the timing hypothesis has as yet only been tested relatively indirectly, by counting stroboscopic flashes, set at 1/10 s intervals, against a printout of light dots delineating respective extents (Wong 1977). In the present study we used video recording from below transparent surfaces, with inbuilt synchronous cumulative (1/100 s) timing (see section 5.1.3).

5.1 *Method*

The hypothesis predicts (i) significant overestimation of the vertical line in T-shapes, (ii) significant differences in latencies for vertical and horizontal lines, and (iii) significant partial correlations between vertical bias and latencies and the reduction or elimination of errors in regressions of latency differences.

5.1.1 *Design.* A Gender × Comparison Lengths (5) × Runs (5) design (repeated measures on the last two factors) was used with the same task as before.

5.1.2 *Subjects.* Ten right-handed graduate and undergraduate (five male, five female) volunteers took part.

5.1.3 *Video-recording apparatus and materials.* Latency and error data were obtained by filming the hands moving over the (darkened) stimuli, from below transparent surfaces, synchronously with cumulative real (1/100 s) time and voice output, while stimulus figures were scanned normally.

The device is housed in two interconnecting units above a (kneehole) stand. The larger (57 cm × 60 cm × 30 cm) unit contains a plate-glass (66 cm × 30 cm) reading surface. It is situated at normal table height (25 cm above the unit base; 76 cm above the floor). A (45°) angled mirror, attached below the reading surface and flanked by two strip lights, reflects the movement of the hands and fingers above raised line designs, embossed on the transparent test sheets. A transparent ruler (with a millimetre scale) is fastened to the underside of the reading surface. The image is picked up by the video camera (Panasonic Wv-155/B with 12.5 mm, F 1.3 Computar lens) which is housed in the interconnecting second (43 cm × 39 cm × 49 cm) unit. A video recorder (Panasonic NV 180), video timer (GYYR G77), monitor, and microphone are linked into the system. Video (solid state) monitors provide visual and auditory outputs. The scan coils of the camera are reversed and the camera is inverted to give a normally oriented picture on the monitor.

Errors and latencies (1/100 s) are read off in frame-by-frame (40 ms) replay. Touching raised stimuli produces a slight depression, seen on the monitor as a slightly brighter circular patch than the surrounding skin on the ball of the finger. The midpoint of that patch, which visibly touches the part of the raised stimulus in that frame, is the reference location for the time that appears on the monitor in that frame. Latencies for finger movements on every location can thus be read off as required (Millar 1997).

Test figures were inverted T-shapes A, produced as before on transparent (20 cm × 20 cm) plastic sheets, and superimposed on rigid transparent plastic plates, presented on the reading surface of the device.

5.1.4 *Procedures.* The conditions, counterbalancing, and procedures were precisely the same as for inverted T-shapes A previously.

5.1.5 *Scoring.* Constant errors in adjustments were scored relative to the vertical standards as before. Three latency measures were taken: V, from the start to the end of scanning the vertical standards; H_a, for left–right scanning of horizontal comparison lines only, excluding latencies for backtracking from junctions to the left start of the line; and H_b, the total latency for horizontal scanning movements, including back-track-ing movements. The V latencies were for 8 cm standards, H_a latencies were for the average (8 cm) of comparison lengths; H_b latencies depended on an average of 12 cm (average 8 cm plus 4 cm on average for backtracking movements). Horizontal H_b latencies were thus based, on average, on 1½ times the length of the bisecting vertical standard. Separate ANOVAs were run to compare H_a and H_b latencies with the latencies for the vertical standard.

5.2 *Results and discussion*

Mean constant errors are shown in table 1, collapsed over gender, since gender had no significant effect ($F_{1,8} = 0.21$, $p = 0.66$) in the Gender × Comparison Lengths (5) × Runs (5) ANOVA, and did not interact significantly with any other factor. Neither Comparison Lengths nor Runs had significant effects on the error data. The mean constant error (PSE = 0.76 cm) differed significantly from zero ($t_9 = 4.41$, $p < 0.002$), as predicted by the hypothesis that the vertical line is overestimated compared to the horizontal comparison length.

Table 1. Mean algebraic errors (in centimetres) in adjusting horizontal comparison lengths to vertical (8 cm) standards, together with standard deviations (SD) for ten subjects.

