Chapter 6
Visual perception of tilted planes

Abstract:
The ball-in-plane task tests whether observers can accurately place a ball by eye in a plane defined by three reference balls located in three-dimensional space. We varied the direction in which the plane was tilted and the shapes of the triangles formed by the reference balls. We found that the observers placed the test-ball too low when they looked at the plane from above. The observers had small negative or positive deviations when they look at the plane from below, with a downward trend when the azimuthal angle diverges from 0°. These data suggest that, at least when the observers looked at the plane from above, they perceived the plane as concave.

In preparation for publication

6.1 Introduction

Visual space has been investigated by means of various tasks. The first experiments were done with parallel and equidistance alleys in the horizontal plane (Hillebrand, 1902; Blumenfeld, 1913). The main conclusion from these experiments was that parallel and equidistance alleys differed from each other: the equidistance alleys were found to lie outside the parallel alleys. Battro, di Pierro Nettro and Rozestraten (1976) used comparable alley experiments on a larger scale in outdoor settings. They found no uniform deformation of visual space across scales and observers. Furthermore, Indow and Watanabe (1984, 1988) investigated the frontoparallel and the horizontal subspaces with alley-experiments. They concluded that the deformation of visual space varies with scale, observers and subspaces (Indow & Watanabe, 1988).

Another task that is often used is a horopter task (an 'apparent frontoparallelity task' is a better name). In this task, observers have to form with light-points or stakes (depending on the experimental set-up) a horizontal line that is frontoparallel. One or more points are fixed and the other points have to be placed in the same plane. Some scientists found that most observers form an apparent frontoparallel line that is concave towards the observer for smaller distances (up to 5 meters) whereas the apparent frontoparallel is convex towards the observer when the distances are larger (Foley, 1991). Other scientists found the apparent frontoparallel plane to be concave for both far and near distances (Koenderink, van Doorn, Kappers, & Lappin 2002); while Battro, et al. (1976) found no consistent pattern for their observers. Nevertheless, most scientists agree that the apparent frontoparallel plane is concave towards the observers at distances of up to 5 meters.

Other methods of studying the relative distances of objects from an observer consist of exocentric pointing, parallelity, body-pointing or collinearity tasks. These tasks were done mainly in the horizontal plane at eye-height. Results were dependent on experimental conditions. For example, Kelly, Loomis and Beall (2004) compared the results of a body-pointing task, in which the observer had to direct his body in the same orientation as a line-segment (defined by two stakes), with a collinearity task, in which the observer had to place a point collinear to two other points. They found similar results for the tasks, although there was a bias in the body-pointing task that was not present in the collinearity task. Furthermore, one should be careful in comparing tasks that may rely on different sources of information. For example, different results can be obtained with a parallelity task (putting a horizontal rod parallel to another rod) and an exocentric pointing task (directing a pointer at a ball). We found that the different results can be explained by the fact that for the parallelity task an observer does not need to know the exact positions of the two rods (Doumen, Kappers, & Koenderink, 2005), whereas this information is essential for the exocentric pointing task. Thus, particular constraints of the tasks do influence the results.

Recently, we developed a three-dimensional exocentric pointing task (Doumen, Kappers and Koenderink, in press A [Chapter 3], in press B [Chapter 4]) to enable us to progress from two-dimensional experiments to three-dimensional versions. The deviations in the horizontal plane found with the three-dimensional exocentric pointing task were comparable to the deviations found with two-dimensional tasks. Furthermore, we found that the relative distance of the ball and the pointer to the observer had no effect on the deviations in the vertical plane. Since the deviations we found for the horizontal plane were dependent on the relative distance, we conclude that visual space is anisotropic, as already mentioned by Indow and Watanabe (1988).

Just as we can expand our knowledge by proceeding from a two-dimensional exocentric pointing task to a three-dimensional one, we can also expand the apparent frontoparallelity task to a three-dimensional version. In the light of the anisotropic data that were produced for different sub-spaces (Indow & Watanabe, 1988), it is a logical step to develop tasks for measuring three-dimensional space. We wanted to investigate three-dimensional space instead of various sub-spaces. In the ball-in-plane-task, a plane is defined by three balls that are suspended from the ceiling. The observer can adjust the height of the fourth ball. The task is to hang the ball in the plane defined by the other three balls. In the experiments described in this paper we investigated the orientation of the plane with respect to the position of the observer. By varying the orientation of the plane, one automatically varies the observer's view of the plane: the observer can look at the plane from above, from below or the plane might pass through the cyclopean eye of the observer. These different views of the pointer may elicit different settings. If we assume that flat planes are perceived as concave (Foley, 1991; Koenderink et al., 2002), we can hypothesize that the observer will hang the test-ball too high when he views the plane from below and too low when he looks at the plane from above.

