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Exocentric pointing in three-dimensional space

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Abstract. A study is reported of an exocentric pointing task in all three dimensions, in near space, with only two visible luminous objects—a pointer and a target. The task of the subject was to aim a pointer at a target. The results clearly show that visual space is not isotropic, since every set direction appeared to consist of two independent components—one in the projection onto a frontoparallel plane (tilt), the other in depth (slant). The tilt component shows a general trend across subjects, an oblique effect, and can be judged monocularly. The slant component is symmetrical in the mid-sagittal plane, requires the use of binocular information, and shows considerable differences between subjects. These differences seem to depend on the amount of binocular information used by each subject. There was a remarkably high level of consistency in the exocentric pointing, despite the absence of environmental cues. The within-subject consistency in the settings of the pointer corresponds to a consistency of about 1 min of arc in disparity of its tip, even though the pointer and target are separated by more than 5 deg.

1 Introduction

Localisation of one object in relation to another plays an important role in a great many of the tasks performed by humans on a daily basis. Think, for example, of preventing a collision while driving a car, threading a needle, judging who is looking at whom in a group of people, or simply reaching for a cup of tea. In these examples the judgment of direction is an important parameter which must be retrieved by the visual system. More specifically, taking the example of reaching for a cup of tea, van Sonderen et al (1988) have shown that relative direction is a major determinant in the programming of movement, and that relative direction is easily accessed. Although the judgment of direction is important, relatively little study has been done into how well humans can perform this (Wagner 1985; Ellis et al 1991; Brenner and Smeets 1995; de Graaf et al 1996; Koenderink and van Doorn 1998). One of the two goals of the experiments reported here was to explore how reliably humans can judge exocentric direction in near 3-D space.

Studying the direction in which an object is located relative to another (exocentric direction) can also provide useful information about the relationship between visually perceived space (visual space) and physical space (Ellis et al 1991; Koenderink and van Doorn 1998). Until now, experiments involving visual space have been restricted to a single plane, usually the horizontal plane at eye level (Blumenfeld 1913; Hillebrand 1929; Blank 1958; Wagner 1985; Koenderink and van Doorn 1998) or a frontoparallel plane (Indow and Watanabe 1984). The second goal of the experiment was to examine whether the results obtained in a single plane also hold for exocentric pointing through all three dimensions. Indow and Watanabe have shown that the results of an alley experiment differ for the frontoparallel plane from those for a horizontal plane. What does this imply for spatial judgments that are not restricted to one of these planes? Is visual space isotropic?

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Subjects were asked to aim a pointer from various locations at a target. In such a judgment task a great many visual cues may contribute to the performance. To permit interpretation of the results, in this study we confined ourselves to an extremely simple setup in which only a target and a pointer were visible to the subject in an otherwise dark 'environment'. Thus, no environmental cues were available. The use of a few luminous objects is in line with most experiments into visual space, and the reduced stimulus configuration allowed examination of the lower limits of the within-subject consistency of pointing. Also, in this situation, all available cues are known.

The results revealed several interesting facts. For example, the deviations from veridical in the pointer settings could be divided into two independent components—one in the projection onto a frontoparallel plane, and one in depth. The latter component showed marked differences between subjects. The results of the second experiment suggest that this was caused by the extent to which subjects used binocular information. There was also a remarkably high level of within-subject consistency in the exocentric pointing.

2 Experiment 1

2.1 *Virtual 3-D setup*

The stimuli were presented in stereoscopic 3-D via a Silicon Graphics Indy computer setup which draws a perspective-projected image from each eye on the screen, one for the right eye and one for the left eye, alternately. The images were viewed through LCD-shutter goggles which were synchronised with the monitor to ensure that each eye received the appropriate images. The images were drawn in red phosphor, because this was the phosphor for which the goggles were most opaque. They were drawn at a rate of 120 images per second (thus 60 images per second for each eye) on the computer screen. The screen consisted of 1280×1024 pixels, which were 0.27 mm $\times$ 0.27 mm in size. In front of the computer screen was mounted a circular band of black cardboard, occluding possible reference directions provided by the straight edges of the screen.

2.2 *Stimuli*

The stimuli consisted of a target and a pointer, both of which were wire-frame figures. The diameter of wire-frame line segments was always one pixel. The pointer consisted of a 4 cm line segment and a ring with a diameter of 3.2 cm. The line segment was perpendicular to the ring, projecting from the centre of the ring outwards (see figure 1). The pointer could rotate around the midpoint of the ring. The target was a dot (1 pixel). Two rings, with a diameter of 1.2 cm, were drawn in depth around the target, in such a way that they intersected each other above and below the dot. These rings were added to prevent the task from becoming a visual-search task, while presenting as little reference directions as possible and providing a small well-defined target (the single pixel).

