Chapter 2
Visual Space under Free Viewing Conditions

Abstract:
Most research on visual space has been done under restricted viewing conditions and in reduced environments. In our experiments, observers performed an exocentric pointing task, a collinearity task and a parallelity task in an entirely visible room. We varied the relative distances between the objects and the observer, and the separation angle between the two objects. We were able to compare our data directly with data from experiments in an environment with less monocular depth information present. We expected that in a richer environment and under less restrictive viewing conditions the settings would deviate less from veridical settings. However, large systematic deviations from veridical settings were found for all three tasks, but the structure of these deviations was task-dependent. The deviations were comparable to those obtained under more restricted circumstances. So the additional information was not used effectively by the observers.

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2.1 Introduction

Humans are capable of interacting adequately with their surroundings on the basis of visual input. We can estimate the positions of objects well enough to interact with them effectively. However, sometimes we make large errors in estimating the positions of objects. For example, when someone standing next to you points to a person who is surrounded by other people, it may be hard for you to locate the person whom he or she is actually referring to.

People tend to make significant and systematic errors when estimating the positions of objects in a visual scene. It is as if "visual space", i.e. how we visually perceive the world around us, is deformed with respect to physical space, the physical lay-out of the world. Over the years many researchers have been interested in quantifying this deformation and in giving it a geometric description. Early experiments on visual space were generally done in dark rooms where observers viewed the stimuli binocularly while their heads were fixed. Such a setup effectively removes monocular distance cues except for accommodation. Thus, in these experiments the focus was on binocular depth cues. Helmholtz (1962), for example, measured apparent frontoparallel planes. Vertical threads that hung in a physically frontoparallel plane were not judged by observers to be in one plane. Therefore, Helmholtz concluded that the apparent frontoparallel plane is not the same as the physical one, but that it is curved. Other early research was carried out with luminous points as stimuli; observers had to do visual tasks which involved rearranging the points. The experiments of Blumenfeld and Hillebrand, who let observers make visual alleys based on parallelity or equidistance, inspired Luneburg to formulate a model for visual space (Luneburg, 1950). For these kinds of tasks under these conditions he suggested that visual space has a Riemannian geometry of constant hyperbolic curvature. Both Zajaczkowska (1956) and Blank (1961) confirmed this notion. Indow and Watanabe (1984, 1988) found that the metric of visual space varies over different planes in the visual world. They found a Euclidean metric for the frontoparallel plane (Indow & Watanabe, 1984, 1988) and Indow (1991) found a curved Riemannian metric for the horizontal plane at eye-height. This suggests that visual space is anisotropic, which contradicts Luneburg's assumption of isotropy. Due to the fact that these experiments were conducted in dark rooms, most monocular depth cues were not available to the observers. So if we want to generalize this knowledge to everyday vision, we should extend this research with experiments done under normal lighting conditions.

Some researchers concentrated on experiments in large open fields in normal daylight. In these open field experiments, distances between objects and observer are larger. Thus, different kinds of information (mainly monocular) become important when observers do tasks involving the estimation of depth in a scene. For example, at distances of more than four meters, binocular depth cues play a less important role. Testing in daylight, contrary to testing in the dark, provides depth-information from pictorial cues like linear perspective and texture. Gilinsky (1951), for example, did research aimed at obtaining insight into the relationship between the perceived distance and the perceived size of objects at distances of up to 22 m (70 feet). She developed a law to describe the compression of visual space perception she found in her experiments. She described perceived distance (P) with the following formula:

$$P = \frac{cr}{c + r} \tag{2.1}$$

where r is the physical distance and c is a constant that represents the distance at which an observer perceives objects that are an infinite distance away. In near space perceived distance is approximately equal to physical distance, but as the physical distance increases perceived distance increases less and less until it saturates at the distance c.

Some scientists concluded that there is no single geometry that can describe visual space under all conditions. For example, Battro, di Pierro Netto and Rozestraten (1976) and Koenderink, Van Doorn, & Lappin (2000) found that the curvature of visual space changed from elliptic to hyperbolic as the distance from the observer increases. Besides that, Koenderink, Van Doorn, Kappers and Lappin (2002) concluded from experiments that the structure of visual space varies over different tasks. Thus, studies that confirm theories with different geometries are not necessarily contradictory, they are merely complementary. According to Wagner (1985), visual space has an affine-transformed Euclidean geometry under full-cue conditions with free head-movements but restricted body-movements. The metric will get close to Euclidean when the perceptual information increases both quantitatively and qualitatively (Wagner, 1985).

Recently, Cuijpers, Kappers and Koenderink (2000a, 2000b, 2001, 2002) did indoor experiments in a room where most pictorial depth cues were eliminated from the visual field by means of wrinkled plastic that prevented observers from seeing the walls. The floor and ceiling of the rooms were not visible due to the fact that the observer was seated in a cabin that restricted the vertical visual field of view. The head of the observer was fixed using a chinrest. In the tasks they used, rods had to be made to point towards a target (exocentric pointing task), towards each other (collinearity task) or had to be put parallel to another rod (parallelity task). The angular deviations from veridical settings were measured. The pattern of these deviations was found to depend on the task. Cuijpers et al. (2002) claimed that there is no such thing as an invariant visual space because the form of the visual space is task dependent.

The experiments of Cuijpers et al. (2000a, 2000b, 2001, 2002) were done with artificial light, distances were less than 4.5 meters and most pictorial depth-information was eliminated from the scene. In this way the information present came mainly from physiological depth-cues. In everyday vision pictorial depth-information is available to an observer. Therefore, to be able to say something about everyday vision one needs to look at how visual space is deformed when contextual information is present. Normally people do not look at luminous points in a totally dark environment. Generally, they look at objects that are surrounded by other objects that can give a great deal of information about the relative positions of the objects. This is evident from the fact that one obtains spatial impressions from flat photographs where physiological cues are lacking or are inconsistent with monocular cues. According to Gibson (1950) visual space is dependent on what fills it; thus in studying visual space one should also look at contextual information. Another example that stresses the amount of information that can be provided by monocular depth cues comes from the perception of amblyopes, people that are unable to use binocular depth information.

Nevertheless they have no trouble perceiving depth in a normal environment. In fact very often they only discover their deficiency when they are subjected to stereo-tests.

Since monocular information provides a rich amount of information about depth in a scene, it seems logical to examine the perceived spatial relations between objects in an environment that provides both monocular and binocular depth cues. So the purpose of the present research is to increase our understanding of the structure of visual space as it occurs to us when both types of depth cues are present. To do this we studied the structure of visual space in an illuminated room under free viewing conditions, i.e. viewing without any restrictions on head movements or size of the visual field. We will test whether visual space is systematically different from physical space under free viewing conditions in a room where monocular depth information is available. Our hypothesis is that in a richer environment for similar tasks the settings will deviate less from veridical settings. We expected this because more pictorial depth cues are present and thereby one would expect more precise estimation of positions of objects (Wagner, 1985). Another issue in this research is whether the differences that Cuijpers et al. found between the different tasks, are also present in our setup.

