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Visual and haptic matching of perceived orientations of lines

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Abstract. In this study we investigated the perception and production of line orientations in a vertical plane. Previous studies have shown that systematic errors are made when participants have to match oblique orientations visually and haptically. Differences in the setup for visual and haptic matching did not allow for a quantitative comparison of the errors. To investigate whether matching errors are the same for different modalities, we asked participants to match a visually presented orientation visually, haptically with visual feedback, and haptically without visual feedback. The matching errors were the same in all three matching conditions. Horizontal and vertical orientations were matched correctly, but systematic errors were made for the oblique orientations. The errors depended on the viewing position from which the stimuli were seen, and on the distance of the stimulus from the observer.

1 Introduction

One of the first processing steps needed for grasping an object in the visual world is perceiving its size and orientation. In this context, it is important to notice that many studies have shown that object properties are not always perceived correctly. Several differences have been reported between real-world space and the representation of this space in the brain. For example, parallel lines in real-world space are not always perceived as parallel lines (Cuijpers et al 2000; Kappers and te Pas 2001), and objects presented at the same distance but at a different viewing angle often do not look equidistant (see, eg, Foley 1980). Moreover, angles between two lines are found to be perceived incorrectly (Chen and Levi 1996; MacRae and Loh 1981; Regan et al 1996) and, related to this observation, the angles of a triangle constructed by arrows pointing towards the perceived vertices of the triangle do not sum to 180° (Koenderink et al 2000). Finally, the estimation of the length of a line depends on whether the line is on a flat or a curved surface (Norman et al 1996, 2000).

Soechting and Flanders (Flanders and Soechting 1995; Soechting and Flanders 1993) investigated whether the differences between the actual orientation of objects and the perceived orientation affect manual matching of orientations of objects. In their experiments, participants were asked to match a visually or verbally presented 3-D orientation with a bar at different locations in space. Systematic errors were made by participants carrying out this task. In another study, Kappers and Koenderink (1999) found systematic errors when participants were asked to match the orientation of a haptically perceived bar with that of a test bar at various places in the horizontal plane.

These results have raised the question whether errors in the percepts of visually and haptically presented bars are similar, and to what extent errors in visual perception of the orientation of a bar affect haptic matching of the orientation. A first attempt to address this question was presented by Cuijpers in his doctoral thesis (2000), where he compared the results of a visual (Cuijpers et al 2000) and a haptic (Kappers and Koenderink 1999) matching task. Cuijpers (2000) showed that the structure of visual and haptic spaces is qualitatively similar but quantitatively different.

However, the experimental conditions for haptic and visual matching were different, leaving open the option that the quantitative differences could be due to differences in the experimental setup of the two matching experiments. In the experiment by Cuijpers et al (2000) the two bars were presented in a horizontal plane at eye height, while in the experiment by Kappers and Koenderink (1999) the stimuli were presented on a table at waist level. In addition, the distance between stimuli differed across experiments. The aim of the present study was to investigate whether errors in visual and haptic matching of line orientations are quantitatively similar. To allow for a quantitative comparison across modalities we asked participants to match visually presented orientations both visually and haptically in the same experimental conditions.

Three experiments were carried out. In the first experiment, participants were asked to visually match the orientation of two lines. Both lines were presented on a large screen which participants viewed from aside. By the choice of the stimulus locations, the influence of viewing angle and distance was tested. On the basis of the results of Cuijpers et al (2000) and Kappers and Koenderink (1999) viewing angle was expected to have an effect, but no effect was expected of viewing distance.

The second experiment involved haptic matching with visual feedback. Participants were presented with the same visual stimulus as in the first experiment. They were asked to match its orientation by holding a bar in the same orientation at one of three different positions. While matching the orientation, the reference line remained visible and the orientation of the bar could be inspected visually. This makes the experiment different from the experiments by Soechting and Flanders (1993), where either the stimulus or the bar could not be seen while matching.

In the third experiment, visual information was eliminated during haptic matching of the reference orientation. This was done to exclude a possible dominant contribution of visual perception to the matching of the bar orientation in experiment 2. If the use of visual information dominated that of haptic information, and if errors in visual and haptic matching differ, a different pattern of results has to be expected for haptic matching with (experiment 2) and without (experiment 3) visual feedback.

2 Experiment 1

In the first experiment, the perceived orientation of visually presented lines in the vertical plane was investigated when participants looked at the stimuli from aside. Two viewing positions were used: one to the left of the stimuli and one to the right. In the experiment, participants were presented with two lines on a large screen, and they were asked to match the orientation of one line (the 'matching line') with the orientation of the other line (the 'reference line'). They did this by adjusting the orientation of the matching line using a remote control until they thought it matched the orientation of the reference line.

2.1 *Method*

2.1.1 *Participants.* The stimulus lines were matched from two viewing positions. Six participants matched the stimuli from the left and seven from the right. Three participants took part in both matching situations. Two of these three were the authors. All other participants were naïve with respect to the purpose of the experiment. Six of the participants (not members of the department) were paid for their participation. All participants had normal or corrected-to-normal vision.

2.1.2 *Apparatus.* An LCD projector (Philips 4750) connected to a Pentium PC (166 MHz) was used for the presentation of the stimuli. Two lines were projected within a 142 cm $\times$ 105 cm computer display image on a 2.5 m $\times$ 2 m projection screen. The resolution of the projected screen was 640×480 pixels. The orientation of one of the projected lines could be adjusted, by means of the computer keyboard, in steps of 2°, 0.5°, or 0.1°.

2.1.3 *Stimuli.* The stimuli consisted of computer-generated lines. Each line consisted of seven dots, each at 13 mm distance within the 142 cm × 105 cm display image. Seven dots were used instead of a solid line, since a solid line would allow participants to estimate its orientation by looking at the staircase pattern of the dots within the line which originated from the finite resolution of the visual display in graphics mode. The seven dots of each line were plotted in white on a black background. The reference line was presented in the upper right part of the screen for both viewing conditions (from the left and the right), with its centre at 122 cm from the left and 13 cm from the top of the display image. The matching line was presented with its centre in the upper left part of the image (13 cm, 13 cm), in the middle upper part of the image (40 cm, 13 cm), or in the middle lower part of the image (40 cm, 40 cm).