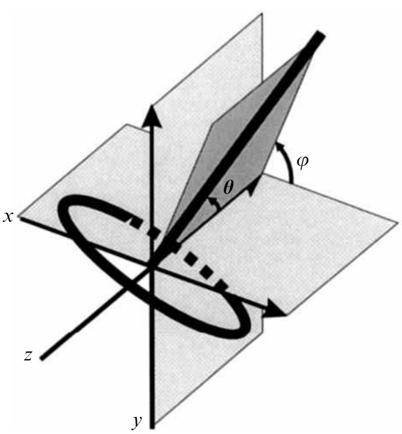

Figure 1. A perspective drawing of the pointer and the variables used for analysing the orientation of the pointer. The pointer consists of a ring that is 3.2 cm in diameter and a pin perpendicular to this ring that is 4.0 cm long. The origin of the variables used for analysing the orientation of the pointer lies at the centre of the ring. This is also the point around which the pointer rotates. The x-axis is horizontal, the y–axis is vertical and the z-axis is the depth axis through the rotation point of the pointer. The slant, θ, is the angle the pin makes with the axis perpendicular to the frontoparallel plane (or z-axis), towards the subject. The tilt, φ, is the angle in the projection onto the frontoparallel plane.

2.3 *Procedure*

Before the actual experiment was started, four things were done. First, the experimenter explained to the subjects, among other things, how the computer setup could present 3-D objects at any location in depth, and this was demonstrated with the help of an example program which showed cubes rotating in space. Second, the subjects were asked for their informed consent. Third, they were tested whether they were able to fuse two images, as presented in the experimental setup. Finally, they were given 15 to 20 min in which to familiarise themselves with the requirements of the task.

The task for the subjects was to aim the pointer at the target. They could manipulate the orientation of the pointer by pressing the arrow keys on the keyboard. The left and right arrow keys made the pointer turn around a vertical axis, and the up and down arrow keys made the pointer change the angle with the vertical axis. The orientation of the pointer could be adjusted in discrete steps of 0.3°. Subjects could take as much time as they needed to adjust the pointer. The final orientation of the pointer was recorded.

Each subject was seated 120 cm in front of the computer screen, with his or her head supported in a chinrest. The subjects were told that on each trial the pointer and target could appear to float somewhere in 3-D space. The programmed location of the target was fixed at 120 cm in front of the cyclopean eye of the subject on the computer screen. The pointer was programmed to appear at one out of possible twenty locations on a virtual hemisphere above the target, keeping the distance between pointer and target fixed at 20 cm. The programmed locations (the rotation point) of the pointer relative to the target are listed in table 1, and illustrated in figure 2.

Both the location of the pointer and the orientation at which it appeared were randomised during the experiment. This random orientation was somewhere between +12° and −12° with respect to the veridical direction towards the target, in any direction.

The group of twenty locations of the pointer was presented twice, after which there was a break. The breaks were inserted to ensure the concentration of the subjects.

Table 1. Positions at which the pointer could appear relative to the target and the corresponding values of slant, tilt, total visual angle, and visual angle of the pointer (see text).

Stimulus	Right/cm	Up/cm	Forward/cm	Slant/°	Tilt/°	Total visual angle/deg	Visual angle of pointer/deg
1	14.1	0	14.1	135	−180	6.70	1.48
2	14.1	0	−14.1	45	−180	6.70	1.29
3	−14.1	0	−14.1	45	0	6.70	1.17
4	−14.1	0	14.1	135	0	6.70	1.38
5	14.1	14.1	0	90	−135	9.43	1.91
6	−14.1	14.1	0	90	−45	9.43	1.90
7	0	14.1	14.1	135	−90	6.70	1.65
8	0	14.1	−14.1	45	−90	6.70	1.18
9	10	14.1	10	120	−125.3	8.20	1.85
10	10	14.1	−10	120	−54.7	8.20	1.53
11	−10	14.1	−10	60	−54.7	8.20	1.51
12	−10	14.1	10	60	−125.3	8.20	1.80
13	8.66	10	15	138.6	−130.9	6.29	1.52
14	15	10	8.66	115.7	−146.3	8.54	1.84
15	15	10	−8.66	64.3	−146.3	8.54	1.50
16	8.66	10	−15	41.4	−130.9	6.29	1.15
17	−8.66	10	−15	41.4	−49.1	6.29	1.16
18	−15	10	−8.66	64.3	−33.7	8.54	1.58
19	−15	10	8.66	115.7	−33.7	8.54	1.84
20	−8.66	10	15	138.6	−49.1	6.29	1.51

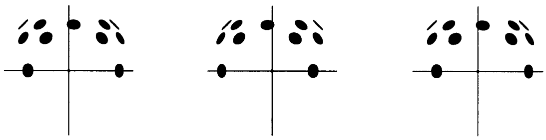

Figure 2. An illustration of the pointer locations as used in experiment 1. Cross-fusing the centre and the right image leads to a 3-D impression of the pointer locations in front of the target, and the centre and the left image leads to a 3-D impression of the pointer locations in front of the target. The distance between the target (always at the centre) and the pointer was kept constant at 20 cm. The pointer locations lie on a sphere. The images can also be fused with a parallel gaze-direction of the eyes, but this will give an overestimated impression of depth.

For each subject, 4–7 settings per location of the pointer were recorded. This varied because the duration of the experiment was limited, and because the subjects were allowed to set the pointer at their own pace.