In this paper we will discuss the results of three experimental conditions in which we varied the angle at which the plane, defined by the three balls, was tilted (the azimuthal angle). Furthermore, we varied the shape of the triangle that was formed by the three balls. We compared the results for conditions where the balls formed an acute, an obtuse and an equilateral triangle. Thus, the goal of the experiment was to obtain insight into the effect of the azimuthal angle of the plane and to find out whether the shape of the triangle influenced this effect.

6.2 Methods

Observers

Twenty-four undergraduate students, who were paid for their efforts, participated as observers in the experiments described below; there were eight observers per experimental condition. They were naive as to the purposes of the experiments and had little or no experience as observers in psychophysical experiments. Before starting these experiments, they had been observers in another experiment that consisted of an exocentric pointing task. However, they were not given any feedback about the purpose and their own performance in that experiment before the end of the following experiments. Furthermore, they all had normal or corrected-to-normal sight and they were tested for stereo-acuity. Each observer had a stereo-acuity of more than 60''.

Set-up

The experiment was conducted in a laboratory room measuring 6 m by 6 m by 3.5 m. The wall opposite the observer was white, with some electrical sockets near the floor. The wall on the left-hand side of the observer contained four blinded windows with radiators underneath them. The wall on the right-hand side of the observer contained two gray doors. The floor was empty except for some markers that were used to position the objects that were used for the former task. A horizontal iron grid was suspended below the ceiling at a height of 3 m above the ground. From this grid, white cubes were hung that contained the balls that were used for the experiments. The balls used were snooker-balls (with a diameter of 6 cm). Three red balls were hung in a triangle (the reference-balls), while another ball (brown or yellow) was hung between the other balls (the test-ball). The height of the balls could be adjusted with a PC with an initial speed of 70 mm/sec. The observer could adjust the height of the test-ball with a remote control. The observer could move the test-ball up and down with two jog-speeds (26 and 62 mm/sec). The observer could press a "ready-button" when he was satisfied with the height of the test-ball. The position of the test-ball was read at that moment and the value was written in an output-file by the PC. The balls were calibrated each morning: balls on the floor were at height 0. The observers sat on a revolving chair that was adjustable in height. All observers were seated at an eye-height of 150 cm.

For each experimental condition, the balls and observers were placed at different positions in the experimental room. The reference balls were hung in different triangles from the grid, as can be seen in Figure 6.1. We performed measurements with an acute, an obtuse and an equilateral triangle (in the azimuthal plane). In Figure 6.1, the circle corresponds to the positions of the observer, and the black dots correspond to the positions of the reference balls in the azimuthal plane. Furthermore, the black lines represent the direction of the steepest upward vector in the plane that was constructed with the reference balls. The center of the lines gives the position of the test-ball in the azimuthal plane. In Table 6.1, the exact coordinates of the positions of the balls and observers are given in cm. Table 6.2 gives the values used for the elevation and the azimuthal angles used for the construction of the planes