Figure 1 shows a top view of the location of the stimuli and their location with respect to the participant. The centres of the matching-line locations are indicated by an asterisk, the centre of the reference-line location by a plus sign.

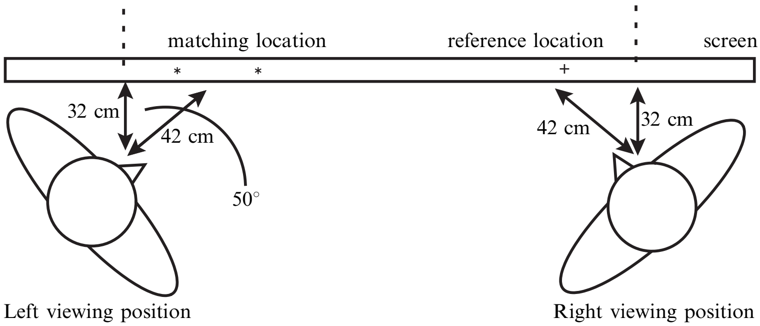

Figure 1. Top view of the location of the stimuli with respect to the viewing positions of the participants. Dashed lines indicate edges of computer-generated display. Asterisks denote the centres of the matching-line locations, which are 13 cm and 40 cm from the left edge of the computer display. The plus sign shows the location of the reference line, which is at 122 cm from the left edge of the computer display. The distance of the left eye to the screen is 32 cm. The distance from the left eye to the straight-ahead position on the screen is 42 cm.

2.1.4 *Design.* Four main orientations of the reference line were used: 45°, −45°, 0° (horizontal line), and 90° (vertical line) with respect to the horizontal. Here we have used the convention that +45° corresponds to a counterclockwise rotation over 45° of a horizontal line.

An additional scatter of 2° or 4° was added to these main orientations. So, for example, for the 45° orientation, the reference line could be presented at an orientation of 41°, 43°, 45°, 47°, or 49°. The participants were told that some scatter had been added to the orientation of the line, so that it would be important to align the two orientations instead of, for example, matching some preconceived orientation relative to external cues, such as gravity or the edges of the screen.

Each combination of the four main orientations and the three matching locations was presented 10 times to each participant. This resulted in a total of 120 trials, which took each of the participants about 30 min to complete. For each trial, the orientation of the matching line was selected at random from a uniform distribution in the range from 0° to 180°. The order of the trials was randomised across participants.

2.1.5 *Procedure.* Participants were seated in a chair at either the left or the right of the computer screen, depending on the viewing-position condition. The height of the chair was adjusted such that the participants were viewing it at the same height as they would have been viewing the screen if they had been standing. This was done to make the results comparable to those of experiments 2 and 3, in which participants were standing.

At the beginning of each trial, two lines, each consisting of seven dots, appeared on the screen and the participant was asked to rotate the matching line using the computer keyboard, until s/he thought the two lines looked parallel.

After the participant had pressed the button to ask for the next trial, a 1000 ms intertrial interval was started in which the screen was cleared. After this interval, two new lines were plotted on the screen.

2.1.6 *Data analysis.* For each trial, two error measures were computed: a signed error and an unsigned error. The signed error was computed as the difference between the orientation of the reference line and the matching line. The unsigned error was the absolute value of the signed error. Statistical tests on means per participant were conducted to test for each reference-line orientation and matching-line location, whether the orientations of the matching lines were different from the orientations of the corresponding reference lines. Additional tests were carried out to check whether systematic errors differed for the different positions of the matching line. To test for the oblique effect, the unsigned errors of the oblique orientations were compared with those of the orthogonal orientations with participants as a random factor. In a two-way MANOVA the effects of orientation (oblique/orthogonal) and matching-line location were tested. Unidirectional tests were used.

2.2 *Results*

In figures 2 and 3 the produced orientations are plotted for the left and the right viewing positions, respectively, together with the orientations of the reference lines for each of the locations of the matching lines. Longer lines represent the orientations of the reference lines, shorter lines the orientations of the matching lines. Results of statistical tests are included in the figure (a Bonferroni correction was used to correct all effects for the number of tests). The reference lines are plotted at the same location as the matching lines for a convenient comparison with the matching lines. In fact, the reference stimuli were to the right of the plot. Mean signed errors (an indication of the size of systematic errors) and mean standard deviations (an indication of the size of variable errors) across participants are presented in table 1.

Table 1. Mean signed errors and mean standard deviations across participants observed in experiment 1. A single asterisk denotes a significant effect at a significance level of 5%.

Location	0°		90°		45°		−45°	
Left viewing position								
Lower right	−2.0417	(2.0716)	0.1033	(2.2650)	−11.8317*	(3.6154)	1.0750	(2.5409)
Upper left	1.1083	(4.8250)	−0.090	(2.5614)	−8.2400*	(3.2109)	11.7033*	(4.0438)
Upper right	−3.7500	(11.8363)	0.1183	(3.1027)	−5.2550	(6.8526)	6.6783*	(4.1006)
Right viewing position								
Lower right	1.4157	(1.8963)	−0.1700	(2.7154)	7.2271*	(4.0560)	−3.3314	(3.2260)
Upper left	0.1786	(1.4708)	−0.5529	(3.1198)	7.8929*	(6.3491)	−5.6486*	(3.8877)
Upper right	0.4529	(1.6580)	−0.0614	(2.9302)	6.3957*	(2.5904)	−4.8371*	(3.0944)

Systematic errors were found for the oblique but not for the horizontal and vertical ('orthogonal') orientations, both for the left and for the right viewing positions. However, for the −45° orientation at the lower-right presentation location, no differences were found between reference-line and matching-line orientations. For the left viewing position there was a small difference between the orientation of the matching line and the reference line for the 45° orientation at the upper-right location, but this difference did not reach significance.