The experiment took place in darkness and lasted about 2 h. This included giving instructions, practice time, and short breaks. No feedback was given, either at the practice trials, or at the experimental trials.

2.4 *Subjects*

Seven subjects (three male: DA, JH, MA; and four female: CE, DL, JN, MI), who were unaware of the purpose of the experiment, participated in it. They all had normal eyesight, or eyesight corrected to normal by contact lenses. Their ages varied from 18 to 24 years. An eighth subject was rejected because she could not fuse the images of the two eyes as presented in the experimental setup.

2.5 *Analysis*

The final orientations of the pointer, as set by each subject, were analysed. This orientation can be expressed in terms of two angles—one indicating slant, the other indicating tilt. The terms slant and tilt have been used in various ways in the literature (Howard and Rogers 1995), and therefore we shall make it quite clear how they are used from here on. Figure 1 shows a pointer with a slant θ and a tilt φ. These angles belong to polar coordinates (r, θ, φ), with the polar axis (z-axis) perpendicular to the frontoparallel plane at the side of the subject, and its origin at the midpoint of the ring of the pointer. The slant, θ, is the angle which the line segment of the pointer forms with the polar axis. A 0° slant means that the pointer points perpendicular to the frontoparallel plane towards the subject, and a 90° slant means that it points in the frontoparallel plane. The tilt, φ, is the angle between the projection of the line segment of the pointer onto the frontoparallel plane and the horizontal. A 0° tilt means that the pointer points horizontally to the right, and a -90° tilt means that it points straight down. Note that the origin of the polar coordinates is connected to the pointer, which varies in position relative to the target (see figure 1). Thus, when the pointer points to the right towards the central target, the pointer itself is located in the left hemifield of the subject (combine figure 2 with figure 1).

2.6 *Results*

Figure 3 shows the raw data of subject JN, expressed in terms of slant and tilt, as described above. The figure shows twenty clusters of points, each corresponding with one location of the pointer. Within one cluster, a dot marks a single recording of the final set orientation of the pointer, a cross marks the orientation at which the pointer would have aimed at the target, and an open circle marks the average of the set orientation of the pointer. This subject had representative standard deviations (size and orientation of the groups of settings). She made the largest systematic errors, thus providing a clear example of possible results.

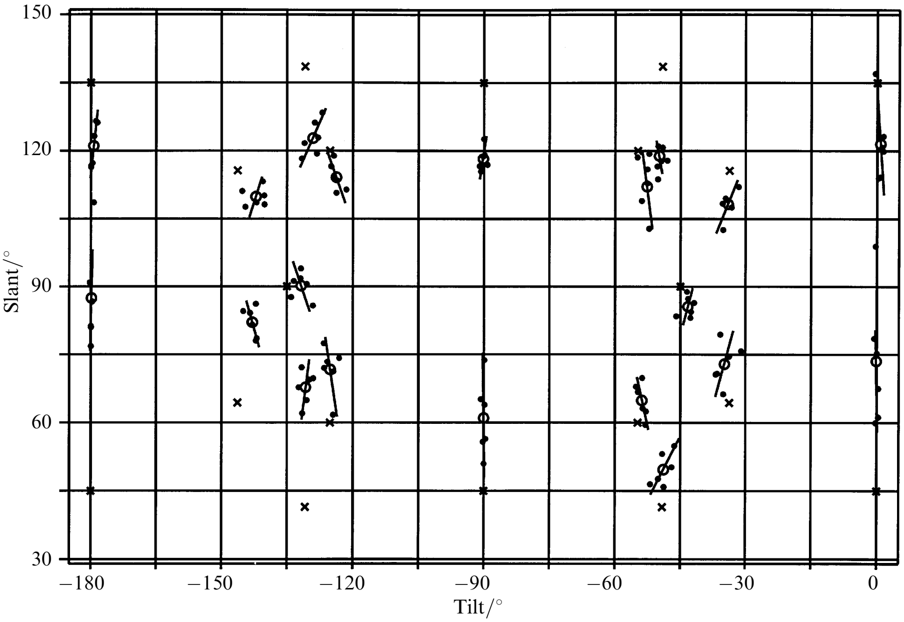

Figure 3. The settings of the orientation of the pointers by subject JN in a plot of the set slant against the set tilt. A dot indicates a single setting of an orientation of a pointer at a certain position. For each position at which a pointer could appear, the orientation was set six times. For each cluster of six repetitions, the cross indicates what the orientation of the pointer should have been in order to point towards the target, the open circle indicates the average setting of the orientation of the pointer of the subject, and the straight line through the cluster indicates the fit of least squares.