	Comparison lengths/cm				
	7.0	7.5	8.0	8.5	9.0
Means	+0.72	+0.60	+0.73	+0.80	+0.94
SD	0.28	0.19	0.41	0.09	0.20

Overall mean = +0.76 cm, PSE; $t_9 = 4.41$, $p < 0.002$.

Latencies in the Vertical/Horizontal (H_a) × Gender × Comparison Lengths (5) × Runs (5) ANOVA showed a significant difference between V and H_a latencies ($F_{1,8} = 5.86$, $p < 0.042$), due to significantly slower vertical scanning. Comparison Lengths were significant ($F_{4,32} = 2.96$, $p < 0.035$), and interacted with V versus H_a latencies ($F_{4,32} = 3.62$, $p < 0.015$). The simple effects of the interaction are graphed in figure 5. The significant increase in latencies with increases in comparison length was due to the horizontal lines which alone varied in length. The vertical standards were all the same length.

A simple regression analysis of the difference between V and H_a latencies on constant errors showed a 3% reduction in the 9.5% vertical errors. It suggests that, when horizontal backtracking movements are ignored, faster left–right scanning of horizontal comparison (scanned last) lengths may explain the residual (see earlier) vertical bias. However, the Pearson correlation coefficient ($r = 0.42$, $p < 0.23$), though positive, was not significant. The result for regressions with z-scores used for errors and vertical latencies (keeping H_a latencies constant) was similar ($r = 0.45$, $p = 0.22$). The significantly positive intercept (0.60, $p < 0.021$) which remained when the difference in laten-cies was held constant ($p < 0.026$), showed no latency effect on the remaining 6.5% vertical bias, which may be attributed to bisection effects.

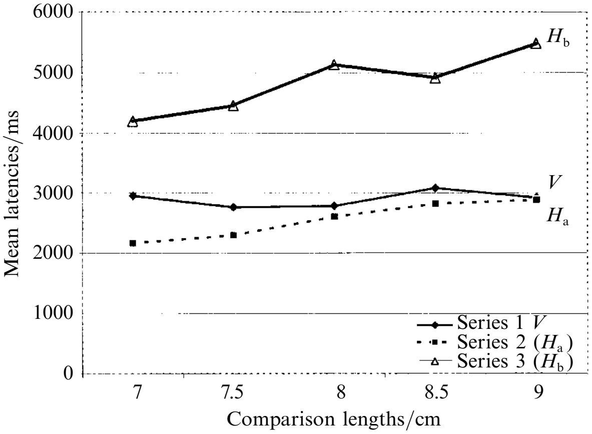

Figure 5. Mean latencies for scanning vertical standards (*V*, Series 1), horizontal comparison lengths for left–right movements only (H_a, Series 2), and for all, including backtracking, movements on horizontal comparison lines (H_b, Series 3) in inverted T-shapes.

In fact, the H_b latencies for horizontal lines, which included the time necessarily spent in backtracking from the T-junctions, were actually significantly longer than vertical latencies ($F_{1,8} = 59.77$, $p < 0.000$). The only other significant effects in the ANOVA were decreased latencies with repeated runs ($F_{4,32} = 5.46$, $p < 0.002$), and the expected interaction showing that comparison lengths influenced scanning the horizontal lines which varied in lengths and did not affect the invariant vertical lines ($F_{4,32} = 5.08$, $p < 0.003$) (figure 5).

It was clear that slow vertical scanning movements as such cannot explain the main vertical error in T-shapes that involve bisection effects, since horizontal scanning takes longer overall. The finding was surprising, in that all ten subjects reported, spontaneously, that they had deliberately tried to use movement timing as a strategy, though they did not find it helpful.

6 Experiment 5

There has been no previous attempt to explain when or why bisection effects occur in touch. Line bisection effects have been found even with very small T-shapes and in total blindness (eg Hatwell 1960). On the other hand, no bisection bias was found when length judgments for pairs of vertical and horizontal lines without bisecting lines were compared with length judgments for pairs of vertical and horizontal lines that both had small bisections (Heller et al 1997).