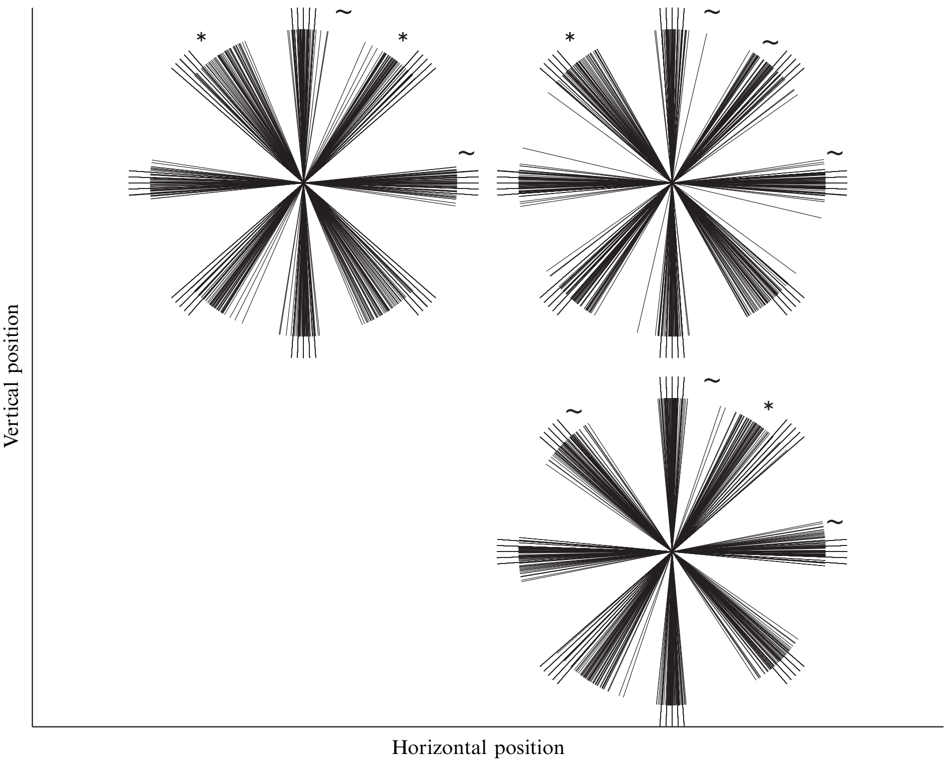

Figure 2. Orientations of the reference lines (longer lines) together with the matching-line orientations (shorter lines). The plot presents results from all trials from all participants. The symbols near the lines show whether the corresponding difference between the orientations of the reference lines and the matching lines were significantly different. Here and in the remaining figures, a tilde sign denotes a non-significant effect; a single asterisk represents a significant effect at a significance level of 5%; and a double asterisk represents a significant effect at a significance level of 1%.

Unsigned errors between oblique and orthogonal orientations were compared to see whether an oblique effect was present in our data set. For the left viewing position, an oblique effect was found ($F_{1,5} = 18.098$, $p = 0.008$), which did not significantly interact with matching-line location ($F_{2,4} = 4.358$, $p = 0.099$). There was an oblique effect for the right viewing position too ($F_{1,6} = 10.746$, $p = 0.017$), which did interact with matching-line location ($F_{2,5} = 10.022$, $p = 0.0018$).

For the left viewing position, the produced orientations for the upper left and upper right matching-line location were found to be significantly different for the $-45°$ orientation ($t_5 = 5.446$, $p = 0.003$). In addition, for both oblique orientations, significant differences were observed for the upper-right and lower-right matching-line location ($-45°$: $t_5 = -5.880$, $p = 0.002$; $45°$: $t_5 = -3.725$, $p = -0.0014$). For the right viewing position no differences were found between the systematic errors for the upper-left and upper-right matching-line positions. Neither were there significant differences between errors for the upper-right and lower-right positions.

2.3 *Discussion*

The results in figures 2 and 3 can be best summarised by stating that an oblique line is perceived to be more oriented towards the vertical at more nearby locations (figure 2). This is equivalent to stating that the orientation of an oblique line is perceived to be more oriented towards the horizontal at more distant locations. In figure 2, the matching line was presented nearby while the reference line was farther away. Because lines

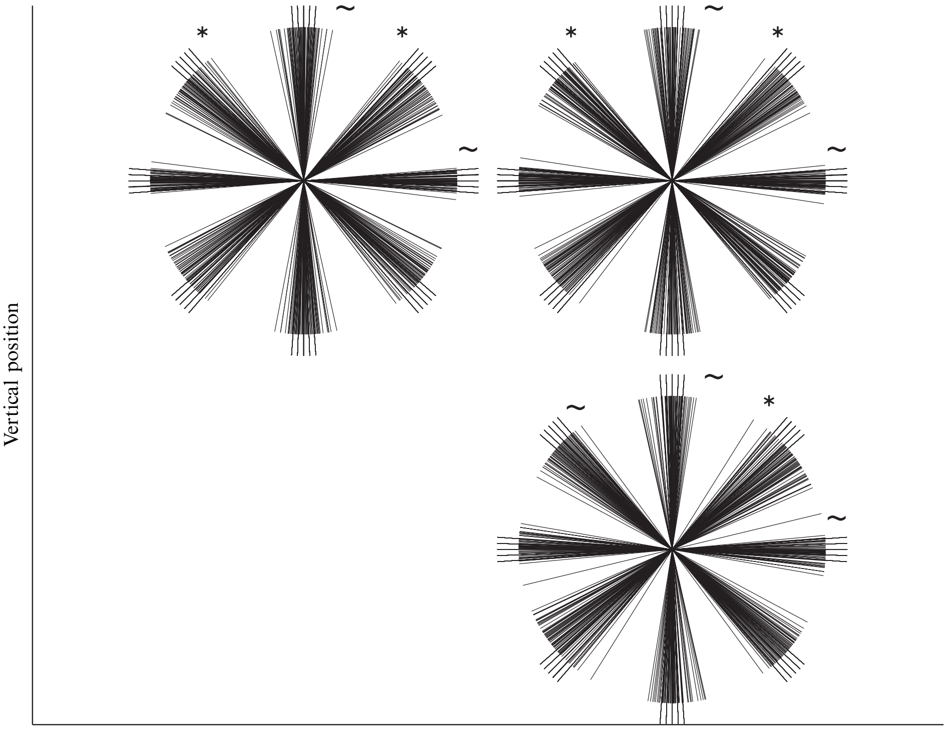

Figure 3. Orientations of the reference lines together with the produced orientations. The plot presents results from all trials from all participants. The data for the right viewing position are shown.