The research was done in a room in our laboratory. The observers were seated, could rotate head and upper-body if they liked and they had an unobstructed view of the floor, ceiling and walls of the experimental room. We used three different tasks. One task was an exocentric pointing task in which the observer had to direct a pointer towards a target. The second task was a parallelity task in which a rod had to be put parallel to another rod. The third task was a collinearity task in which two rods had to be placed in one line. We manipulated two different parameters for the three tasks. One of these parameters was the relative distance, which is the ratio of the distances between the two objects and the observer. The second parameter was the separation angle, i.e. the visual angle between the objects. For the parallelity task we had a third parameter, namely the orientation of the reference rod. The separation angle and the relative distance were chosen as parameters because together they can quite naturally give an indication of the positions of the objects with respect to the observer. Besides that, they were the major parameters in the experiments of Cuijpers et al. (2000a, 2000b, 2002). Since we want to test whether a room full of depth information will change the structure of visual space, it is important to be able to use Cuijpers' data as a baseline for our measurements.

2.2 General methods

Observers

The three tasks described in this paper involved the same four observers. The observers were undergraduates and were paid for their efforts. They all had normal or corrected to normal sight and were tested for binocular vision. All observers had stereovision with good acuity. The observers had no knowledge about the goal of the experiment and received no feedback regarding their performance during the experiment. They were tested individually.

Experimental setup

The experiment was set up in an empty room measuring 6m by 6m by 3.5m. On the left-hand wall blinded windows were visible. Under the windows were central heating radiators. Opposite the observer was an empty wall and on the right of the observer was a wall with two doors. On every wall, electric sockets were visible near the floor of the room. The ceiling was partly covered with oblong fluorescent lights and air-conditioning equipment. The room was illuminated with these artificial lights. On the floor, points were marked for the positioning of the objects. These points were marked at three different distances from the observer (1.5 m, 2.6 m and 4.5 m) at three different angular separations (20°, 40° and 60°) symmetrical around the line bisecting the room (see Figure 2.1). The objects used in the tasks consisted of yellow disks perpendicular to green rods. The rods were 25 cm long and 1.0 cm thick, and were sharp at each end. The disks had a diameter of 8.2 cm and a thickness of 1.0 cm. The rods were placed at eye-height and could be rotated around the vertical axis. The rods that were used as objects are depicted in Figure 2.2. The observer used a remote control to rotate the rods. The feet of the objects were square-shaped and contained a protractor from which the experimenter could read the pointing direction. A screen in front of the foot of an object prevented the observer from seeing the protractor and the square which was aligned with the walls. The observer's chair could be adjusted so that the objects were at eye-height. No chinrest was used and head movements were permitted.

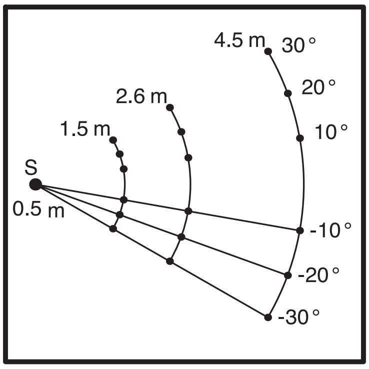

Figure 2.1
Schematic view of the experimental room. The black dots indicate the positions of the objects in the room. The larger black dot represents the position of the observer (S).

Procedure

For every trial, two objects were placed on the marks in the room. We used three different separation angles (20°, 40° and 60°) and the objects were at three different distances from the observer (1.5 m, 2.6 m and 4.5 m). For every combination of positions on the floor, one object was always on the left of the observer and the other on the right. This setup gives a

Figure 2.2
A picture of the two rods that were used in the parallelity task and the collinearity task.

total of 27 possible combinations of positions on the floor (3 separation angles, 3 distances to one object and 3 distances to the second object).

For the analysis we used positive and negative separation angles. Positive separation angles (20°, 40° and 60°) were used for the trials in which one of the objects, the reference object, was positioned to the left of the observer and the other object, the test object, was positioned to the right. Negative separation angles (-20°, -40° and -60°) were used when the reference object was on the right of the observer, and the test object on the left.

The observers were allowed to move their heads, but were told to stay seated. In between the trials, the observers were asked to close their eyes so that they could not see the movements of the experimenter and the objects while the experimenter read the pointing direction of the test rod and changed the setup for the next trial.

All observers were tested with the three tasks. One task was completely finished before starting a second one. The order of the experiments was partially counterbalanced. This way, every observer had a unique order of experiments. The experiments were all conducted in sessions of approximately one hour. Mostly, the observers were tested for one hour each day, but sometimes we had two sessions a day with a break of at least 30 minutes in between the sessions.

2.3 Experiment 1: Exocentric pointing task

Methods

The exocentric pointing task involved the use of a pointer and a target. The target was an orange sphere with a diameter of 6.5 cm and was positioned at the same height as the pointer (at eye-height for the observer). For this task an object as described above was used as pointer, the only difference being that it had only one sharp conical end. The task was to rotate the pointer in such a way that it pointed towards the centre of the target. Each position on the floor was used as reference position (position of the target) and as test position (position of the pointer), so the number of combinations (27) has to be multiplied by two. Because we repeated every possible combination three times, the total number of trials

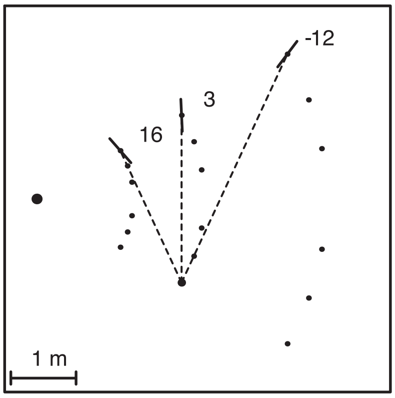

Figure 2.3
Schematic view of the experimental room with settings for the exocentric pointing task. The dashed lines represent veridical settings for the exocentric pointing task for conditions where the separation angle was -60°. The distance from the reference stimulus to the observer was 2.6 m. The solid lines represent the means of the settings for three trials for observer AW. They are shown for three different distances between the observer and the pointer. The numbers indicate the mean deviation from veridical settings in degrees.

needed for this task was 162 (27x2x3). It took each observer about three hours to complete the 162 trials.

Results

In the exocentric pointing task qualitatively similar systematic deviations were found for all observers, although the magnitude of the deviations was observer-dependent. In Figure 2.3 an example is given of the settings for observer AW, a separation angle of 60° and a distance of 2.6 m to the target. The lay-out of the floor is presented in this figure together with the three combinations of positions of target and pointer that are possible with a fixed target-position. The dotted lines represent the veridical pointing directions and the small thick lines represent the means of three settings of the observer. The numbers indicate the deviation from veridical directions in degrees. It is important to notice that the sign changes when the relative distance switches from larger than 1 to smaller than 1.

The influence of two parameters was analyzed, i.e. the separation angle and the relative distance. Figure 2.4 shows graphs for observer AW in which the deviation is plotted against the separation angle. A line is fitted through the data points in the figure using a least squares method. The five graphs represent the five relative distances that were used. For a relative distance of 0.3 and 0.6 the slopes are positive and for a relative distance of 1.7 and 3 the slopes are negative. For a relative distance of 1 the fit approaches a horizontal line. Table 2.1 gives the slopes in numbers for each observer and each relative distance. An asterisk indicates whether the slope deviates significantly from zero at a confidence level of .95. The same pattern was found for three observers, i.e. the slope deviated significantly from zero when the two rods were at different distances from the observer. The deviations for observer TL were very small and therefore the slopes were smaller. The results for BL, also, showed two slopes that did not deviate significantly from zero. However, in general the observed deviations could very well be approximated as a linear function of the separation angle.