We based our explanation on the discrepancy in findings, which we found instructive. We assumed that junction points act as misleading spatial reference anchors, or barrier points, in addition to the start and endpoints of the line in length judgments. In indirect comparisons, when both the vertical and horizontal comparison lines have a junction point, or both lines lack junction points (Heller et al 1997), there is no discrepancy. In direct comparison of orthogonal bisected with bisecting lines, however, there is a disparity in anchor cues. The bisected line has a junction point which the bisecting line lacks. There is evidence that kinaesthetic length judgments are distorted by the length of an immediately prior movement (eg Adams and Djikstra 1966; Millar and Ittyerah 1991). The scanning movement that immediately precedes the required length judgment is the length of line that projects beyond the junction point on the horizontal line. The adjustment of the comparison line to the standard would thus be influenced by the short length beyond the junction.

The hypothesis predicts that the final short movement, beyond the junction of a bisected horizontal line, distorts the length judgment of the whole of the bisected line, and produces a consequent overestimation of the vertical bisecting line. We tested the hypothesis with 'junction' shapes, in which the vertical line joins the horizontal at five different locations.

6.1 *Method*

6.1.1 *Design and subjects.* A Gender × Junction (5) × Runs (5) design was used with the method of adjustment as before. Subjects were thirty-one right-handed volunteers (twenty female, eleven male, mean age 14.6 years) from a local high school.

6.1.2 *Materials, conditions, and procedures.* The stimulus figures were embossed on test sheets, as described earlier. Each figure consisted of an 8 cm vertical standard, which joined an 8 cm horizontal comparison length at one of five locations (shown in figure 6). The vertical junctions were, respectively, at 0 cm distance from the start (J0 = L-shape), at 2 cm (J2), at 4 cm (J4), at 6 cm (J6), and at 8 cm (J8 = reversed L-shape).

The conditions, instructions, procedures, and scoring were precisely the same as for the inverted T-shapes A. The order of presentation was counterbalanced over runs (5) and subjects, as before.

6.1.3 *Predictions.* The hypothesis predicts the largest overestimation for J6 (smallest final segment after the junction), and little or no effect at the initial J0 (L) junction that is not divided. No firm prediction was possible for J8 (reversed L), because it required a double horizontal movement from the junction, but no movement beyond the junction. The shape was included, nevertheless, for completeness.

6.2 *Results and discussion*

The mean constant errors, with standard error bars, are graphed in figure 6. The Gender × Junction × Runs ANOVA produced a highly significant effect of the location of the vertical junction on the horizontal line ($F_{4,116} = 31.3$, $p < 0.000$). Neither Gender ($F_{1,29} = 0.15, p < 0.70$), nor Runs ($F_{4,116} = 2.07, p < 0.09$) were significant, or interacted with any other factor.

The junction result shows that the vertical overestimation varied significantly with the location of the junctions on the bisected horizontal line. As predicted, the difference increased from a slight negative bias for L-shapes (no bisection), to significantly positive vertical bias relative to the bisecting line, as segments beyond the junction got smaller (figure 6). As predicted also, the largest overestimation (15.88%) was for figure J6, the shape with the smallest segment projecting beyond the junction point. The overestimation for J6 was larger than for the middle (J4) junction figure, which is

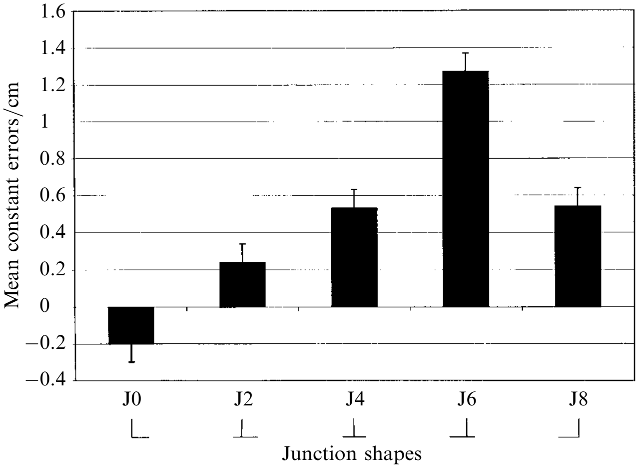

Figure 6. PSE (mean constant errors from zero and error bars), in adjusting horizontal comparison (8 cm) lengths to vertical (8 cm) standards in junction shapes in which the vertical line joins the horizontal lines at J0 (0 cm from the start, no section, right projection = 8 cm), J2 (2 cm from the start, right projection = 6 cm), J4 (at 4 cm from the start, right projection = 4 cm), J6 (at 6 cm from the start, right projection = 2 cm), and J8 (at 8 cm from the start, right projection = 0 cm).

the inverted T-shape A (6.63%). The *t*-test on the predicted difference showed that the difference between J6 and J4 was highly significant ($t_{30} = 5.87$, $p < 0.000$, two-tailed).