farther away seem to be perceived more oriented to the vertical, participants rotated the nearby matching line towards the vertical to match the perceived orientation of the reference line. In figure 3 the reference line was presented nearby and the matching line was farther away. In this condition, the distant matching line was perceived to be oriented more to the vertical such that participants rotated its orientation towards the horizontal to match the perceived orientation of the nearby reference line.

In a previous study on haptic perception, Kappers and Koenderink (1999) reported that differences between the orientation of a reference bar and a matching bar increased for larger angles between the reference bar and matching bar relative to the subject. The radial distance relative to the subject did not appear to have any effect. That study deals with bars in a horizontal plane, whereas our study deals with the orientation of lines in a vertical plane. Therefore, it is appropriate to address the question to what extent any differences in orientation of the matching line and reference line in our study have to be attributed to the different viewing angle or to the different distances of the lines relative to the observer. The results of viewing from the left and right sides are compatible with both hypotheses. Therefore, we did a pilot experiment, in which we asked two subjects, who also participated in the first experiment, to visually match the stimuli of experiment 1, while sitting right in front of the screen at a distance of about 32 cm. In this condition, the distances of the participant relative to the reference line and the upper-left matching line are the same and the viewing angle in this condition is much larger than for the same stimuli in experiment 1. The results revealed much smaller consistent (signed) errors for the oblique stimuli, suggesting that the errors have to be attributed mainly to distance, rather than to the viewing angle.

In only a few studies on visual perception subjects have been tested in viewing conditions other than straight ahead. Some experiments have been carried out in which a drawing or a picture was looked at from different angles (Cutting 1988; Deregowski and Parker 1995; Goldstein 1987; Halloran 1993). In these experiments, drawings were shown in which perspective was used to suggest a 3-D scene. For example, Goldstein (1987) presented a picture of three columns in a 3-D scene to participants, and asked them to estimate the distance in depth from one column to the other. Estimated depth and perceived orientations of painted objects were found to be quite independent of viewing angle, an effect known as the 'differential rotation effect'. In our experiments, we did not try to induce depth in our stimuli. The stimuli were 2-D lines with no intention to make them look as if they would point outside the plane of the screen. In fact, none of our participants reported that s/he perceived the lines coming outside the plane of the screen. In addition, we found a strong effect of viewing position, and therefore the 'differential rotation effect' does not apply to our data.

3 Experiment 2

In the second experiment we tested whether the systematic effects found in experiment 1 for visual matching in the vertical plane are also found when participants have to match the orientation of the perceived line using a hand-held bar.

3.1 *Method*

3.1.1 *Participants.* Seven participants took part in the experiment. Two of them were the authors. Five of the participants had also participated in experiment 1. Two participants were paid for taking part. All participants had normal or corrected-to-normal vision.

3.1.2 *Apparatus.* For stimulus presentation, the same PC and LCD projector were used as in experiment 1. In experiment 2 participants were asked to match the orientation of the reference bar by adjusting the orientation of a hand-held bar. The bar used was 29 cm long and weighed 0.32 kg. The orientation of the bar was measured with the Optotrak 3020 system (Northern Digital Inc.), which determined the position of two infrared light-emitting diodes (IREDs), attached to the bar at a distance of 20 cm. The accuracy of the orientation of the bar could be measured with an accuracy better than 0.5°.

3.1.3 *Stimuli and design.* The stimuli and the design of the experiment were almost the same as in the location of the matching line in experiment 1. Instead of the matching line, a small circle was presented at the location of the matching line in the first experiment. The circle indicated to the participant where to match the orientation of the reference line by the orientation of the hand-held bar.

3.1.4 *Procedure.* Participants were standing at the left position illustrated in figure 1. All participants were asked to hold the bar in their right hand, although two participants were left-handed. No differences were found in the pattern of results for the left-handed and the right-handed participants. Participants were instructed to use a powerful grip to hold the bar. At the beginning of each trial, the reference line appeared at the upper right of the screen (as in experiment 1), and a circle appeared at one of the three matching locations (upper left, upper right, or lower right). Participants would then move the hand-held bar towards the location of the circle while orienting the bar such that they thought its orientation matched that of the reference bar. 2 s after the presentation of the line an auditory signal told the participant to hold the orientation of the bar as fixed as possible. A second tone, presented 1.5 s after the first tone, indicated that the arm could be moved back to the starting position near the waist. During the interval between the two auditory signals the orientation of the bar was measured by the Optotrak system. After each 30 trials there was a break of about 1 min.

3.1.5 *Data analysis.* The mean location (averaged over 90 samples) of each IRED during the measurement period was calculated. Trials in which one of the IREDs was not visible to the Optotrak system (about 5 trials per participant), or in which participants moved the bar during the period in which the Optotrak system measured the orientation of the bar (about 2 trials per participant), were removed from the data analysis. For the remaining trials, the orientation of the bar was calculated by fitting a line through the two mean IRED locations. The calculated orientations were analysed in the same way as those observed in experiment 1.

3.2 *Results*

In figure 4, the orientations of the hand-held bar are shown together with the orientations of the reference line. Data of all participants are plotted in one figure. The symbols near the lines present the significance level of the differences between matching-line and reference-line orientations across participants. The mean errors and mean standard deviations across participants are shown in table 2.