2.6.1 *Correlation between slant and tilt.* When looking at the various clusters of raw data points, the first thing to notice is that the variance in the slant is much larger than the variance in the tilt. Moreover, the various settings lie roughly along lines of constant tilt, ie the various settings of the pointer appear to lie in planes which are perpendicular to the frontoparallel plane. In order to quantify the correlation, least-squares fits through each of the twenty groups of settings were calculated (short lines in figure 3). In general, these fitted lines do not differ significantly from vertical ones. A Kolmogorov–Smirnov test over all stimuli and subjects did not reject the hypothesis that the measured orientations of the fitted lines are normally distributed around a vertical orientation (Kolmogorov–Smirnov $Z = 0.84$, $p = 0.48$). A two-tailed t-test of the orientation of the fitted lines showed that the hypothesis that the best-fit lines have a vertical orientation ($p = 0.32$) cannot be rejected. Thus, there seems to be no correlation between these variables, because the various settings lie parallel to one of the axes of the two variables that were chosen to express the orientation of the pointer. This is illustrated in figure 4, which shows the orientation of the best-fit lines, averaged over all subjects, for each of the twenty pointer locations. The grey area indicates the variance in the orientation of the fitted lines between subjects. They measure plus and minus twice the standard deviation in the orientation. The average lines and grey areas are drawn at the average location of subject averages, and have a length plus and minus twice the average standard deviation in the slant for that location of the pointer.

It is important to note that the slant and tilt were not the angles over which the subjects could adjust the orientation of the pointer. Thus, the lack of correlation between the slant and the tilt emerges purely from the data, and is not a product of the interface. This is also reflected in the typical adjustment behaviour of the subjects, who continuously alternated their use of the two pairs of arrow keys.

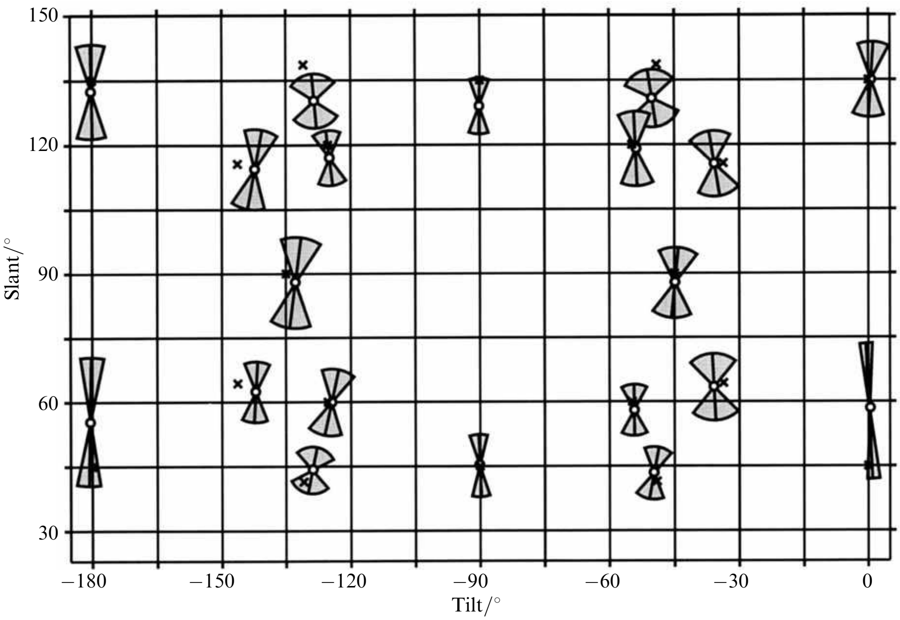

Figure 4. For each position where the pointer could appear, the cross indicates what the orientation of the pointer should have been in order to point towards the target, the open circle indicates the setting of the orientation of the pointer averaged over the subject averages. The straight line through the open circle equals the orientation of the least-squares fits averaged over subjects. The grey area indicates plus and minus twice the between-subject standard deviation in the orientation of the least-squares fits, indicating the variance between subjects (see text).

2.6.2 *Systematic errors in the tilt.* Figure 5 is a plot of the systematic errors in the tilt, against the value of the tilt. These systematic errors are defined as the difference between the veridical value of the tilt and the average angle of tilt as it was set by the subject for that location of the pointer. The sign convention was chosen such that a positive value means that the pointer was aimed above the target. When there was more than one pointer location with the same veridical tilt (but different slant), the errors were averaged. In our setup this means an averaging of the errors in the tilt of two pointer locations which lie symmetrically with respect to the frontoparallel plane of the target. A two-tailed paired t-test could not reveal a significant difference ($p = 0.06$, $t_{63} = 1.90$).

The systematic errors are generally smallest for a value of the tilt of 0°, −90°, or −180°, where the smallest within-subject standard deviations were also measured (figure 5). Furthermore, the systematic errors are largest near −30° and −150°. The systematic errors in the tilt show a general trend common to all subjects. This pattern means that under oblique angles the subjects tend to point below a straight line that would connect the target and the pointer. This tendency seems to be somewhat stronger for pointers aiming leftwards towards the central target (tilt between −180° and −90°) than for those aiming rightwards towards the central target (tilt between 0° and −90°).