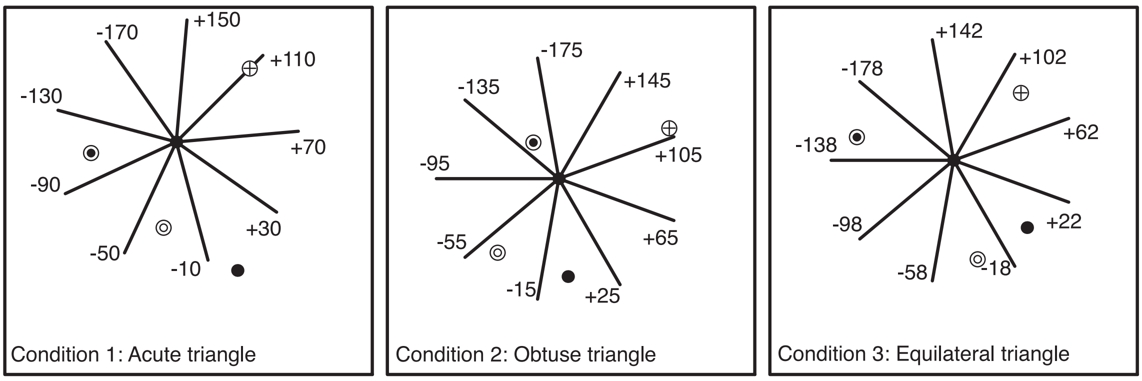

Figure 6.1
Top-views of the room for the three different experimental conditions. The black dot represents the position of the observer. The three differently filled circles give the positions of the reference balls in the azimuthal plane. The point where the lines meet is the azimuthal position of the test ball. The lines represent the directions in which the plane is tilted (the azimuthal angle); the plane is defined by the heights of the reference balls.

Table 6.1 *The azimuthal positions of the balls and observer in cm*

	Ref ball A		Ref ball B		Ref ball C		Test-ball		Observer	
	x	y	x	y	x	y	x	y	x	y
Exp 1	120	120	-20	-120	-140	-20	0	0	100	-210
Exp 2	180	80	-100	-100	-40	60	0	0	15	-160
Exp 3	110	110	40	-160	-160	40	0	0	120	-110

Table 6.2 *Definitions of the planes. The heights are given in mm from the ground. The azimuthal angles of the plane are given as the angle between the line direction of the steepest upward vector of the plane (in the horizontal plane) and the line from test-ball to observer.*

	Elevation	Heights	Azimuthal angles*
Exp 1	25°	1150 / 1325 / 1500	-170° + i 40°
Exp 2	28°	1150 / 1325 / 1500	-175° + i 40°
Exp 3	30°	1500 / 1650 / 1800	-178° + i 40°

* $i \in \{0,8\}$

for each experiment. The elevations were 25°, 28° and 30° respectively, We used nine azimuthal angles, distributed evenly from -180° to +180°. The height of the plane was varied because otherwise the observer would always have had to put the test-ball at the same height. Thus, for each azimuthal angle, we had three different heights. These heights are defined by the veridical heights of the test-ball and are given in Table 6.2. The results obtained for these three different heights were averaged in the analysis. Thus, each experimental condition consisted of 9x3 = 27 trials (# azimuthal angles, # veridical heights).

Procedure

The procedure was the same for each experimental condition. The observers were informed about the remote control and the task at hand. They were told that the task was to put the brown or yellow ball in the plane defined by the red balls. In experimental condition 3, the experiment with the equilateral triangle, we used a brown test-ball, whereas in the other experiments a yellow ball was used. In a pilot experiment we found no differences between settings of observers when differently colored balls were used. The observers were allowed to rotate the chair and their heads, but were not allowed to make upper-body-movements to the side or forwards (backwards was not possible). Before starting the experiment, we conducted a test-series of three trials so that the observer could get used to the remote control and the task he had to do. If there were no questions, we started the real experiment. First the computer placed all balls at a specified height. The reference balls were hung at the heights that defined the first plane. The test-ball was hung at a random height that was between 75 cm below and above the veridical value. A light appeared on the remote control when the observer could move the test-ball. The observer had 50 seconds time to adjust the height of the test-ball. After 40 seconds, the light on the remote control flickered to draw the observer's attention to the fact that he had only 10 seconds left to finish the trial. The observer pressed the "ready-button" when the correct position was reached before the end of the 50 s period. After the trial was terminated (by a button-press or when the end-time was reached) the balls were hung at different heights and everything started afresh. Most observers finished each trial well within 50 seconds. On the rare occasions when this was not the case, the observer was adjusting the height only a few mm up or down. The observers were told that if the 50 second period was over and the position of the test-ball was really wrong, then they should say so. These trials were retested after the entire experiment had finished. This only happened in the case of five trials in all three experiments with all observers.

Analysis

We calculated the shortest distance from the measured position of the test-ball to the plane defined by the reference-balls. In this way, we ensured that the size of the deviations was not dependent on the elevation of the plane.