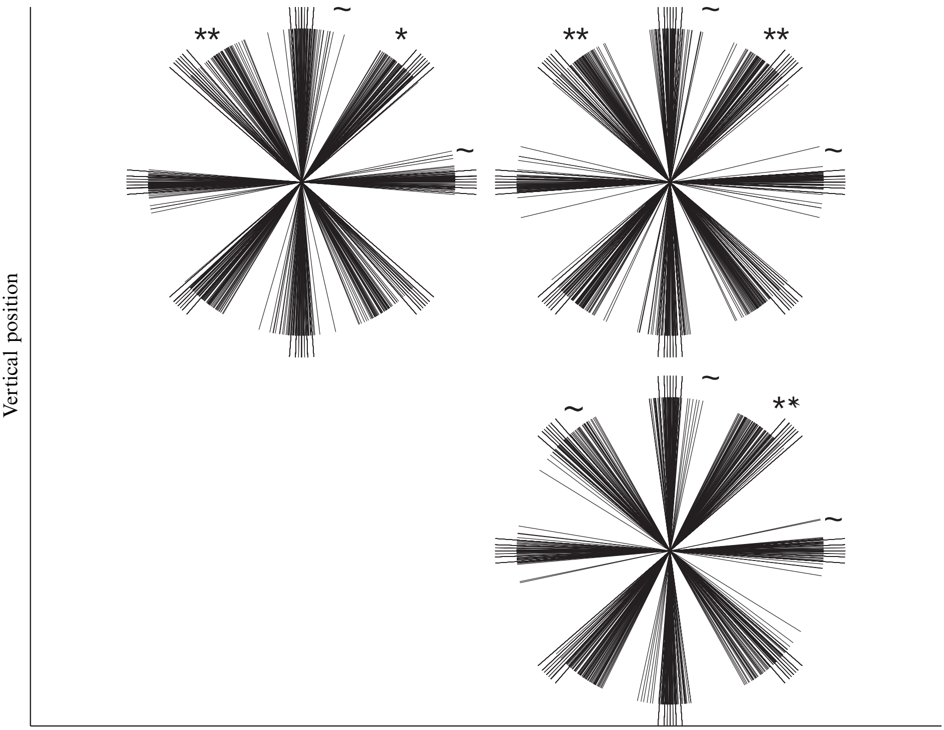

Figure 4. Orientations of the reference lines together with the orientations of the matching lines for all participants for the three matching locations.

Table 2. Mean signed errors and mean standard deviations across participants observed in experiment 2. A single asterisk denotes a significant effect at a significance level of 5%. Double asterisks represent significant effects at a significance level of 1%.

Location	0°		90°		45°		−45°	
Lower right	−0.4978	(2.3613)	0.3771	(3.8801)	−10.1933**	(5.1686)	4.1686	(3.3705)
Upper left	−1.5171	(2.2855)	1.4234	(3.0848)	−5.9513*	(4.2122)	12.1187**	(4.0941)
Upper right	0.1427	(2.5358)	0.1154	(3.1121)	−7.5173**	(4.8091)	8.8953**	(2.9565)

The orientations of the matching lines for the upper-right and lower-right stimulus locations differed for the $-45°$ orientation ($t_6 = -3.917$, $p = 0.008$), but not for the $45°$ orientation ($t_6 = -2.380$, $p = 0.055$). Differences were found between orientations produced at the upper-left and upper-right stimulus locations both for the $45°$ orientation ($t_6 = 3.971$, $p = 0.007$) and the $-45°$ orientation ($t_6 = 4.933$, $p = 0.003$). A clear oblique effect was found ($F_{1,6} = 312.479$, $p < 0.01$), which did not interact with stimulus location ($F_{2,4} = 2.861$, $p = 0.148$).

Since five of the participants of experiment 2 also took part in experiment 1, it was possible to compare the size of the effects in both experiments directly. For this comparison, data from the left viewing position of experiment 1 were used. Figure 5 shows the produced orientations of experiment 1 in the outer circle, together with the orientations of experiment 2 in the inner circle. The symbols near the lines indicate the significance level of the differences in signed errors. No significant differences were found for signed and unsigned errors in experiments 1 and 2.

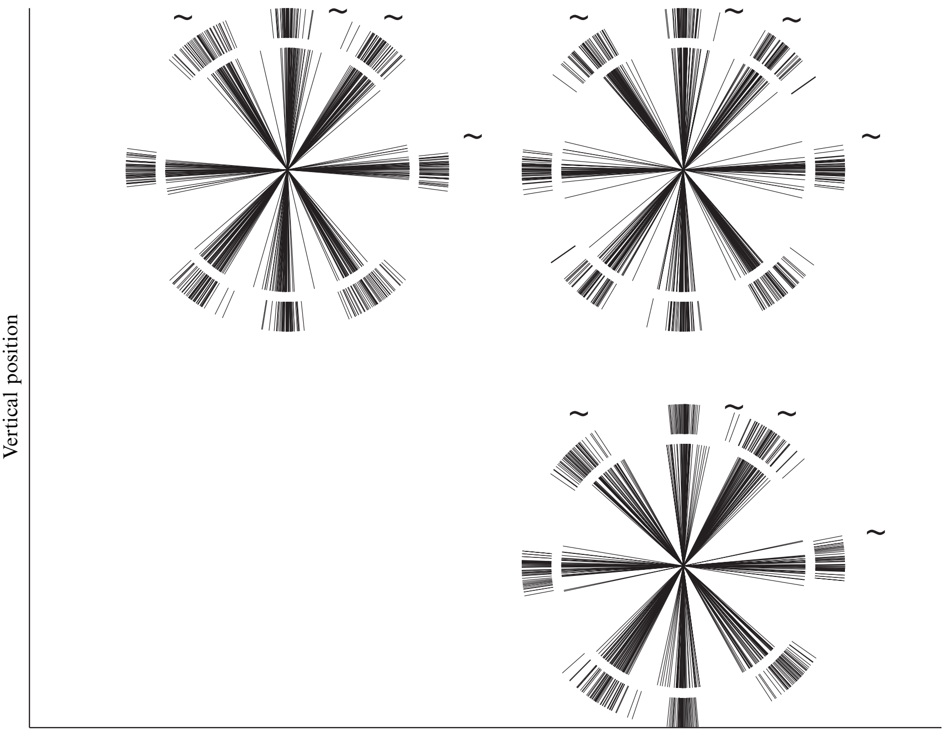

Figure 5. Orientations of matching lines of experiments 1 and 2. The lines at the outer circle show the orientations of experiment 1, those in the inner circle the orientations of experiment 2.