The trend in the systematic errors in the tilt (figure 5) is very similar to that found in the experiments by Sittig and de Graaf (1994). Their subjects were asked to perform a three-dot alignment task on a frontoparallel surface (computer screen). Under oblique orientations, the subjects generally placed the middle dot below the straight line that would connect the outer two dots. The size of these errors is comparable to the errors found in our experiment. Their task can be interpreted as two dots being a simplified pointer pointing towards a third dot. The similarity between the two sets of results would suggest that the physical presence of a plane was of little consequence and little significance in their experiment.

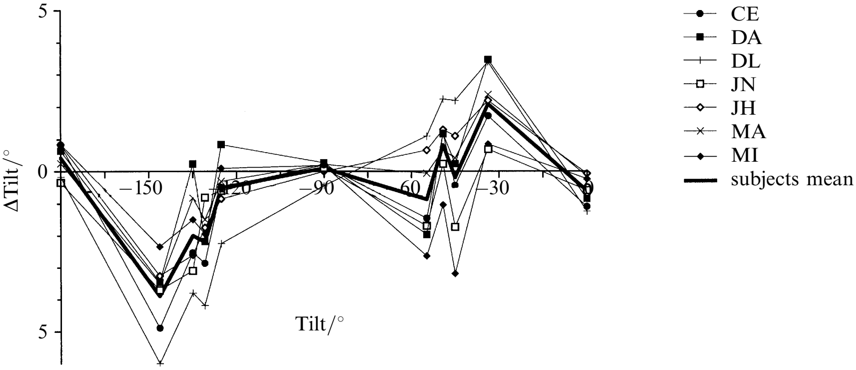

Figure 5. The systematic error in the tilt, ΔTilt, plotted against the veridical tilt for each subject. When there was more than one pointer position with the same veridical tilt (but different slant), the errors were averaged. A positive value means that the pointer aimed above the target. The thick solid line indicates the average over subjects. See figure 8 for within-subject standard deviations.

As said, the systematically smallest errors and within-subject standard deviations were found at the tilts of 0°, −90°, and −180° (see figure 5). These angles represent a vertical or horizontal orientation in projection onto a frontoparallel plane. These orientations are special to the human visual system (oblique effect, Appelle 1972). Lederman and Taylor (1969) suggested that locations or orientations are perceived in terms of their distance from anchors or references, and that systematic errors increase with increasing distance from the anchor. In these terms, our results indicate that the vertical and horizontal were used as orientation anchors. Since a black circular band occluded the horizontal and vertical edges of the computer screen, these reference directions could not be derived from the visual scene. The minor irregularities near −45° and −135° suggest that an orientation midway between anchors may also be special.

2.6.3 *Systematic errors in the slant.* Systematic errors in the slant are plotted against the value of the slant in figure 6. These systematic errors are defined as the veridical value of the slant minus the average angle of slant as it was set by the subject for that location of the pointer. The errors were averaged for pointer locations with the same veridical slant (but different tilt). This averaging does not lead to a loss of information when the errors in the slant are symmetrical with respect to the midsagittal plane, as will be shown in figure 7.

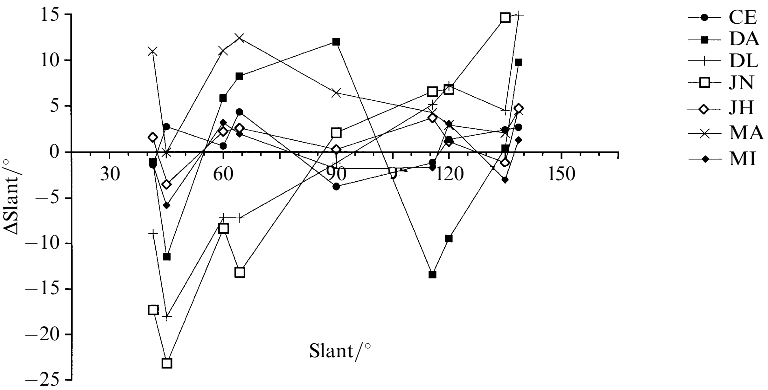

Figure 6. A similar plot to figure 5, this time for the slant. The systematic errors, ΔSlant, are defined as the veridical value of the slant minus the average indicated angle of slant. See figure 9 for within-subject standard deviations.

The first point of significance is that the systematic errors in the slant can be much larger than those found in the tilt (compare figures 5 and 6). Second, unlike the systematic errors in the tilt, the systematic errors in the slant do not show a clear trend over all subjects. Each subject has quite different but significant and consistent errors. At least three types of pattern emerge from the systematic errors in the slant. Subjects JN and DL can be seen to constantly underestimate the depth difference between the locations of the target and the pointer, without compressing the target or the pointer. This underestimate is about 40% for subject JN, and about 25% for subject DL. Subject MA points too steeply (ie is biased towards the vertical) when the pointer points forwards, from the back half of the virtual sphere towards the target, but does the reverse in the opposite half of pointer locations. In other words, these results fit the pattern of a target location further back in the virtual sphere, with a slight overestimate of the depth difference between the target and the pointer. The pattern of subjects CE, JH, and MI fits well with the veridical, because their systematic errors are about equal in size to the measured within-subject standard deviations. Finally, the results of subject DA are rather chaotic and difficult to describe. This subject also presented the largest standard deviations, around 7°, as compared with the typical within-subject standard deviations of about 4°.