The PSE for shape J8 (reversed L-shape) also showed a significant overestimation (6.75%) of the vertical ($t_{30} = 4.72$, $p < 0.000$). In fact, people were observed to overshoot the J8 junction in scanning the horizontal line during tests. The overshooting is intelligible in the context of counterbalanced presentations of figures, since all other (counterbalanced) figures had projections to the right beyond the junction point. The observation of overshooting J8, coupled with the finding that J8 also showed a significant vertical bias, thus suggests that the finding is also consistent with the hypothesis.

The result, showing an increase in vertical overestimations with decreases in the length of the section beyond the junction, is consistent with the assumption that junction points in bisected lines act as spatial anchors. It thus supports the hypothesis that bisection effects in touch are due to disparities in spatial anchor cues for movement extents.

The spatial hypothesis was tested further, by adding spatial reference information. Current external spatial reference cues are severely reduced in touch without vision (Millar 1994). Scanning figures with one finger further reduces the convergence of movement information with body-centred reference cues (Ballesteros et al 1998; Millar et al 1994). Reference information was therefore enhanced in the next experiment, by providing an external surrounding frame, and by instructing subjects to use both hands to explore the frame and figure. The instructions stressed the relation between scanning movements for the frame and the figure, and also emphasised two-handed scanning relative to body-centred cues.

7 Experiment 6

The hypothesis was that two-handed exploration of the frame in relation to the shape, with additional emphasis on reference information to enhance spatial coding, would affect the length bias in T-shapes significantly. In principle, additional reference information could either increase or decrease the overestimation of vertical relative to bisected horizontal lines by increasing or decreasing disparities in reference cues. However, the hypothesis that junction points in bisected lines act as additional anchor cues that are lacking in the bisecting line suggests that using the two hands in parallel relative to an external frame, and to the body midline, produces more congruent spatial reference for the two scanning movements. The disparity in junction cues should thus have less effect, so that the amount of overestimation due to bisection is reduced.

7.1 *Method*

7.1.1 *Design.* A Reference Frame (frame – two hands/no frame – one hand) × Gender × Compar-ison Lengths (5) × Runs (5) design (repeated measures on the last two factors) was used with the same task as before.

7.1.2 *Subjects.* Twenty right-handed volunteers (ten male, ten female, mean age 14.5 years) from a local secondary school were tested on inverted T-shapes A under the frame – two hands condition. The data were compared with results for the inverted T-shape A in single-handed scanning without reference instructions (experiment 2).

7.1.3 *Materials, conditions, and procedures.* Inverted T-shapes A were prepared as before, from opaque (20 cm × 20 cm) Braille paper, with the vertical line of the shapes in the centre of the test sheet. To provide a spatial frame for the shape, the test sheets were fastened to highly tangible rigid plastic (20 cm × 20 cm) plates. The edge of the plates provided a hard, highly tangible square frame surround for the T-shapes.

The procedures and conditions were the same as in the previous experiments for shape A. The only exception was in the frame – two hands condition. Subjects were told to use both hands to feel the rigid frame surrounding the stimulus figure in relation to feeling the vertical line of figures, using similar downward movements. Subjects were instructed to relate the downward scanning movements to their body midline and to the vertical sides of the frame.

7.2 *Results and discussion*

Mean constant errors in frame/no-frame conditions for the five comparison lengths are graphed in figure 7, showing the magnitude of the illusion (PSEs) in the two conditions. The Gender × Reference Frame × Comparison Lengths × Runs ANOVA produced a significant main effect of the Reference Frame factor ($F_{1,26} = 13.19$, $p < 0.001$). The finding shows the predicted significant reduction of the illusion in the frame – two hands condition, compared to the no-frame – one hand condition. Comparison Lengths were also significant ($F_{4,104} = 64.72$, $p < 0.000$), owing, as before, to the context effect of the comparison lengths.