3.3 *Discussion*

Both for haptic and visual matching, systematic errors were found for the oblique orientations but not for the horizontal and vertical orientations. The direction and size of the effects were the same for both matching tasks. One could argue that vision of the edges of the screen near the matching stimulus might have resulted in the lack of systematic effects for the orthogonal orientations in experiments 1 and 2. Participants might have compared the matching-line orientation to the edges of the screen. To see whether participants actually used this information, scatter was added to the reference-line orientations. If participants used the edges of the screen to orient the matching-line orientations, smaller correlations between orientations of matching and reference lines would be expected for orthogonal than for oblique orientations, since the edges were a better reference for vertical and horizontal orientations.

Table 3 shows the values of these correlations. The correlations shown were computed within each main orientation. Therefore, they summarise how accurate participants were at matching the small variations of a few degrees around each main orientation. For all three matching conditions correlations were higher for the orthogonal than for the oblique directions, with mean values near 0.60 and 0.37, respectively. This implies that participants better matched the small variations in orientation for the orthogonal directions than for the oblique directions, which obviously argues against the use of the edges of the screen to match lines at orthogonal directions.

Table 3. Mean correlations (Pearson product – moment correlation coefficient) across participants between presented and produced orientations for experiments 1 and 2.

Main orientation	Experiment 1, left	Experiment 1, right	Experiment 2
0°	0.55	0.81	0.60
90°	0.52	0.80	0.38
45°	0.35	0.61	0.20
−45°	0.36	0.53	0.21

Additionally, if participants used the edges of the screen, larger matching errors for orthogonal orientations would have been expected for matching locations farther away from the edges of the screen. This was not found. Participants matched the orthogonal orientations equally correctly for all three matching locations.

Participants might have carried out the haptic matching of experiment 2 as if it were a visual matching task, since they had sufficient time to reorient the bar before its orientation was measured. If participants strongly relied on the visually perceived orientation of the bar, similar results should be expected in experiments 1 and 2.

In experiment 3, a mask made the bar and the hand invisible to the participant while matching the visually presented orientation. If participants of experiment 2 relied primarily on visual information of the orientation of the bar and if haptic and visual matching actually result in different matched orientations, different results have to be expected for experiments 2 and 3.

4 Experiment 3

In experiment 3, participants were asked to match the orientation of a reference line by orienting a hand-held bar. The field of view was restricted to the reference line by a piece of cardboard which occluded the remainder of the visual field. Although hand and bar could not be seen, participants could see the reference line while matching its orientation.

4.1 *Method*

4.1.1 *Participants.* Seven participants took part in the experiment. Two of them were the authors. Two participants were paid for their participation. All participants had normal or corrected-to-normal vision. Two participants were left-handed.

4.1.2 *Apparatus and stimuli.* Apparatus and stimuli were the same as in experiment 2. A piece of cardboard prevented the participant from seeing his/her hand and the bar while matching the reference orientation.

4.1.3 *Design.* Each participant took part in two sessions of 120 trials each. The number of trials was doubled with respect to the first two experiments because the variance in the produced orientations was found to be much larger without than with visual feedback. In all other aspects the design of the experiment was the same as in experiment 2.

4.1.4 *Procedure.* There was one difference with respect to the procedure of experiment 2. A piece of cardboard prevented the participant seeing his/her hand and the bar while matching the orientation of the reference line. Participants were asked to keep fixating the reference stimulus while matching its orientation. Below the reference line, the Dutch words for 'upper left', 'lower right', and 'upper right' were printed to indicate the location at which the orientation had to be matched (the same locations as in experiments 1 and 2). At the beginning of the experiment, participants held their hands at the locations where they thought they would have to match the orientation, in order to agree on the locations to be used. During the experiment, the experimenter watched where participants matched the reference location. If the bar was held at a location closer to one of the other matching locations than to the instructed matching location, the experimenter would tell the participant in which direction to change the location of the bar.

Participants did not always hold the bar at exactly the matching location, since they could not see where they were holding their hand while matching. The mean coordinates of the locations where the bar was held were 33 cm from the left and 27 cm from the top (33 cm, 27 cm) of the computer display for the upper-left condition, (99 cm, 35 cm) for the upper-right location, and (113 cm, 133 cm) for the lower-right location.

4.1.5 *Data analysis.* For each trial, the location of the centre of the two IREDs at each side of the bar was computed. This centre location was entered in a three-means clustering algorithm where the instructed locations were used as starting values. This way the produced locations were grouped into three clusters together with the corresponding produced orientations. The orientations of each cluster were analysed with the same data analysis procedures as in experiments 1 and 2.

4.2 *Results*

Orientations of reference and matching lines are plotted in figure 6. The orientations are presented at the location at which participants had to match the reference orientation. Data of all participants are plotted in one figure, as was done for experiments 1 and 2. Near the lines, the results of *t*-tests of the difference between reference-line and matching-line orientations are shown. As in experiments 1 and 2, significant differences were found for the oblique orientations, except for the $-45°$ orientation at the lower-right location. Mean errors and mean standard deviations across participants are presented in table 4.

Table 4. Mean signed errors and mean standard deviations across participants observed in experiment 3. Single asterisks denote a significant effect at a significance level of 5%. A double asterisk represents a significant effect at a significance level of 1%.