Another way in which the systematic errors in the slant component differ from those in the tilt is that, with respect to the mid-sagittal plane, the former appear to be symmetrical. This is the one thing all subjects have in common in their slant settings. It is illustrated in figure 7, where the systematic error in the slant of a stimulus in the right hemifield is plotted against that of the stimulus located symmetrically to it with respect to the mid-sagittal plane. In the graph, the line of perfect symmetry is drawn, and is a fairly good fit through the points.

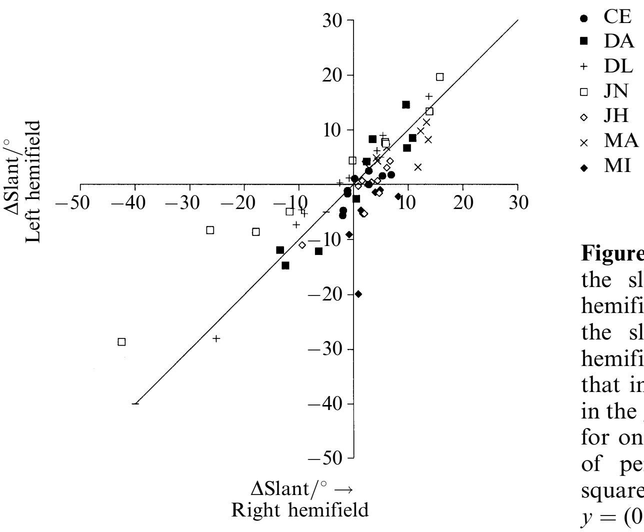

Figure 7. A plot of the systematic error in the slant for a stimulus in the right hemifield against the systematic error in the slant of the stimulus in the left hemifield which is the mirror image of that in the mid-sagittal plane. One point in the graph represents one pair of stimuli for one subject. The solid line is the line of perfect correspondence. The least-squares fit through the points is the line $y = (0.9 \pm 0.1)x - (0.8 \pm 0.9)$.

2.6.4 *Standard deviations.* The measured within-subject standard deviations are small. Figure 8 shows the standard deviations in the tilt settings as a function of the tilt for each subject. These standard deviations in the tilt also show an oblique effect. They are smallest, about 0.5° – 0.7°, for the vertical and horizontal orientation. This corresponds to a 1 min of arc shift of the endpoint of the pointer. The standard deviations are about twice as large for oblique angles.

Figure 9 shows the measured standard deviations in the slant settings for each subject. The within-subject standard deviations in the slant lie between 2.5° and 6°. The value is roughly constant over all veridical values of the slant, and thus roughly constant over all locations of the pointer (see figure 9 in combination with table 1).

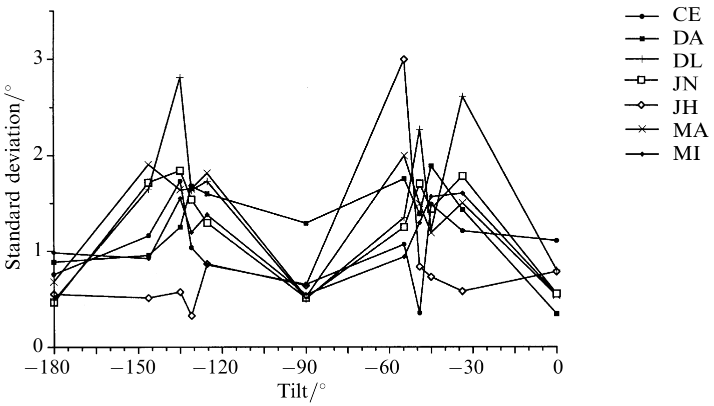

Figure 8. A similar plot to figure 5, this time for the within-subject standard deviations in the tilt. The standard deviations in the tilt settings are plotted against the veridical tilt for each subject. When there was more than one pointer position with the same veridical tilt (but different slant), the within-subject standard deviations were averaged. The within-subject standard deviations are smallest for horizontal or vertical orientations (tilt equals 0°, −90°, or −180°).

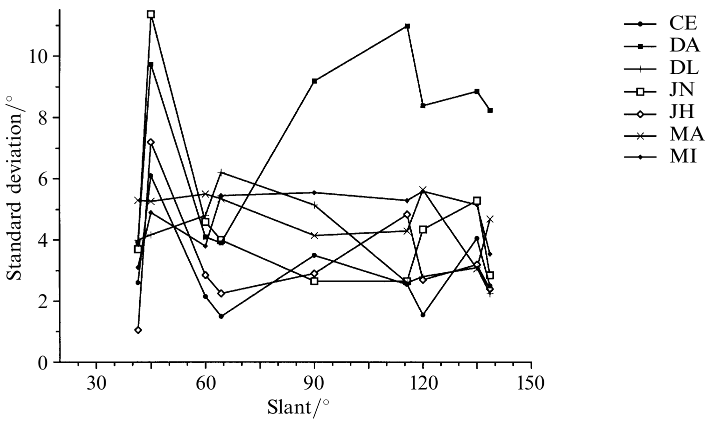

Figure 9. A similar plot to figure 8, this time for the within-subject standard deviations in the slant settings.