Figure 2.5 is a graph in which the slopes of the lines in Figure 2.4 are plotted against the relative distance on a logarithmic scale. A large slope means that the deviations were very large for the larger separation angles, and vice versa. So the slopes in Figure 2.5 give indirect information about the size of the deviations for one relative distance. The data for the four observers are plotted on separate lines. As can be seen in the Figure 2.5, the lines have the same shape, which indicates that the observers show comparable behavior. We will address three points. First, an overshoot was present when the relative distance was smaller than 1 (the pointer was closer to the observer than the target). This means that the observers directed the pointer towards a point further away in depth than the target actually was. In contrast, an undershoot was present when the relative distance was larger than 1 (the pointer was further away from the observer than the target). This means that the observer directed the pointer towards a point closer to himself than the target actually was. Second, the size of the slopes approached 0 for a relative distance of 1. When the target and the pointer were at the same distance from the observer, the settings were almost veridical. Third, the slopes were larger for relative distances of 0.6 and 1.7 than for relative distances of 0.3 and 3.

Discussion

The deviations increase linearly with the separation angle. This means that when the two objects are further apart, i.e. the visual angle is large, the deviations are larger. An effect of relative distance was also found. There is an overshoot when the target is further away from the observer than the pointer and an undershoot when the target is closer to the observer. At a relative distance of 0.6 or 1.7 the deviations were larger than for the relative distances of 0.3 and 3. This could be due to the fact that when the relative distance approaches zero or infinity, the angle between the line connecting the observer with the more distant object and the line connecting the two objects approaches zero. In these cases, the task resembles an egocentric pointing task. Thus, the closer the relative distance approaches zero or infinity, the smaller the deviations are likely to be.

In the case of two observers (AW and TL) when the two objects were at the same distance from the observer (a relative distance of 1), the settings were close to veridical. For the other two observers a small overshoot was present at this relative distance.

Comparing these results with the data of Cuijpers and colleagues (2000a), we see that the same pattern of results was found for the relative distance. Cuijpers and colleagues (2000a) did not find any effect of the separation angle. However, they looked only at the separation angle for

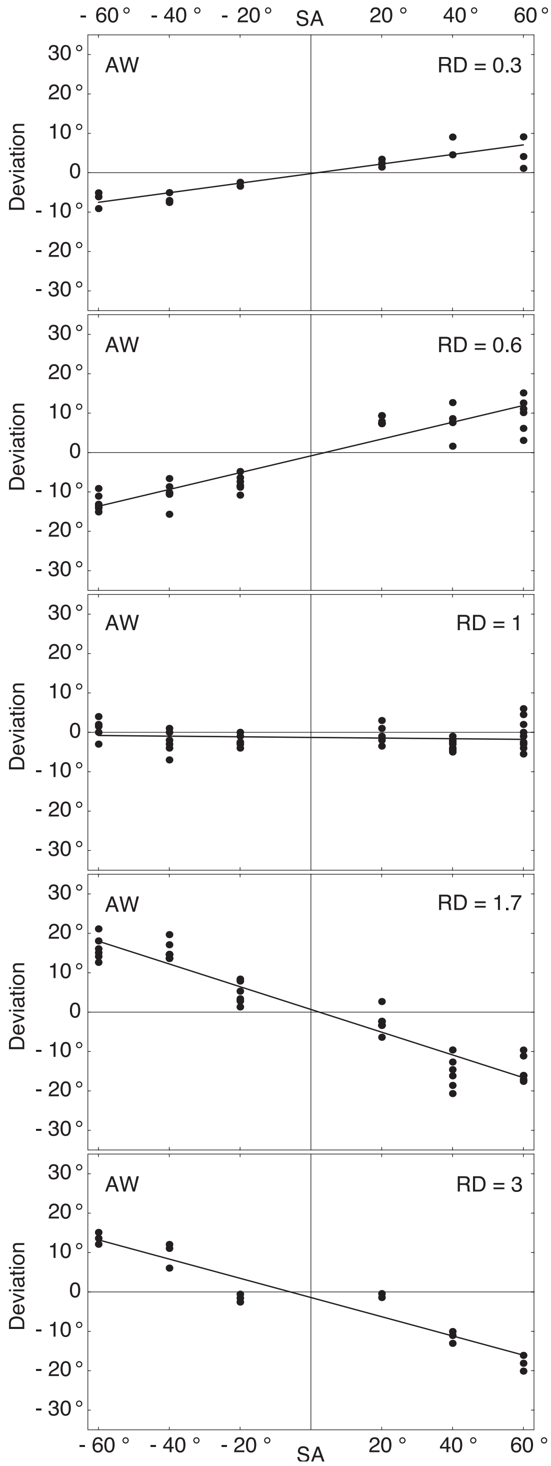

Figure 2.4
In each graph the deviations from veridical settings for the exocentric pointing task are shown as a function of separation angle for each relative distance. These are the data for observer AW. A line is fitted through the data points.

combinations of positions with a relative distance of 1 and for these trials we also found only minor deviations.

Table 2.1.
The Slopes of the Linear Fits through the Data Points as a Function of Relative Distance for all Observers in the Exocentric Pointing Task

	Relative Distance				
Observer	0.3	0.6	1.0	1.7	3.0
JP	0.11*	0.18*	-0.08*	-0.17*	-0.07*
AW	0.12*	0.21*	-0.01	-0.29*	-0.24*
BL	-0.02	0.04	-0.12*	-0.27*	-0.23*
TL	0.01	0.12*	-0.	-0.07*	-0.01

* *The slope deviates significantly from 0 (α = .05).*

2.4 Experiment 2: Parallelity task

Methods

For the parallelity task two rods were used, as described in the general methods section. One of the rods, the reference rod, was placed at a certain orientation by the experimenter. The task for the observer was to rotate the other rod, the test rod, so that the two rods were parallel. To clarify the word parallelity, we gave the observers an example of two parallel lines on paper. The reference rod could be either on the left or the right side of the room. Thus, as in the pointing experiment, the number of combinations of positions was doubled. Furthermore, four different orientations of the reference rod (22°, 67°, 112° and 157°) were used for every combination of the reference and test positions. We chose these orientations so that we could compare four oblique orientations with an even amount of rotation between them. We repeated all the measurements three times. As a result, the experiment consisted of 648 trials for each observer (27x2x4x3). Usually 54 trials were performed per session. Each session lasted an hour, so 12 hours were needed per observer.

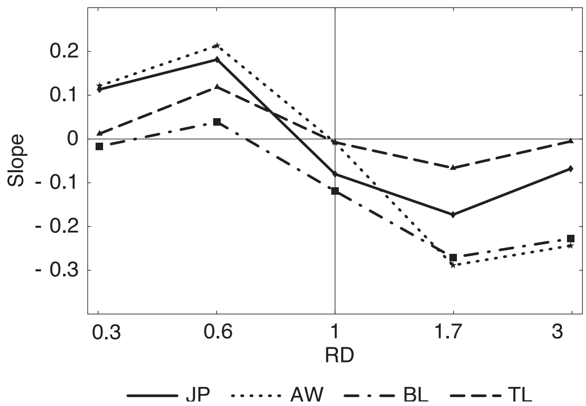

Figure 2.5
In this figure the slope of the lines from Figure 2.4 are plotted as a function of relative distance. The data for the different observers are given on separate lines.