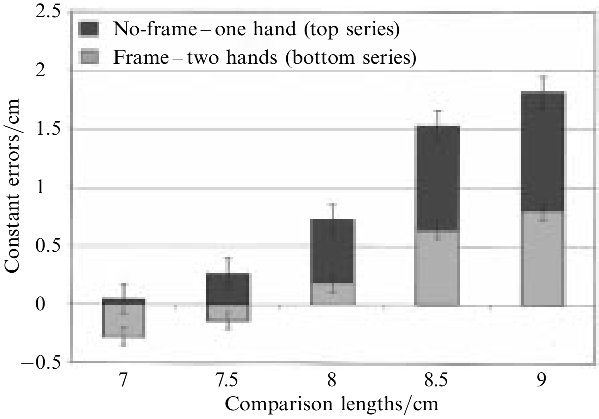

Figure 7. PSE (mean constant errors from zero and error bars) in adjusting horizontal comparison lengths to vertical standard lines in inverted T-shapes A in the no-frame – one hand (top series) and the frame – two hands (bottom series) conditions.

Neither Runs, nor Gender produced significant main effects. It should be noted that there were no predictions from the hypotheses about effects of Runs or of Gender. Both were included in all analyses only for the sake of completeness. The number of trials (five runs) used in all experiments here was determined by the need to establish stable responses for the two experimental conditions. The number of runs was not intended as a test of practice effects, which would require a much larger number of trials. The inclusion of Runs as a factor in the ANOVA here produced a small but significant interaction between Runs and Gender ($F_{4,104} = 2.77$, $p < 0.03$), and between Runs and Reference Frame ($F_{4,104} = 3.01$, $p < 0.02$). Both interactions were qualified by a significant higher-order interaction between Gender × Runs × Comparison Lengths and the Reference Frame factors ($F_{16,416} = 1.74$, $p < 0.038$). Tests on simple effects of either of the lower-order interactions were, therefore, not meaningful, or justified statistically. The patterns of mean errors for runs in relation to gender and to frame conditions are, nevertheless, shown in table 2. It is clear from the table that the pattern of error differences between males and females that gave rise to the Runs × Gender interaction fluctuated irregularly between the 5 trials. There was no consistent deterioration or improvement over trials for either gender. The pattern of error differences that gave rise to the Runs × Reference Frame interaction also failed to show evidence of any consistent improvement or deterioration over the 5 trials for either the no-frame – one hand condition or for the frame – two hands condition. The frame – two hands condition produced lower errors than the no-frame – one hand condition in all trials with the exception of trial 3. The pattern of errors suggests transitory changes in heuristics, or loss of attention to instructions, halfway through the trials. But since both interactions were qualified by the higher-order interaction, the error patterns can

Table 2. Mean constant errors (in centimetres) and standard deviations (SD), for the lower-order interactions between (a) Runs and Gender, and (b) Runs and Reference Frame in experiment 6.

	Trials				
	Run 1	Run 2	Run 3	Run 4	Run 5
(a) Gender					
Females	0.53	0.23	0.32	0.48	0.38
SD	0.55	0.52	0.35	0.52	0.47
Males	0.38	0.47	0.40	0.27	0.48
SD	0.57	0.44	0.54	0.50	0.64
(b) Reference Frame					
No frame	0.73	0.51	0.36	0.54	0.59
SD	0.47	0.50	0.42	0.51	0.52
Frame – hands	0.19	0.19	0.35	0.21	0.27
SD	0.51	0.44	0.46	0.48	0.55

[Note that both the interactions (a) and (b) on which these figures are based are qualified by a higher-order interaction, and depend on using Runs as a factor in the ANOVA, see text.]

only suggest fluctuation in performance over the course of a testing session. The higher-order interaction suggests the involvement of combinations of all factors, including individual difference variables, which may be expected with relatively few trials with unfamiliar stimuli. It should be noted that the simple effects based on the main ANOVA showed that all the interactions were due to the inclusion of Runs as a factor. Thus, the Gender × Reference Frame × Comparison Lengths ANOVA only showed significant effects of the Reference Frame factor ($F_{1,26} = 13.32$, $p < 0.001$) and of the Comparison Lengths ($F_{4,104} = 64.68$, $p < 0.000$), and produced no significant interactions of any kind. The higher-order interaction with Runs thus merely suggests fluctuations in responses which may be expected during initial trials with a novel task.