6.3 Results

Figures 6.2 A, B and C give an impression of the observer's visual field for the different experimental conditions. Each figure gives nine panels for the nine different azimuthal angles used at a height (of the test-ball) of 150 cm. The circles with the cross, circle and disk in the middle represent the positions of the balls A, B and C in the visual field. The gray triangles represent the surface areas in the visual field limited by the reference balls. The surface is dark gray when the observer looks at it from below, and light gray when he looks at it from above. The open circle (sometimes not visible) represents the veridical position of the test-ball, whereas the black disk represents the mean position in which the test-ball was hung by the observers.

The results of the three experimental conditions are shown in Figure 6.3. Each graph represents the data for one condition. The deviation from the plane is plotted against the azimuthal angle. The deviations are given in cm; a positive deviation means that the ball was positioned above the plane, whereas a negative deviation means that the ball was positioned below the plane. The error-bars give the standard errors of the mean. The azimuthal angle is the number of degrees separating the projection of the steepest upward vector (of the plane) on the horizontal plane from the orientation of the line between observer and test-ball. A positive azimuthal angle of 30° means that the steepest upward vector is oriented 30° rotated counterclockwise from the observer. Thus, the observer is looking from below at the plane when the azimuthal angle is between –90° and 90°; otherwise he is looking at the plane from above. What can be seen in all graphs is that there is a downward trend when the azimuthal angle diverges from 0°. Most deviations were negative which indicates that the observers usually place the ball too low. For the acute and equilateral triangles the trials with azimuthal angles close to 0 have positive deviations. Thus, the ball is placed closer to veridical, or sometimes even above the plane, when the observer looks at the plane from below. However, the downward trend is also present for these trials.

Figure 6.4 shows the standard deviations plotted against the azimuthal angles. Each azimuthal angle was measured three times for each observer. The standard deviations were calculated for these trials for each observer. The points represent the means of the standard deviations for all observers. The error-bars give the standard error of the mean of these values. The three graphs represent the data for the three experimental conditions. However, we did not find that the azimuthal angle had an overall effect on the standard deviations.