Results

An example of the settings of observer BL with one distance to the reference rod and one orientation is given in Figure 2.6. The figure shows the layout of the floor of the experimental room. The point on the left represents the position of the observer, the other points the positions that were used for the rods. The figure gives both a graphical and a numerical view of the data. The lines and numbers (in degrees) represent the means of three trials for a reference orientation of 67° and a distance of 4.5 m between observer and reference rod. For this reference distance all possible combinations with the test distance are shown, as well as three different separation angles. The test rods on the outer line were tested with the reference rods on the outer line on the other side of the room (separation angle of 60°), the rods on the middle lines were also tested together (separation angle of 40°) and the same was done for the rods on the inner lines (separation angle of 20°).

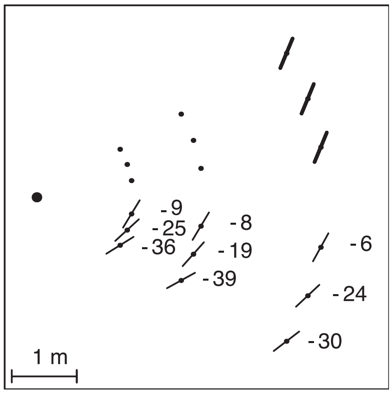

Figure 2.6
Schematic view of the experimental room with settings for the parallelity task. The thick lines represent the orientations of reference rods (distance 4.5 m, reference orientation 67°). The thin lines represent the means of three settings of observer BL. The numbers give the deviations from veridical settings in degrees.

Systematic deviations from veridical settings were found for all the observers. However, the size of the deviations was dependent on the observer. The size varied from 0° to 44°, observer AW produced the smallest deviations.

We will now look more closely at the three different parameters which may influence the pattern of deviations found in this experiment. These parameters are the separation angle, the relative distance and the reference orientation.

Figure 2.7 shows the graphs for observer BL and a reference orientation of 67° in which the deviations are plotted against the separation angle. Each graph represents the data for one relative distance. Each point in the graphs represents one trial. A line is fitted through these data points using a least squares method.

The slopes of the fits that were plotted in Figure 2.7 are plotted in Figure 2.8 against the relative distance. Each graph contains the data for one observer. The data for the four reference orientations are given on separate lines. The error bars indicate the confidence intervals for the slopes. The lines are nearly horizontal and the points for each reference orientation are all within the range of the confidence intervals of the other points on the line, so the relative distance has no effect on the slope. The slope-values represent the dependence of the deviations on the separation angle. This gives an indication of the range of the deviations that were measured. The more the slope deviates from zero, the wider the range of deviations. Thus, our method yields a pattern that resembles the one produced by plotting the deviations directly against the relative distance. We not only looked at the influence of the relative distance, we also looked at the effect of the absolute distance between the observer and the two rods. The absolute distance had no effect on the size of the deviations.

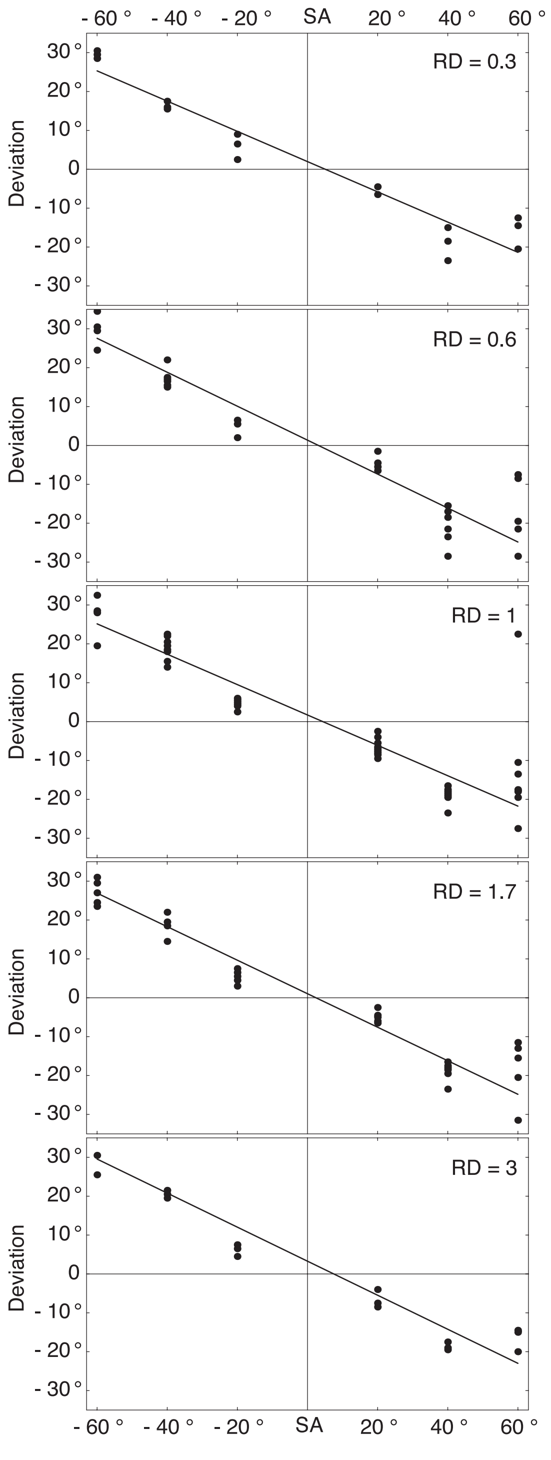

Figure 2.7
In each graph the deviations from veridical settings for the parallelity task are shown as a function of separation angle for each relative distance. These are the data for observer BL for a reference orientation of 67°. A line is fitted through the data points.

In Figure 2.8 it can be seen that the lines representing the different reference orientations are very similar for two observers (BL and TL). The results for the other two observers (AW and JP) show an effect of the reference orientation. For a reference orientation of 22° and 157°, the effect of the separation angle was small (the slopes in Figure 2.8 are small) but for the other two orientations, the effect of the separation angle was larger. For observers AW and JP a significant difference was found for reference orientations 22°/157° and 67°/112° (student's t-test, $p < 0.0001$ for both observers). This difference was not present for the other two observers ($p = 0.12$ for TL, $p = 0.15$ for BL).

The slopes of the linear fits of Figure 2.7 are shown in Table 2.2. The slopes are the means of all relative distances and two reference orientations (22° and 157°, 67° and 112°). All slopes deviated from zero significantly at a confidence level of .95.

Discussion

For the parallelity task the deviations increase linearly with separation angle. No effect of distance was found. So the distances between the two objects and the observer, and the ratio of these distances did not matter.