Location	0°	90°	45°	−45°
Lower right	−4.7441 (4.9380)	0.2877 (4.8218)	−12.1142** (6.6763)	−2.1080 (6.4514)
Upper left	−5.8967 (5.7180)	−2.1210 (6.1586)	−6.7651* (7.9533)	9.2611* (5.1658)
Upper right	−4.0328 (4.4919)	−1.0419 (6.0510)	−8.3715* (6.4237)	7.0739* (3.2532)

No significant difference was found between signed errors for the upper-left and the upper-right positions (for the $-45°$ orientation: $t_6 = 1.385$, $p = 0.215$; for the $45°$ orientation: $t_6 = 1.760$, $p = 0.129$). The signed errors for the oblique orientations at the upper-right and lower-right positions were significantly different (for the $-45°$ orientation: $t_6 = 2.507$, $p = 0.046$; for the $45°$ orientation: $t_5 = 6.746$, $p = 0.001$).

Unsigned errors for oblique and orthogonal directions were significantly different ($F_{1,6} = 28.377$, $p = 0.002$). The oblique effect did not interact with stimulus position ($F_{2,5} = 0.144$, $p = 0.870$).

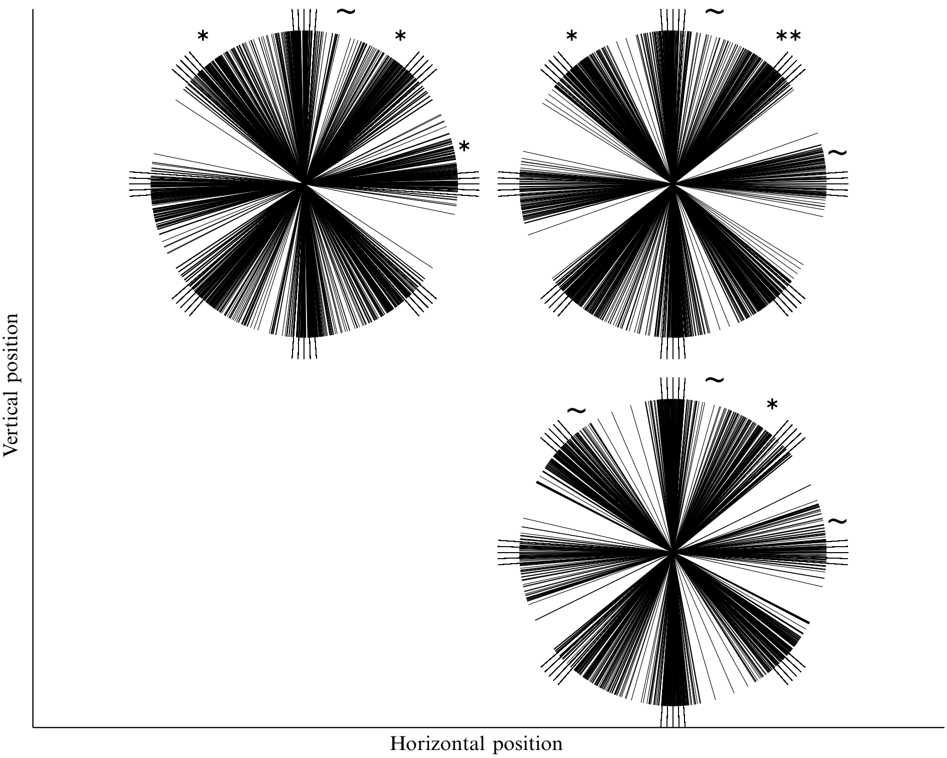

Figure 6. The orientations of the reference lines (long lines) together with the matched orientations (short lines) for all participants.

Because five of the participants of experiment 3 also participated in experiment 2, the results of the two experiments could be compared by using within-subject tests. In figure 7, the produced orientations in both experiments are shown. The lines at the outer circle present data from experiment 3, and lines at the inner circle data from experiment 2. The symbols near the lines show the outcomes of *t*-tests comparing the signed errors of both experiments. As the symbols show, no significant differences were found in the signed errors of the two experiments.

In a three-way MANOVA the effects on unsigned errors of matching condition (with or without visual feedback), matching-line location, and reference-line orientation were tested. Significant effects of matching-line location ($p = 0.030$) and reference-line orientation ($p = 0.002$) were found. No interaction effects were found.

4.3 *Discussion*

The design of experiment 3 was somewhat similar to that used by Soechting and Flanders (1993), who asked participants to match the orientation of a visually presented bar with a bar at waist level. In their study, participants always fixated the reference bar during the matching task, so that they had no visual information about the orientation of the matching bar near their waist. Systematic errors were reported for slanted orientations but not for horizontal and vertical orientations of the reference bar. In this respect their data are similar to ours. Unfortunately, subjects in their study and in our study viewed the stimuli from very different viewing angles. In our experiment, participants looked at the reference lines from aside (either from the left or from the right), while in the experiment by Soechting and Flanders the stimuli were presented in front of the participants. Since experiment 1 showed that viewing position has an effect on matching errors, the different viewing positions of the participants make it difficult to compare the results of the two studies quantitatively.