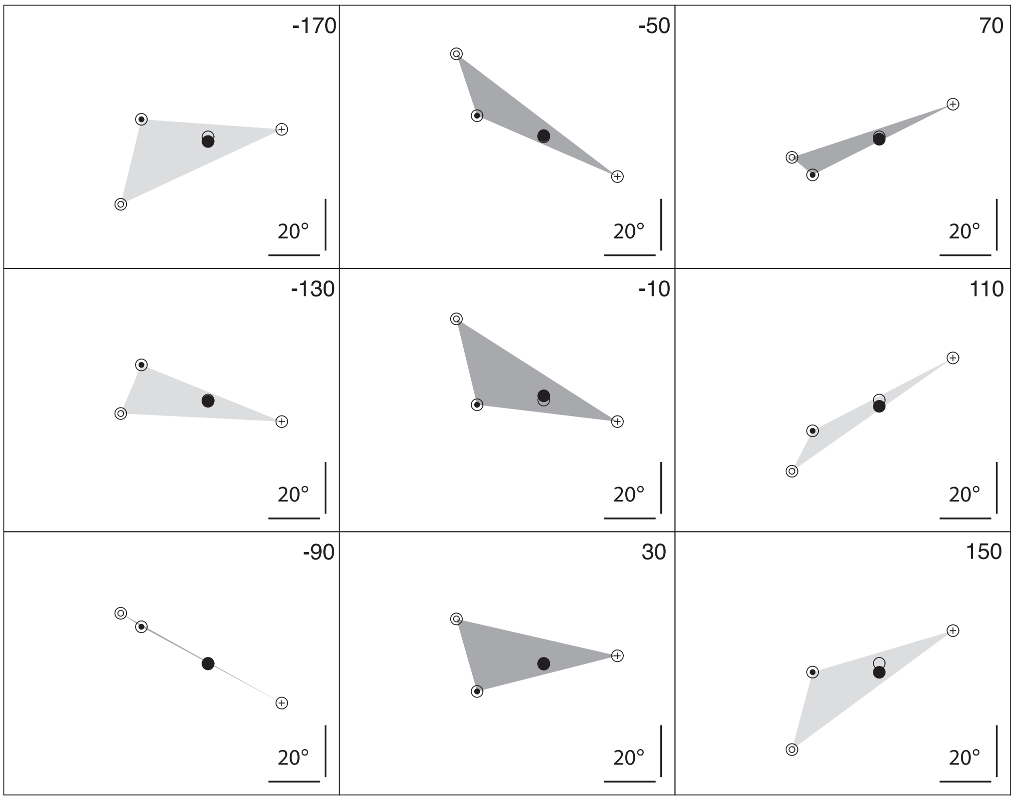

Figure 6.2 A: *The visual field in the acute triangle condition*

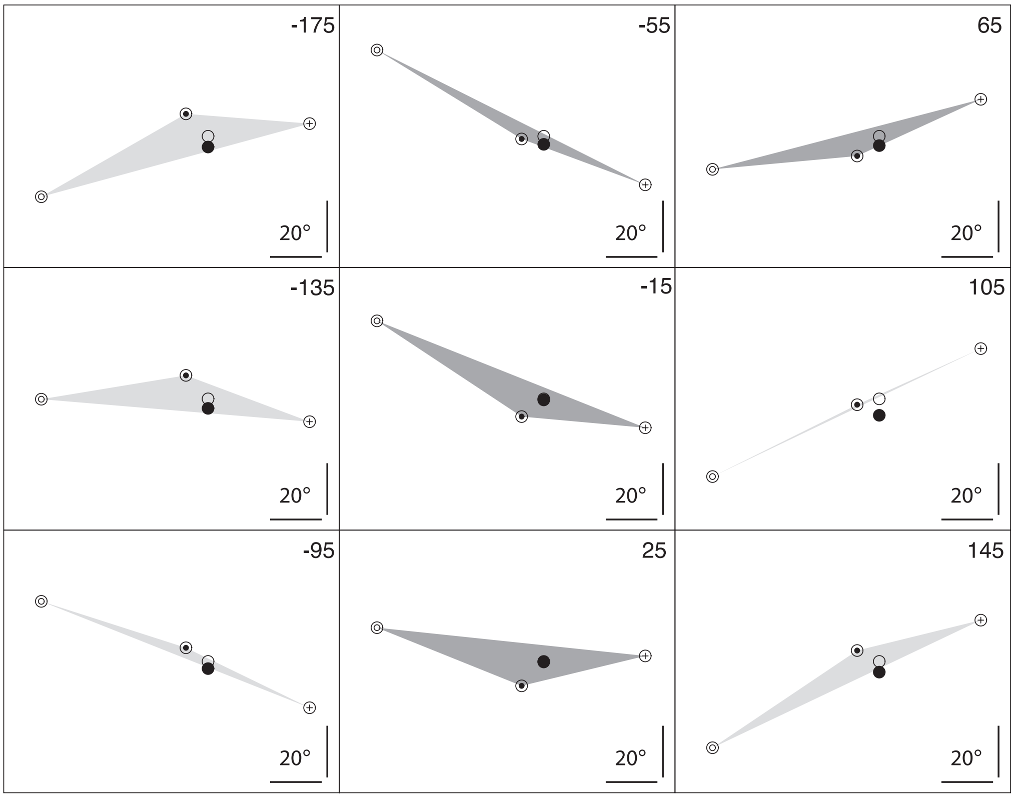

Figure 6.2 B: *The visual field in the obtuse triangle condition*

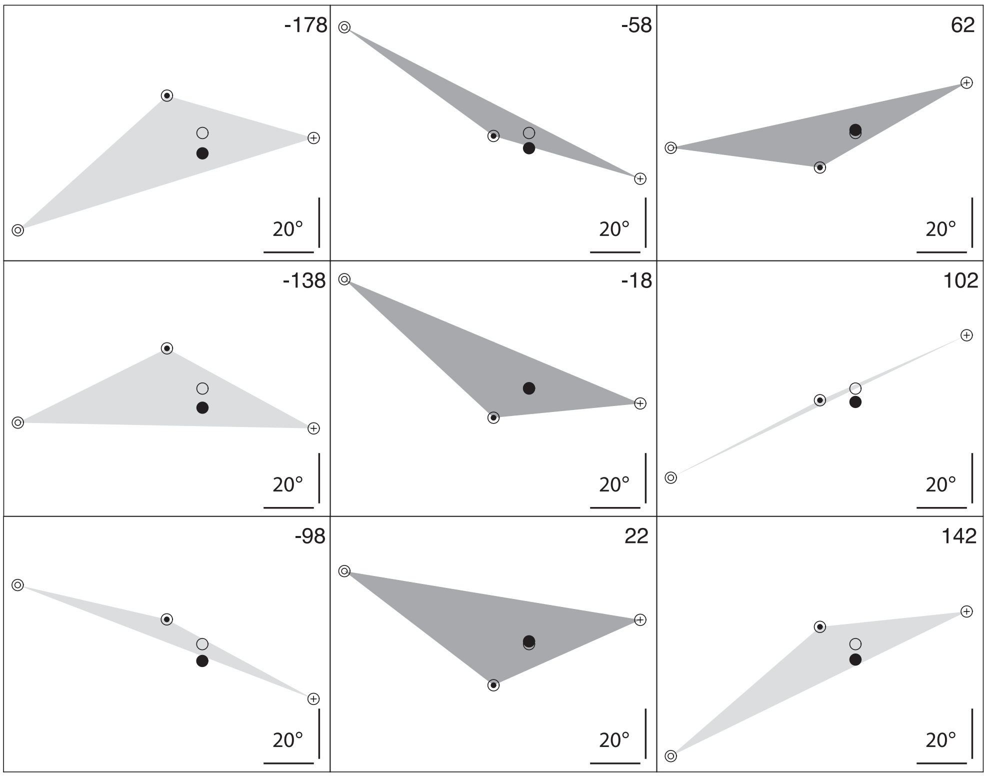

Figure 6.2 C: *The visual field in the equilateral triangle condition*
Figures A, B and C show nine panels with the observer's visual fields for the different azimuthal angles at a plane height of 150 cm. The circles containing a cross, a disk or a circle represent the positions of the reference-balls A, B and C in the visual field, respectively. The gray triangle represents the triangle in the visual field formed by the reference-balls. The triangle is dark gray when the observer sees the plane from below, and light gray when seen from above. The circle represents the veridical position of the test-ball, the disk the mean value of the settings of all observers.

Besides plotting the deviations against the azimuthal angle, we looked at other variables that varied with the azimuthal angle. Among these are the vertical visual angle, the total visual angle and the surface area of the triangle. Looking at Figure 6.2, one can see that the surface area in the visual field is not correlated to the size of the deviations. We plotted the deviations of all conditions against the three-dimensional surface area, the vertical visual angle and the total visual angle and we fitted a line through these points. We found no dependence on the three-dimensional surface area ($p = 0.318$), a trend for the vertical visual angle ($p = 0.055$) and a significant effect of the total visual angle ($p = 0.005$). However, the R^2 values were too low to be regarded as a good fit (0.001, 0.105, and 0.242 respectively).