For two observers an effect of reference orientation was found. For these observers, the slopes of the fits were very small for two orientations (22° and 157°) and a bit larger for the other two orientations (67° and 112°). This means that, for these observers, there was an interaction of reference orientation with separation angle, the size of the effect of separation angle being dependent on the orientation of the reference rod. The difference

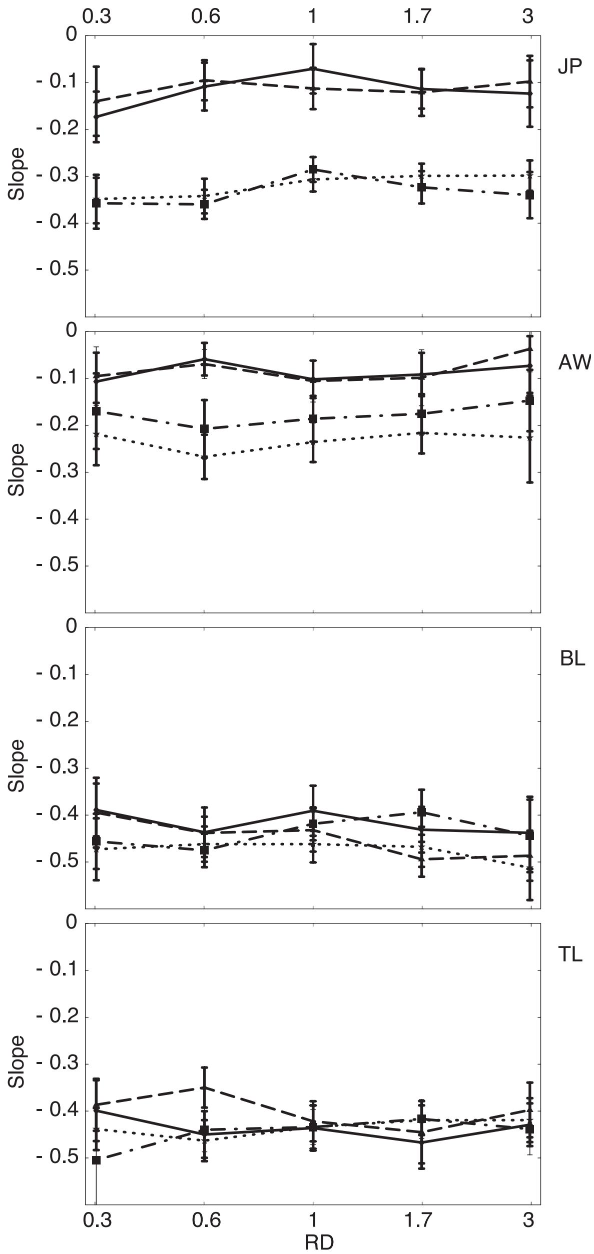

Figure 2.8
In each graph the slopes of the lines from Figure 2.7 are plotted as a function of relative distance for each observer. The data for the different reference orientations are given on separate lines.

Table 2.2 *The Slopes of the Linear Fits through the Data Points as a Function of Relative Distance for all Observers in the Parallelity Task*

Observer	Angle (deg)	Mean slope*
JP	22/157	-0.11
	67/112	-0.32
AW	22/157	-0.08
	67/112	-0.20
BL	22/157	-0.43
	67/112	-0.46
TL	22/157	-0.42
	67/112	-0.44

**The slopes are the means of the slopes found for all relative distances and two reference orientations.*

between the observers might be due to the different kinds of information that they abstracted from the scene in order to do the task.

The data were compared with the data of Cuijpers et al. (2000b). In their setup, a linear effect of separation angle was found without any effect of the relative distance. Observers differed greatly with regard to their dependence on reference orientation. However, they placed their reference rod at different orientations (0°, 30°, 60°, 90°, 120° and 150°). For most observers, they found that the slopes of the non-oblique orientations were negligible. As a possible explanation for this oblique effect they hypothesized that the observers were able to use some information about the 0° and 90° orientations from the walls of the room or the cabin in which they were seated, although an attempt had been made to conceal this information. They examined this further by varying the orientation of the observers, the cabin, in which the observers were seated, and the stimuli with respect to the walls. Some observers were dependent on the orientation of the walls, while some were mo dependent on the orientation of the cabin. A third group was somewhere in between (Cuijpers, R.H., Kappers, A.M.L., & Koenderink, J.J., 2001). In addition to this oblique-effect, they also found differences between the oblique orientations, for some observers. For these observers smaller deviations were found for trials in which a normal sized deviation would give a non-oblique setting. Since the perception of these non-oblique orientations is veridical, this is a conflicting situation. So the settings of these observers were somewhat in between veridical and non-oblique settings. Following this line of thinking one would not expect to find such good fits for our data as shown in Figure 2.7, because for all reference orientations one would have found smaller deviations for the positive or negative separation angles than for the other (dependent on the orientation). The difference could be due to the multiple sources of information about the orientation of the rod. If an observer, for example, is constantly looking at both the rod and the yellow disc perpendicular to it, he will have another pattern of deviations as an observer who looks primarily at the rod.

Thus, with minor exceptions the results of Cuijpers et al. (2000b) have the same size and follow the same pattern as the results presented in this paper. Therefore, for this task it can be concluded that the additional context did not make the settings of the observers more veridical.

2.5 Experiment 3: Collinearity task

Methods

For the collinearity task, the same two rods were used as in the parallelity task. The observer had two remote controls in his hands, enabling him to rotate the two rods. The task was to align the two rods, so they pointed towards one another. The instructions were that the observers had to rotate the rods so that they were in one line. Besides being given this verbal instruction, the observers were shown a picture of two collinear lines. The number of trials for this task was 81 (27x3 repetitions). It took the observer about two hours to perform this task.

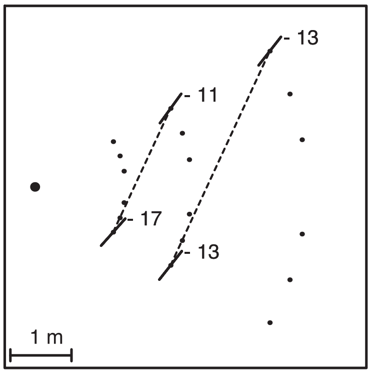

Figure 2.9
Schematic view of the experimental room with settings for the collinearity task. The dashed lines represent veridical settings for the collinearity task for conditions where the separation angle was -60° and the relative distance 0.6/1.7. The solid lines represent the means of the settings for three trials for observer AW for three different conditions. The numbers indicate the deviation from veridical settings in degrees.

Results

In the collinearity task systematic deviations were found for all observers. The size of the deviations was observer-dependent. Figure 2.9 gives an example of settings for observer AW. The means of the settings of three repetitions are shown graphically and numerically (deviations from veridical settings in degrees) for two different combinations of positions on the floor. The dotted lines are the veridical orientations of the rods.