The key finding was that the bisecting/bisected line illusion was more than halved, from 6.88% to 3.00%, by relating two-handed scanning of inverted T-shapes to an external frame and to the body midline. The finding suggests that congruent spatial frame information is an important factor in the haptic length illusion. Nevertheless, though the vertical overestimation for the inverted T-shapes was much larger in the no-frame – one hand condition (PSE = +0.55 cm, $t_9 = 7.69$, $p < 0.000$), the PSE for the frame – two hands condition also differed significantly from zero (PSE = 0.24 cm, $t_9 = 5.27$, $p < 0.000$).

The remaining vertical error is similar to the residual bias found for inverted T-shapes when bisection effects had been subtracted (experiment 3). Since the same highly significant stimulus range effects were found here as for inverted T-shapes, in contrast to rotated T-shapes in the earlier study, the remaining error may also relate specifically to shape and/or orientation cues in inverted T-shapes.

8 Summary and general discussion

The results of the first two experiments did not support the hypothesis that the vertical illusion in touch is explained by discrepancies in movement inputs involving the whole arm and shoulder. Right-handed scanning produced a negative vertical bias in ipsilateral, as well as in contralateral space (experiment 1), suggesting that the bias could not be explained solely by the greater involvement of shoulder inputs during lateral scanning in contralateral hemispace alone. The findings suggest that spatial cues are involved also. That would account for the absence of bias for the left hand. More important, the negative bias for the right hand can be explained by the fact that scanning on either side of the body midline affords fewer reliable body-referent cues in blind conditions, and therefore fewer reference inputs by which movement discrepancies can be calibrated, or related consistently to body-centred frames. Thus, when the vertical lines of the L-shapes were aligned to the body midline, right-handed scanning did not produce a vertical bias (experiment 2).

The interpretation of the findings in terms of an involvement of spatial cues can also account for the apparent discrepancies in previous results. As noted earlier, all previous findings of vertical overestimation depended on using the outstretched arm at shoulder height, or with angular changes in the plane of presentation, or on movements with the elbow deliberately raised. Interestingly enough, Cheng (1968) originally suggested that vertical lines are overestimated because the vertical axis of the field described by radial movements pivoting around the egocentric body midpoint at shoulder height is more compressed than the field described by tangential movements.

Our explanation is completely consistent with that suggestion, though it differs in emphasis and generality. Cheng and later workers stressed discrepancies in specific movements. We stress the relation of kinaesthetic (movement) cues to spatial reference anchors. There is good evidence that movements depend on multiple spatial reference frames (Jeannerod 1988; Paillard 1991). It is assumed here that reliable spatial reference information results from the convergence and partial overlap of multiple modality-specific cues from external egocentric and figure-based sources (eg Graziano and Gross 1994; Millar 1994; Stein 1992).

We therefore suggest that length biases are due to disparities in the reference cues from multiple external body-centred and figure-based sources, which act as reliable reference anchors for movement extents, when the cues are congruent and concur (Millar 1994). Thus, the previous finding that vertical lines in L-shapes are not overestimated in the upright (frontoparallel) plane (Day and Avery 1970) is intelligible when the movements are considered in relation to that spatial plane. Scanning movements and body-centred directions in the frontoparallel plane afford congruent spatial cues. Similarly, the fact that no vertical bias has been found for very small L-shapes in table-top space (Hatwell 1960; Heller et al 1997) can be explained by the size of the stimuli. The stimuli were too small for body-centred cues to constitute relevant reference anchors for the scanning movements. By contrast, scanning movements in our study were unconstrained in table-top space, and our L-shapes were large enough (8 cm) for scanning movements to relate to body-centred cues (see earlier).

The findings suggest that the task of comparing orthogonal lines in L-shapes (without bisection) involves the congruity of scanning movements with body-centred cues. Congruity versus disparity in reference frames for scanning movements also explains the apparent contradictions in previous findings on the 'verticality' bias. The findings on L-shapes implicate differences in scanning movements in the vertical length illusion in touch. But they also suggest that the congruity or disparity of reference cues, which act as anchors for the extent of movements, is a crucial condition in predicting decreased and increased bias.

Line bisection and verticality (T-shape and L-shape) effects were not identical. As mentioned previously, it has been suggested that the two factors are independent in the visual horizontal – vertical illusion (Künnapas 1955). Here, the findings on rotated and inverted T-shapes (experiment 3) showed that bisecting lines are overestimated, and bisected lines are underestimated, whether the bisecting line is vertical or horizontal.