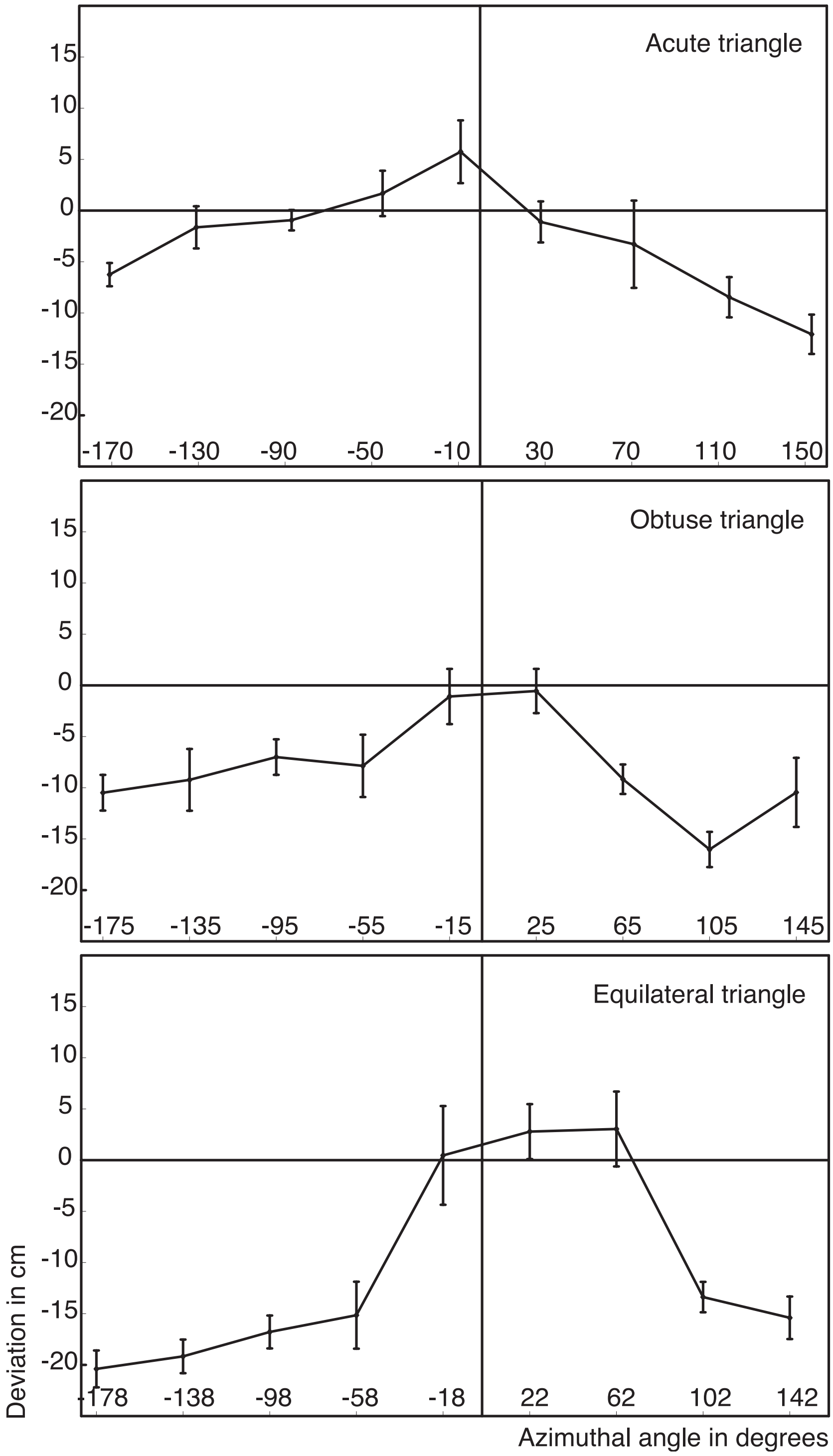

Figure 6.3

The three graphs give data for the three experimental conditions: for the acute, the obtuse and the equilateral triangle respectively. In each graph, the deviation from veridical settings (given in cm) is plotted against the azimuthal angle. A positive deviation means that the observer hung the test-ball above the veridical position, a negative deviation means that he hung the test-ball lower than the veridical position. The data-points give the means of all observers, the error-bars the standard error of the means.