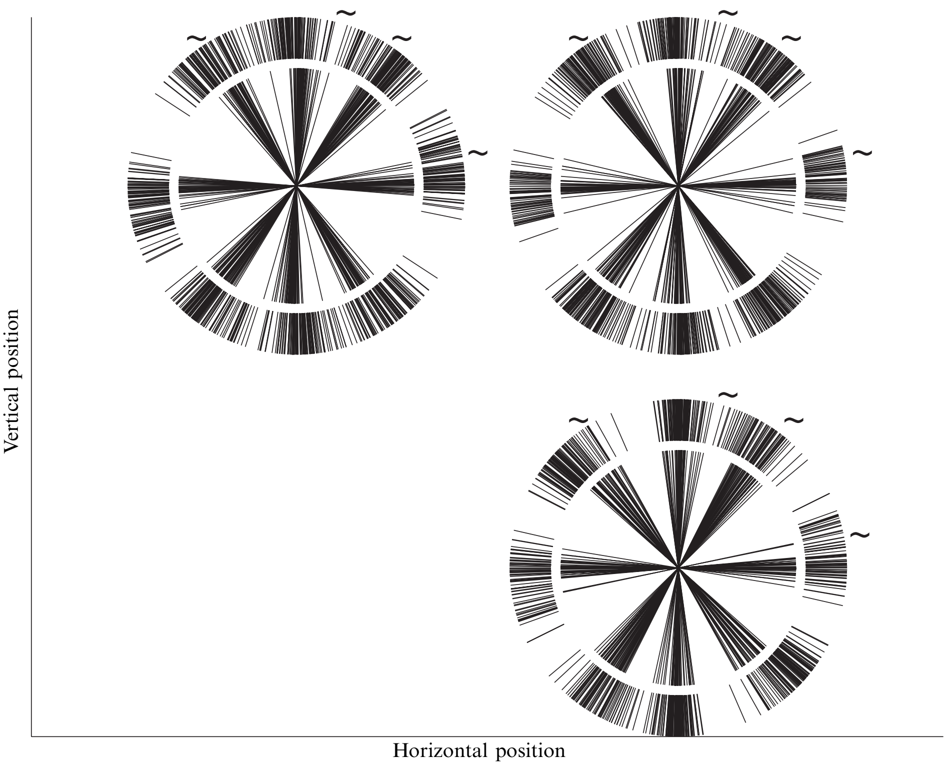

Figure 7. Produced orientations for experiments 2 and 3. Lines at the outer circle show data of experiment 3, those in the inner circle data of experiment 2.

An oblique effect was found by comparing unsigned errors. In view of the variability of matching in figure 6, this may be somewhat surprising. Figure 6 does not seem to show a large oblique effect, since oblique orientations seem to be produced with almost the same accuracy as orthogonal directions. A reason for the unexpected oblique effect might be the use of unsigned errors to test for the oblique effect (see, for example, Luyat et al 2001). In the presence of systematic errors, it might be better to test for differences in variance. We have used the variance to test for an oblique effect in our data and found no significant oblique effect ($p = 0.168$) with this measure.

5 General discussion

We have found clear systematic effects when visually presented oblique orientations had to be matched in three different tasks: (i) visual matching, (ii) haptic matching with visual feedback, and (iii) haptic matching without visual feedback. The systematic errors were identical for the three matching situations, not only qualitatively but also quantitatively.

Part of the explanation of the matching errors might be that participants could not fully correct for geometric distortion of the two lines on the retina. In general, when two parallel lines are projected on the plane of the retina, their projection will not be parallel. Only parallel horizontal and vertical lines will have parallel retinal projections. This might explain why the orientations of horizontal and vertical lines were matched correctly, and why systematic errors were found for oblique lines. However, the errors made by the participants were smaller than those expected on the basis of the geometric distortion. Therefore the distortion of orientations by projection on the retina can be only a part of the explanation.

Our study suggests that systematic errors in matching are primarily due to errors in visual perception of the lines, while the variable errors in matching are primarily due to errors in haptics. As explained in section 1, errors in visual perception have been reported frequently in the literature. Some workers have reported that motor responses to visual stimuli reflect errors in visual perception, while others have suggested that motor responses may be insensitive to errors in visual perception. Obviously, our results are in agreement with the former.

References

Chen S, Levi D M, 1996 "Angle judgement: Is the whole the sum of its parts?" *Vision Research* **36** 1721 – 1735

Cuijpers R H, 2000 *The Geometry of Visual Space* PhD thesis, University of Utrecht, Utrecht, The Netherlands

Cuijpers R H, Kappers A M L, Koenderink J J, 2000 "Large systematic deviations in visual parallelism" *Perception* **29** 1467 – 1482

Cutting J E, 1988 "Affine distortions of pictorial space: Some predictions for Goldstein (1987) that la Gournerie (1859) might have made" *Journal of Experimental Psychology: Human Perception and Performance* **14** 305 – 311

Deregowski J B, Parker D M, 1995 "Viewing angle and the perceived orientation of pictorial elements: geometric or representational effects?" *Perception* **24** 1139 – 1153

Flanders M, Soechting J F, 1995 "Frames of reference for hand orientation" *Journal of Cognitive Neuroscience* **7** 182 – 195

Foley J M, 1980 "Binocular distance perception" *Psychological Review* **87** 411 – 434

Goldstein E B, 1987 "Spatial layout, orientation relative to the observer, and perceived projection in pictures viewed at an angle" *Journal of Experimental Psychology: Human Perception and Performance* **13** 256 – 266

Halloran T O, 1993 "The frame turns also: Factors in differential rotation in pictures" *Perception & Psychophysics* **54** 496 – 508

Kappers A M L, Koenderink J J, 1999 "Haptic perception of spatial relations" *Perception* **28** 781 – 795

Kappers A M L, Pas S F te, 2001 "Deformation of visual space at the ECVP in Groningen" *Perception* **30** 1275 – 1276

Koenderink J J, Doorn A J van, Lappin J S, 2000 "Direct measurement of the curvature of visual space" *Perception* **29** 69 – 79

Luyat M, Gentaz E, Corte T E, Guerraz M, 2001 "Reference frames and haptic perception of orientation: Body and head tilt effects on the oblique effect" *Perception & Psychophysics* **63** 541 – 554

MacRae A W, Loh H K, 1981 "Constant errors occur in matched reproduction of angles even when likely biases are eliminated" *Perception & Psychophysics* **30** 341 – 346

Norman J F, Lappin J S, Norman H F, 2000 "The perception of length on curved and flat surfaces" *Perception & Psychophysics* **62** 1133 – 1145

Norman J F, Todd J T, Perotti V J, Tittle J S, 1996 "The visual perception of three-dimensional length" *Journal of Experimental Psychology: Human Perception and Performance* **22** 173 – 186

Regan D, Gray R, Hamstra S J, 1996 "Evidence for a neural mechanism that encodes angles" *Vision Research* **36** 323 – 330

Soechting J F, Flanders M, 1993 "Parallel, interdependent channels for location and orientation in sensorimotor transformations for reaching and grasping" *Journal of Neurophysiology* **70** 1137 – 1150

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