We performed two kinds of analysis for this task. First, we looked at the two rods that were placed in the same

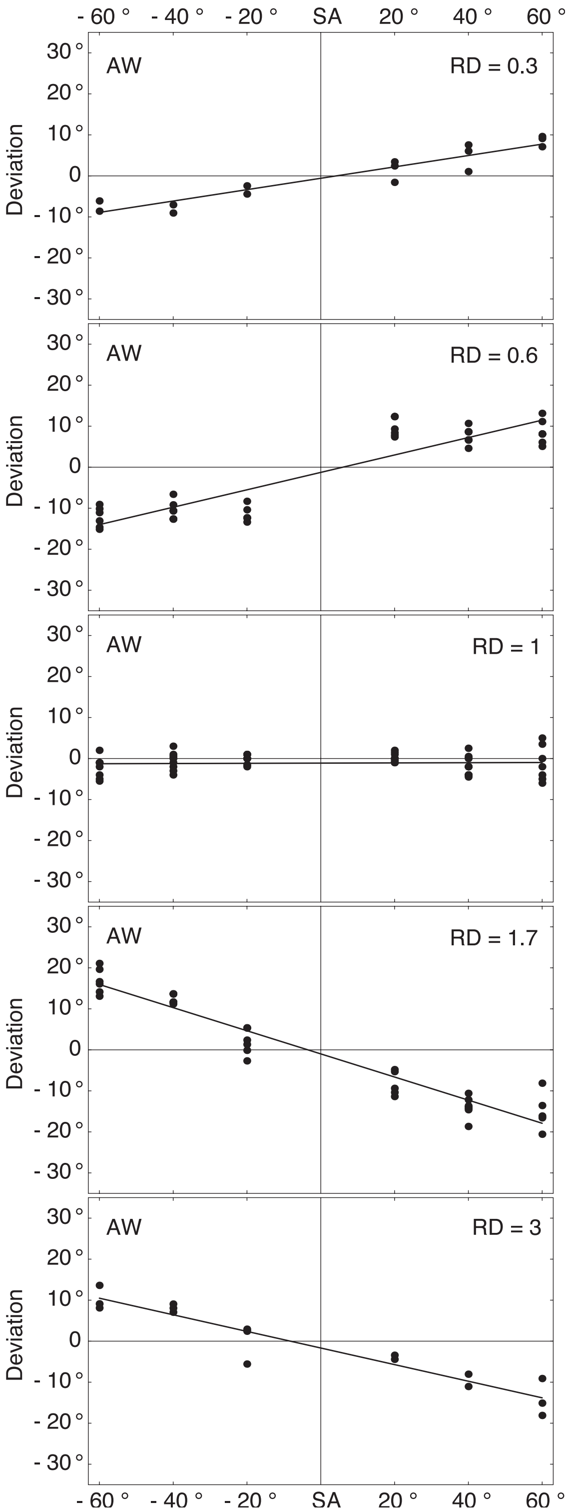

Figure 2.10
In each graph the deviations from veridical settings for the collinearity task are shown as a function of separation angle for each relative distance. These are the data for observer AW. A line is fitted through the data points.

trial separately. Second, we looked at the combination of the settings of the two rods.

The first analysis we did is the same as the analysis we did for the other two tasks. We looked at the two rods separately and dealt with them in the same way as we dealt with the pointers in the pointing task. One rod was the test-rod and we took the centre of the other rod as the target. Again we looked at the effect of the separation angle and the relative distance on the size of the deviations. We therefore plotted the deviations against the separation angle in different plots for every relative distance (see Figure 2.10 for the data for observer AW). A line was fitted through these data using a least squares method. As can be seen in Figure 2.10, for a relative distance of 0.3 and 0.6 the slope is positive and for a relative distance of 1.7 and 3 the slope is negative. For a relative distance of 1 the slope for this observer is zero. Table 2.3 shows the slopes of the different fits for all observers and relative distances. The asterisks indicate whether the fit deviates significantly from zero. This was the case for most fits, with some exceptions. The slopes are plotted against the relative distance on a logarithmic scale in Figure 2.11. The data for the different observers are plotted on separate lines. As can be seen in this figure, when the relative distance is smaller than 1, the slopes tend to be positive. This means that when the rod is closer to the observer than the target (in this case the middle of the other rod) the observer tends to overshoot. On the other hand, when the target is closer to the observer than the rod, the observer tends to undershoot. The slopes are larger for a relative distance of 0.6 and 1.7 than for a relative distance of 0.3 and 3 respectively, which is the same pattern as we found for the pointing task. For two observers the slopes are zero at a relative distance of 1. For the other two observers, the slopes are negative at this relative distance.

We will discuss three different hypothetical situations that can occur if the two rods are viewed together. The first one is a veridical setting of rods. The second possibility is that the two rods are placed with deviations with an opposite sign, both overshooting or undershooting. The third possibility is that the rods are placed with deviations of a corresponding sign, so one of the rods is overshooting and the other undershooting. In the first situation both the sum of and the difference between the deviations of the two rods will be zero. If the rods are placed with deviations of the same size but with a different sign, the sum of the deviations will be zero. This is a special case of the second possibility, that is, deviations with opposite signs. If the two rods are placed parallel, i.e. with deviations of the same size (not equal to zero) and sign, the difference between the deviations will be zero, but the sum will not be zero. This is a special case of the third possibility.

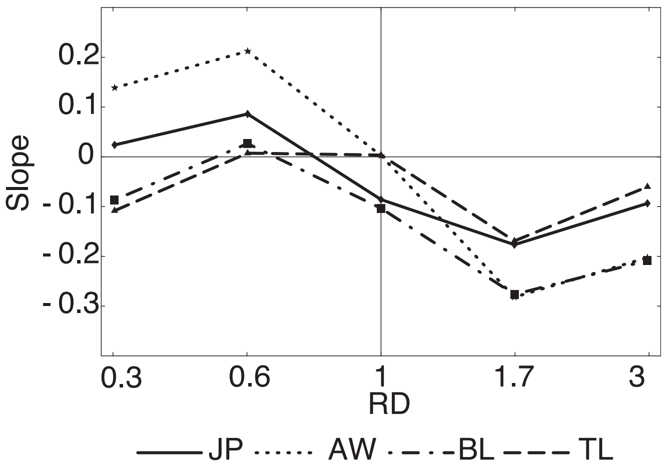

Figure 2.11
In this figure the slope of the lines from Figure 2.10 are plotted as a function of relative distance. The data for the different observers are given on separate lines.

Table 2.3. *The Slopes of the Linear Fits through the Data Points as Function of Relative Distance for all Observers in the Collinearity Task*

	Relative Distance				
Observer	0.3	0.6	1.0	1.7	3.0
JP	0.02	0.09*	-0.09*	-0.18*	-0.09*
AW	0.14*	0.21*	-0.	-0.28*	-0.20*
BL	-0.09*	0.26*	-0.10*	-0.28*	-0.21*
TL	-0.11*	0.01	-0.	-0.17*	-0.06

* *The slope deviates significantly from 0 (α = .05).*

In Figure 2.12 we have plotted the sum of the deviations of the corresponding rods as a function of the relative distance (on a logarithmic scale). Separate plots show the data for the four different observers. Each point represents the mean of 3 repetitions and for some relative distances a point represents a couple of combinations of points that have the same