In other words, it does not seem to depend on the eccentricity of the pointer. Subject CE has the smallest standard deviations, about 3° on average. These standard deviations correspond with changes in depth of the tip of the pointer of about 0.25 min of arc of relative disparity on average (see figure 10).

2.6.5 *Discussion of standard deviations.* It is not an easy task to compare the depth detection thresholds with those reported in the literature, for two reasons. First of all, the literature reports results of hyperacuity tasks with relatively small stimuli. The depth-detection threshold can be as small as several seconds of arc disparity, for features located in the plane of fixation (Mitchison and Westheimer 1984; Lappin and Craft 1997). The second reason which makes comparison difficult is the fact that the thresholds are reported to increase rapidly with increasing in-depth distance to the fixation point (Blakemore 1970; McKee et al 1990), and we did not know, during our experiment, where the subjects were looking. Nevertheless, the data reported by Blakemore (1970) were used to attempt a tentative estimate in our experiment. In agreement with the reported dependences, Blakemore's data (averaged over subjects and averaged over convergent/divergent) were fitted with a function that changed exponentially with increasing depth difference between the detection plane and the plane of

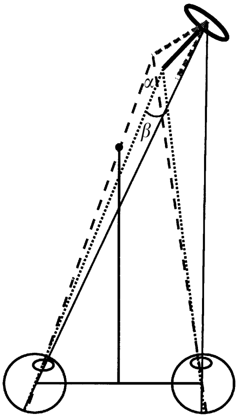

Figure 10. Illustration of the relation between the within-subject standard deviations in the slant settings and the corresponding change in relative disparity via a schematic top view of the target, the pointer, and both eyes of the subject. The solid outlined pointer represents the pointer at an average set orientation, and the dashed pointer pins represent the pointer at an orientation equal to the average plus or minus the standard deviation. The moveable endpoint of the pointer has a well-defined disparity which changes in depth. A shift in orientation of the pointer over a range of one standard deviation corresponds to a change in relative disparity of $\alpha - \beta$.

fixation (depth pedestal), and changed quadratically with increasing eccentricity. In our experiment there are two distinct points, with well-defined disparity, at which subjects could be looking—the midpoint of the ring around which the pointer rotated and the target. With respect to the moveable endpoint of the pointer, the midpoint of the ring is on average at 1.5 deg eccentricity and 3.5 min of arc depth pedestal, and the target is on average at 6 deg eccentricity and 10 min of arc depth pedestal in the opposite direction. If these values are applied to the fit of the Blakemore data, we find thresholds of 0.7 min of arc and around 2 min of arc, respectively. Blakemore set the threshold at 75% correct. For our subject CE, 75% of the slant settings lie within a range of 7° (2.3 times the standard deviation). This corresponds with a change in relative disparity of about 0.6 min of arc.(1) Thus, the observed within-subject standard deviations in our pointing task are indeed small, especially when taking into account that (a) the task extends over a total visual angle between 6.3 and 9.4 deg, (b) the target lies in a different depth plane than the pointer, and (c) the task is not a hyperacuity task with two lines presented closely together.

Finally, it should be noted that the subjects were allowed to move their eyes freely. However, vergence eye movements are a much weaker cue to depth than relative disparity (Collewijn and Erkelens 1990)

2.7 *Discussion*

Exocentric pointing in all three dimensions simultaneously has shown that the deviations consist of two independent components. We can therefore conclude that visual space is not isotropic. The same split in independent components was suggested by Wagner (1985), on the basis of the results of his experiments, which were much larger in volume and under full-cue conditions. This split could explain why, for Indow and Watanabe (1984), alley-experiments performed on a plane at eye level produced different results from those performed on a frontoparallel plane.

The small within-subject standard deviations in the slant suggest that all depth information in the images of the two retinas is combined in an effective way. We investigate this in more detail in experiment 2.

(1) In this discussion of the within-subject standard deviations, we compare point disparities and not orientation disparities. The reason for this is that the orientation disparities can only be used as a cue for the in-depth orientation of the pointer when the torsion of the eyes is known. Our stimuli lack a clear horizontal line that is needed to torsionally align the two retinal images of the eyes (Howard and Rogers 1995, page 424). Moreover, reports by Mikaelian et al (1990) and Courjon et al (1981) suggest that extraretinal signals about the torsion of the eyes are not used in orientation judgment since induced changes in cyclotorsion do not induce tilt aftereffects.

3 Experiment 2

3.1 *Introduction*

In experiment 1, relative disparity is not the only source of depth information. As well as binocular information, there are two main sources of monocular information about the spatial orientation of the pointer—the perspective shape of the pointer and the slow movement during adjustment of the orientation of the pointer. Monocular cues such as these can dominate binocular cues (Ames 1951; Stevens and Brookes 1988). In our setup, the weak depth cue of the accommodation of the eyes is in conflict with the other cues. The purpose of this second experiment was to gain more insight into the contribution of various depth cues. Could an effective combination of depth cues explain the small within-subject standard deviations? Do subjects have a strategy dominated by monocular information, or a strategy dominated by binocular information, or does it depend upon the subject?