As far as we know, no previous explanation of line bisection effects in touch has been put forward, nor of the conditions under which they occur. We propose that the bisection illusion can also be explained by discrepancies in spatial reference cues. We assumed that junction points act as spatial anchor or boundary (barrier) cues for movement extents. In T-shapes there is a disparity in barrier points when the lengths of bisecting and bisected lines are compared. Bisected lines have a junction point, in addition to start and end locations, which bisecting lines lack. The disparity explains the negative vertical bias for rotated T-shapes, and the positive bias for inverted T-shapes (experiments 3 and 5). It also accounts for the absence of bisection effects found previously (Heller et al 1997) when both the lines being compared either had or lacked the additional junction point. That condition produces no disparity in spatial reference cues (see earlier).

We tested the hypothesis that orthogonal sectioning lines distort length judgments because they produce disparate spatial (boundary) cues for comparing movement extents, by varying the location of vertical junctions on horizontal lines. On the basis of previous evidence it was assumed that the small line segment that is encountered last, beyond the junction on the horizontal line, determines the size of vertical illusion. The results supported the hypothesis (experiment 5).

The spatial hypothesis was supported further by the finding that the illusion was more than halved by providing congruent reference information (experiment 6). Spatial reference information here refers to conditions that can be specified operationally, and which can be manipulated. The reference conditions in experiment 6 were produced by providing an actual spatial frame surround for the shapes, and instructing subjects to relate two-handed scanning movements to the frame and to their body midline.

The spatial hypothesis explains both the vertical and the bisection illusion by disparities in spatial reference cues. These are precisely those reference cues which act as reliable spatial reference and anchor information for movements when they concur and coincide. The similarity of illusions across modalities can thus be accounted for without assuming that modality-specific information is irrelevant, or that cross-modal processes necessarily require unspecified (deliberate or learned) cognitive mediation. It is assumed instead that the same multiple reference frames that operate in vision (eg Paillard 1991) also operate in touch. Convergence and disparities in reference cues from multiple modality-specific external, egocentric, and figure-based sources for orthogonal stimuli can thus be assumed for touch and for vision.

The hypothesis that length illusions are due to disparities in reference cues explains the similarities between the tactual and visual length illusions. The illusions are not necessarily precisely the same in the two modalities. In active touch without sight, the balance of proprioceptive to external inputs is weighted more towards body-centred cues, unless additional external information is provided (Millar 1994). Disparities in reference cues are thus not always precisely the same for vertical or bisection effects in the two modalities.

The order effects in scanning, though relatively minor (experiment 3), implicate short-term motor memory in biasing errors. Slower scanning of vertical standards, compared to the left – right distance of comparison lengths (experiment 4) may also be involved. There were reductions in scanning speed with repetition, especially when the backtracking movements were excluded. There was no doubt that movement time increased with movement distance. But scanning latencies did not explain the main error data. Further work is needed to probe speed – error relations, in view of the deliberate, but evidently unsuccessful, attempt by subjects to use speed as a measure of length in these conditions.

The intriguing finding that the range of comparison lengths affected inverted and rotated T-shapes differently (experiment 3), also needs further investigation. The results suggest figure-based shape and/or orientation cues, or 'baselines' that are assigned to figures, in addition to disparities due to segmentation. These could explain the residual vertical bias for inverted T-shapes (experiments 3 and 6). But this requires further investigation.

It should perhaps be pointed out that the findings for the junction and frame experiments provide completely new evidence on conditions that increase and reduce the length illusion in touch. The reduction of the powerful illusion for the inverted T-shapes to less than half its magnitude, by deliberately providing additional, congruent reference information, also has practical implications. It suggests means of reducing errors in judging relative distances that should be useful particularly in map recognition by visually handicapped people.