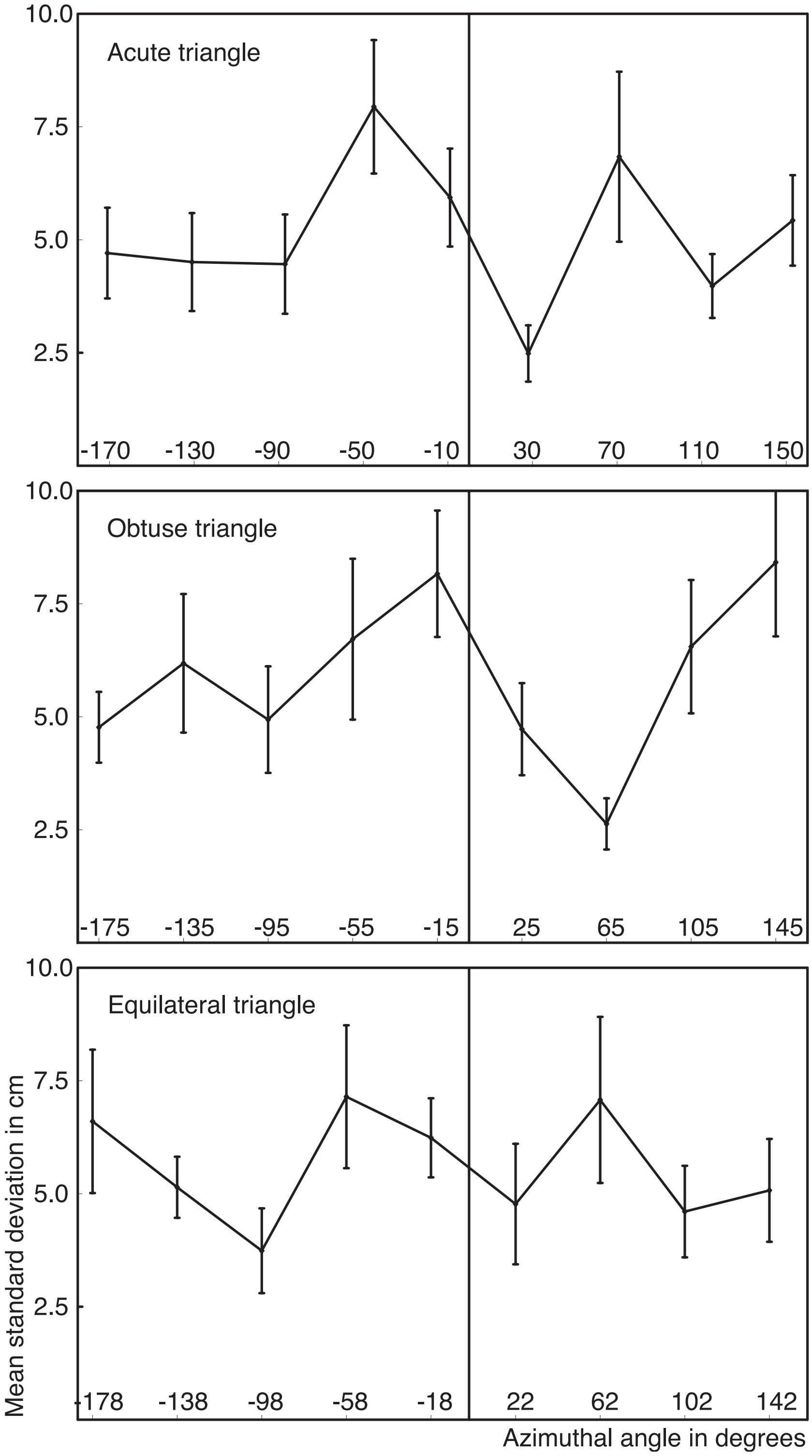

Figure 6.4
The three graphs give data for the three experimental conditions: for the acute, the obtuse and the equilateral triangle respectively. In each graph, the intra-observer standard deviations (given in cm) are plotted against the azimuthal angle. Each data-point gives the mean of the standard deviations of all observers, the error-bars give the (inter-observer) standard error of the means.

6.4 Discussion and conclusions

In this chapter we looked at the effect that a few parameters had on the deviations we found with the ball-in-plane-task. Parameters involving the surface area of the triangle did not affect our data and from these data we cannot conclude that the sizes of the deviations are dependent on the visual angle.

The most important result, however, is that the deviations decrease (become (more) negative) when the azimuthal angle diverges from 0°. Usually, the observers hang the ball too low when they look at the plane from above. Thus from the data we can conclude that at this scale flat planes are seen as concave when the observers look at the plane from above. This is in agreement with the results obtained with an exocentric pointing task (when pointing frontoparallel) and an apparent frontoparallelity task (Foley, 1991; Koenderink, et al., 2000, 2002). However, the sign of the deviations is less clear when the observers look at the plane from below. Small negative and positive deviations were found in these trials with a downward trend when the azimuthal angle diverges from 0°. We did not expect to find small deviations in these trials since most observers said they found these trials more difficult. In the trials in which the observers looked at the plane from below or above the background behind the balls differed. When the observer looked at the plane from above, he could see the walls and floor behind the balls. However, when he looked at the plane from below, he could see the ceiling behind the balls as well as the walls. Since the ceiling was covered with an iron grid, the visual field in these trials is much more crowded. This is probably why observers thought that the trials in which they had to look at the plane from below were more difficult.

From these data we can conclude that the best description we can give for the perception of flat planes is that they are perceived as concave at distances of up to 5 m from the observer. Although most deviations are close to veridical when the observers look at the plane from below, the description fits very well when the observers look at the plane from above.