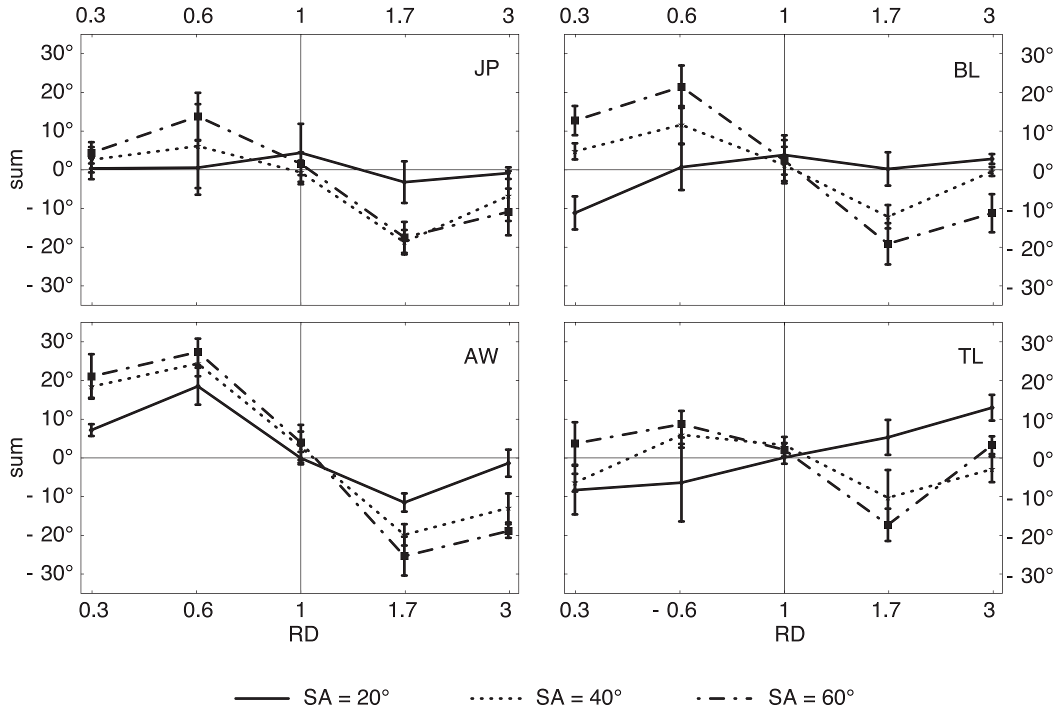

Figure 2.12
In each graph the sum of the deviations is plotted against the relative distance for one observer. The standard deviations are given via error-bars. The different lines represent different separation angles.

relative distance. The standard deviations are given via error-bars. What can be seen in the graphs is that the sign of the sum changes when the relative distance changes from smaller to larger than 1. If the relative distance is 1, then the sum is zero for all observers. The sum is larger for relative distances of 0.6 and 1.7 than for relative distances of 0.3 and 3 resp. For the smallest separation angle (20°) the relative distance had only a minor effect.

The difference between the deviations of the two bars is plotted in Figure 2.13 against the relative distance. Again the separate graphs represent the different observers, the relative distance is given on a logarithmic scale and the error-bars represent the standard deviations. Overall, the differences between the deviations are smaller than the sums of the deviations. The differences are not dependent on the relative distance. For observers AW and TL, for a relative distance of 1 the difference is zero. Since the sum is also zero, this means that the settings were veridical. For the other two observers, the difference was not equal to zero at a relative distance of 1. With a sum of zero, this means that the data were symmetrical. There was only a minor effect of separation angle on the difference between the deviations.

Discussion

First we will discuss the analysis in which we looked at the two rods separately. We performed this analysis mainly because we wanted to be able to compare it to the results of the exocentric pointing task. The same pattern was found for both tasks. As for the pointing task, the data of the collinearity task revealed a linear effect of the separation angle (see Figure 2.10). There was an effect of relative distance in that there was an undershoot when

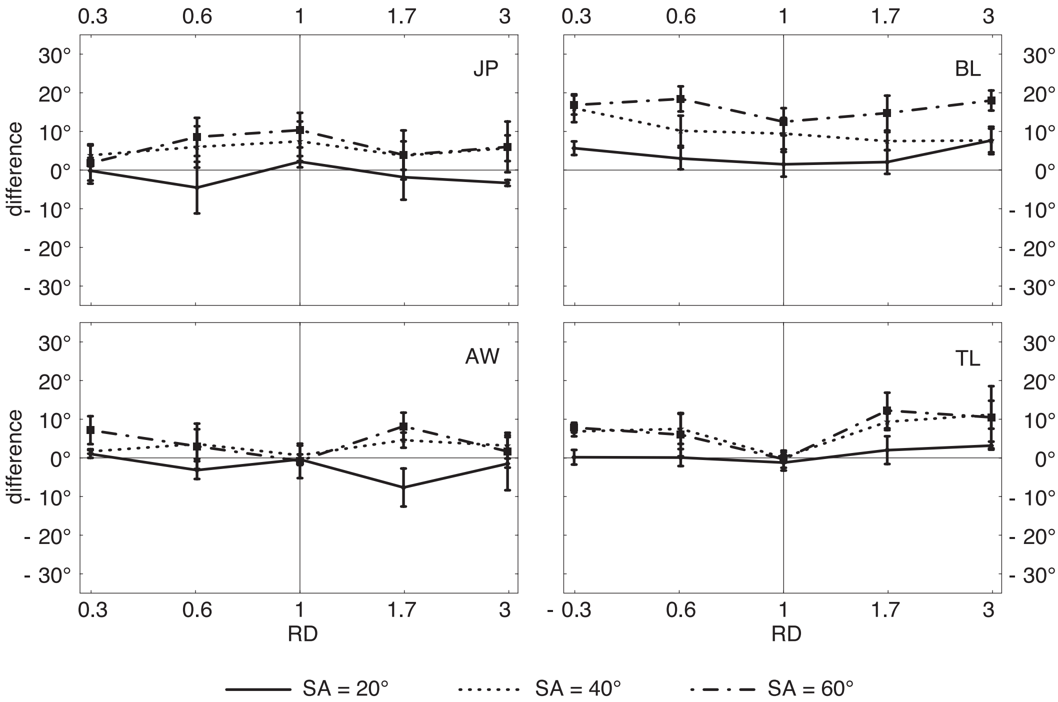

Figure 2.13
In each graph the difference between the deviations is plotted against the relative distance for one observer. The standard deviations are given via error-bars. The different lines represent different separation angles.

the relative distance was smaller than one and an overshoot when the relative distance was larger than one (see Figure 2.11). Again larger deviations were found for relative distances of 0.6 and 1.7 than for the relative distances of 0.3 and 3. A possible explanation is, as in the case of the pointing task, that if the relative distance deviates more from 1, the exocentric task will become more egocentric.

For two observers, AW and TL, we found (close to) veridical settings for a relative distance of 1. For the other two observers, we found settings with an overshoot. This pattern is the same as the one we found for the pointing task with the same two observers with veridical settings.

Looking at the results for two rods together we found that the sum of the deviations was dependent on the relative distance and separation angle. This is comparable to what Cuijpers et al. (2002) found. The difference was constant over different relative distances (with the exception of two observers who had a difference of zero when the relative distance was 1) and depended slightly on the separation angle. Cuijpers et al. also found a constant difference, even without the slight dependency on separation angle. Because (at least in geometry) collinearity is a special case of parallelity, one would expect the differences found between the settings of the two bars in the collinearity task to be of the same size as the deviations found for the parallelity task. This is not the case in the present experiments. Overall, the differences found for the collinearity task are smaller than the deviations found for the parallelity task. Next to that, the pattern of deviations is qualitatively different. The same discrepancy between the two tasks was found by Cuijpers et al. (2002). This shows that the geometrically similar parallelity task and the collinearity task are fundamentally different for the human observer.

2.6 General discussion and conclusions

As can be seen directly from the graphs (see Figures 2.5 and 2.11) the results of the exocentric pointing task are very similar to the results of the collinearity task. The same size and pattern of deviations was found. Even the distinction between two groups of observers, when one looks at the deviations found for a relative distance of 1, is the same. For this condition the same observers have veridical settings (AW and TL) for both tasks. Close to veridical settings for this condition were not found by Cuijpers and colleagues (2000a, 2002) as clearly as we did. An explanation for this difference could be as follows. When both objects were at the same distance from the observer, the veridical pointing direction was parallel to the back-wall. So for this condition there was direct information from the context available for the observer to do the setting.