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References

Adams J A, Djikstra S, 1966 "Short-term motor responses" *Journal of Experimental Psychology* **71** 314 – 318

Ballesteros S, Millar S, Reales J M, 1998 "Symmetry in haptic and in visual perception" *Perception & Psychophysics* **60** 389 – 404

Burtt H E, 1917 "Tactual illusions of movement" *Journal of Experimental Psychology* **2** 371 – 385

Cheng M F H, 1968 "Tactile-kinaesthetic perception of length" *American Journal of Psychology* **81** 74 – 82

Collani G von, 1979 "An analysis of illusion components with L and T figures in active touch" *Quarterly Journal of Experimental Psychology* **31** 241 – 248

Day R H, Avery G C, 1970 "Absence of the horizontal – vertical illusion in haptic space" *Journal of Experimental Psychology* **83** 172 – 173

Day R H, Wong T S, 1971 "Radial and tangential movement directions as determinants of the haptic illusion in an L figure" *Journal of Experimental Psychology* **87** 19 – 22

Deregowski J, Ellis H D, 1972 "Effect of stimulus orientation upon haptic perception of the horizontal – vertical illusion" *Journal of Experimental Psychology* **95** 14 – 19

Fick A, 1852 "Erörterung eines physiologisch-optischen Phänomens" *Zeitschrift für rationelle Medicin* **2** 83 – 94

Finger F W, Spelt D K, 1947 "The illustration of the horizontal – vertical illusion" *Journal of Experimental Psychology* **37** 243 – 250

Gescheider G A, 1997 *Psychophysics: The Fundamentals* (Hillsdale, NJ: Lawrence Erlbaum Associates)

Graziano M S, Gross C G, 1994 "The representation of extrapersonal space: A possible role for bimodal visual – tactile neurons", in *The Cognitive Neurosciences* Ed. M Graziano (Cambridge, MA: MIT Press) pp 1021 – 1034

Harris V A, Hayes W, Gleason J M, 1974 "The horizontal – vertical illusion: Binocular and dichoptic investigations of bisection and verticality components" *Vision Research* **14** 1323 – 1326

Hatwell Y, 1960 "Étude de quelques illusions geométriques tactile chez les aveugles" *L'Année Psychologique* **60** 11 – 27

Heller M A, Calcaterra J A, Burson L L, Green S L, 1997 "The tactual horizontal – vertical illusion depends on radial motion of the entire arm" *Perception & Psychophysics* **59** 1297 – 1317

Heller M A, Joyner T D, Dan-Fodio H, 1993 "Laterality effects in the haptic horizontal – vertical illusion" *Bulletin of the Psychonomic Society* **31** 440 – 442

Jeannerod M, 1988 *The Neural and Behavioural Organisation of Goal-directed Movements* (Oxford: Clarendon Press)

Künnapas T M, 1955 "An analysis of the 'vertical – horizontal' illusion" *Journal of Experimental Psychology* **49** 134 – 140

Kumar S, 1977 "Short-term memory for a non-verbal tactual task after cerebral commissurotomy" *Cortex* **13** 55 – 61

Millar S, 1994 *Understanding and Representing Space: Theory and Evidence from Studies with Blind and Sighted Children* (Oxford: Clarendon Press)

Millar S, 1997 *Reading by Touch* (London: Routledge)

Millar S, Ballesteros S, Reales J M, 1994 "Influence of symmetry in haptic and visual perception" paper presented at the 35th Annual Meeting of the Psychonomics Society, St Louis, MO, November 11 – 13

Millar S, Ittyerah M, 1991 "Movement imagery in young and congenitally blind children: mental practice without visuo-spatial information" *International Journal for the Study of Behavioural Development* **15** 125 – 146

Milner B, Taylor L, 1972 "Right hemisphere superiority in tactile pattern recognition after commissurotomy" *Neuropsychologia* **10** 1 – 15

Paillard J, 1991 "Motor and representational framing of space", in *Brain and Space* Ed. J Paillard (Oxford: Oxford University Press) pp 163 – 182

Pepper R, Herman L M, 1970 "Decay and interference in the short-term retention of a discrete motor act" *Journal of Experimental Psychology, Monograph Series* **83**, whole number 11

Poulton E C, 1979 "Models for judging sensory magnitude" *Psychological Bulletin* **86** 777 – 803

Stein J F, 1992 "The representation of egocentric space in the posterior parietal cortex" *Behavioral and Brain Sciences* **15** 691 – 700

Tedford W H Jr, Tudor L L, 1969 "Tactual and visual illusions in the T-shaped figure" *Journal of Experimental Psychology* **81** 199 – 201

Wong T S, 1977 "Dynamic properties of radial and tangential movements as determinants of the horizontal – vertical illusion" *Journal of Experimental Psychology: Human Perception and Performance* **3** 151 – 164