If we compare these data to the data of the parallelity task (see Figure 2.8), we see a very different pattern. One of the differences is the size of the deviations: for the parallelity task the deviations are larger than for the other two tasks. In the parallelity task, the orientation of the reference rod and the test rod are misjudged. For the pointing task only the orientation of the test rod (the pointer) can be misjudged because there is no reference rod. For the collinearity task, one can split the task in two parts: pointing from one rod to the other and vice versa. This way, the orientation of one rod is not as largely dependent on the orientation of the other rod as it is in the parallelity task. Along this line of reasoning, one would expect the deviations of the parallelity task to be twice the size of the deviations in the other two tasks. This is exactly what we found in our experiments. The second difference is the effect of relative distance. Contrary to the other tasks, for the parallelity task no effect of relative distance was found. This distinction was also found by Cuijpers et al. (2000a, 2000b, 2002).

This quantitative and qualitative distinction between the parallelity task and the collinearity task seems to be quite strange when one considers the fact that in geometry, collinearity is a special case of parallelity. However, when one compares the two tasks one can distinguish between the way the tasks are performed. For the parallelity task, the observer does not have to look at the exact positions of the two objects. Instead, the view on the objects themselves is important. On the other hand, for the collinearity task this spatial relationship between the two objects is an essential part of the task next to the view on the objects. The collinearity task resembles a pointing task in which the task is to point with one pointer to the centre of the other pointer. So perhaps, it is not surprising to find a pattern and size of deviations comparable to that found for the pointing task. The comparison of the three tasks indicates that the concept of a single visual space is problematic. Apparently, "visual space" is deformed differently depending on the information in the environment necessary to do a certain task. One can describe the settings of the parallelity task geometrically by means of the separation angle and the reference orientation. The distance information is irrelevant for this task. This is totally different from the dependence on relative distance in the exocentric pointing and collinearity task. Thus, it is to be expected that human observers should perform differently in this task as compared to the other tasks. Furthermore, one would expect to find more veridical settings for the pointing and the collinearity task as compared to Cuijpers et al. data, since there is an increase in information about depth from monocular depth cues like linear perspective and texture segregation. In contrast, the performance for the parallelity task is less dependent on this kind of information about distances.

In the parallelity task a different degree of dependence on reference orientation was found for our observers. Cuijpers and colleagues (2001) discussed a difference between observers in dependence on references like the walls or the cabin the observers were seated in. But this was mainly a difference between oblique and non-oblique orientations. So this cannot explain our findings with differences between various oblique angles. Cuijpers et al. (2000b) noted a small difference between observers for oblique settings, but their explanation did not fit our data. An alternative explanation might be related to the degree of change in the view of an object when an object is rotated a small amount. For example, when an observer only looks at the rod and the rod is perpendicular to the line of sight, a rotation of 5° does not change the image of the rod on your retina as much as it would change the image of a rod collinear to the line of sight. On the other hand, if an observer looks both at the rod and the disc around it, the attended image on the retina will always have a rather large change. Thus, this difference in amount of change depends upon by the sources of information people use when performing a task.

For the pointing and collinearity task the veridical settings of the pointers can be described using the following formula:

$$\tan\beta = \frac{\sin\alpha}{\frac{r_1}{r_2} - \cos\alpha} \tag{2.2}$$

where β is the angle between the line between the pointer and the target, and the line between the pointer and the observer (Koenderink, Van Doorn, & Lappin, 2003). To use this formula for the collinearity task, we define one rod as the pointer. The middle of the other rod can be defined as the target. The variable α represents the separation angle between the two objects, and r_1 and r_2 represent the distance to the pointer and the target respectively. Traditionally, the focus has been on the perceived distances and how they are derived from the physical distances (r_1 and r_2). Different models have been fitted to different data-sets. For example, Wagner (1985) compared his data, acquired under full-cue conditions, to four models. Two of these were Riemannian models, one spherical, the other hyperbolic. These models did not fit his data: the spherical model produced such strange fits that it was rejected. The hyperbolic model did not produce good fits either, which was explained by noting that the model was made for reduced-cue conditions. Another model Wagner describes is an affine contraction model, which describes an affine transformation in depth (only in the direction straight ahead) using Cartesian metrics. Because humans are not thought to depend on Cartesian coordinates in dealing with depth, this model is refined into the vector compression model, which uses polar coordinates and fits very well to Wagner's data. In this model the physical distance is multiplied by a constant. In trying to explain our results with Equation 2.2, this constant will cancel out in the ratio that represents the relative distance. Thus, since multiplication of the distances with a constant has no effect on the pointing direction, the vector compression model cannot explain our results. We looked at Gilinsky's formula for perceived distance (Gilinsky, 1951) as can be seen in Equation 2.1. We replaced r_1 and r_2 from Equation 2.2 with $P(r_1)$ and $P(r_2)$. The equation did not fit our data well, but that is not surprising since Gilinsky formulated her theory on the basis of data obtained with larger distances. She described visual space as compressed. A compression of visual space does not suit our data, obtained with smaller distances. In fact, for two observers we found a (bad) fit with a negative constant, which is nonsense in the Gilinsky formula. For negative values of c, the formula is expanding, not compressing. Therefore, for the tasks in which spatial information was most important, the settings should be described by an expanding distance function (like a powerlaw) rather than a compressing distance function. This difference, possibly due to the varying distances used, is consistent with the ideas proposed by Battro, di Pierro Netto and Rozestraten (1976) and Koenderink, Van Doorn, & Lappin (2000) that the geometry varies with distance from observer to objects.

The data described above are quite similar to the data found by Cuijpers et al. (2000a, 2000b, 2002). This is not what we expected since the experiments were conducted in a very different environment. The walls, ceiling, floor, radiators, windows, doors, etc. were visible in our experiments in contrast to Cuijpers et al.. Despite this extra information provided by linear perspective, texture segregation, size constancy etc., the observers show a comparable magnitude and pattern of deviations. This can be explained in the following way. Perhaps the structure that was provided to the observers was not rich enough, so a richer structural context could make a difference. Wagner (1985) talked about the quantity and the quality of depth information and concluded that if both were maximal then visual space should be Euclidean. If one reduces both the quantity and the quality of the perceptual information, the deformation of visual space will increase as well. So a next step in this research should be to elaborate the context provided to the observers, and see whether the deformation of visual space will decrease. For example, we could put textures on the walls and floors or place extra objects in the room.

In summary, one cannot speak of a single visual space since the structure is dependent on the task that the observer is doing and the distance between the objects and the observer. The structure of visual space for two tasks that require spatial information from the objects (the exocentric pointing task and the colinearity task) and a distance of 1.5 to 4.5 meters between observers and objects, can be described by an expanding distance function like a powerlaw. For the parallelity task, a distance function is useless since the information about the exact positions of the objects is not necessary to do the task. Another conclusion that can be drawn from these data is that the settings of the observers in this environment full of monocular depth cues, were similar to the settings found for data obtained in a much poorer environment. Thus, the structure in this richer environment was not used effectively by the observers.