3.2 *Methods*

Five subjects participated in this experiment, in which the experimental setup was the same as in experiment 1. Three of these subjects (DL, JH, and MI) had taken part in the previous experiment. Subjects PT and ES were new, naive subjects (both female, aged 22 and 24 years). All subjects gave informed consent and all were unaware of the purpose of this experiment. They were tested for stereopsis with a standard TNO-test (Walraven 1975). All subjects passed this test.

The experiment began with a practice period for the subjects of about 15 min. The method was the same as in the previous experiment, except that now only four locations of the pointer were used [slant and tilt: (64.3°, −146.3°), (138.6°, −130.9°), (120°, −54.7°), (45°, 0°)]. In this practice trial the pointer appeared randomly around the veridical, at an orientation within 25°. The practice series was followed by four experimental series where the pointer could appear at four other locations [slant and tilt: (64.3°, −33.7°), (127.8°, −63.4°), (158.9°, −134°), (60°, −125.3°)]. Two of these locations were not used in experiment 1. The four experimental series were presented in the order of increasing amount of binocular information. In the first series (condition M) the pointer was presented only to the right eye, thus monocularly. In the second series (condition CB) the circle of the pointer was presented binocularly, but the pin of the pointer was presented only to the right eye. In the third series (condition PB) this was reversed and the circle was presented only to the right eye while the pin was viewed binocularly. In the last series (condition B), as in the previous experiment, the whole pointer was viewed binocularly. The target was viewed binocularly in all four series.

Throughout the series, the pointer started at an orientation of the pin in a frontoparallel plane (slant 90°), with the tilt differing less than 30° from that of the veridical. Each location of the pointer was presented nine times in each of the four series.

3.3 *Results*

During the experimental series, all subjects made the following two comments. In the first series, M, they said that they could not see which way (forward or backward) the pointer was pointing. As they went from series M to series B, they claimed that they experienced increasingly ‘more depth’.

The results of the practice series showed that all subjects who participated in experiment 1 generally reproduced their previous results well. Thus the errors did not vary significantly over time.

Figure 11 shows the results for the slant, grouped per subject and per location of the pointer. We only show the results of the subjects for whom we have also shown results in the previous experiment. Of the other subjects, the results of subject PT are similar to those of subject JH, and the results of subject ES are similar to those of subject DL.

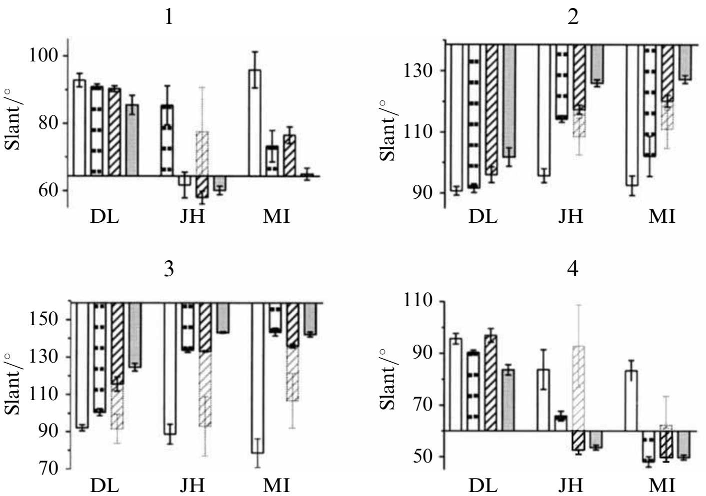

Figure 11. Grouped per subject (DL, JH, MI), the results are plotted for the conditions with variable binocular information about the pointer. The four numbered sections of the graph correspond to the four possible positions of the pointer (1, 2, 3, 4). The white bars belong to condition M (pointer viewed monocularly by the right eye). The dotted bars belong to condition CB (circle of the pointer was viewed binocularly and the pin of the pointer was viewed monocularly by the right eye). The dashed bars belong to condition PB (pin of the pointer was viewed binocularly and circle of the pointer was viewed monocularly by the right eye). The grey bars belong to condition B (whole pointer was viewed binocularly). The length of a bar indicates the systematic error. The standard error of the mean is plotted, in each bar, once above and once below the average. The pointer always appeared at a starting orientation with the pin in a frontoparallel plane (slant $= 90°$). Sometimes the figure shows two bars with errors in condition PB. In these cases the group of repeated measurements was clearly divided into two subgroups: one pointing backward and one pointing forward. The black outlined bars and whiskers indicate the mean and standard error of the mean for the subgroup of set orientations in the right direction. The grey bars and whiskers indicate the mean and standard error of the mean of the whole group.

When the pointer was viewed monocularly (M), all subjects set the slant of the pointer at an angle that did not differ significantly from a frontoparallel orientation (which was also the starting orientation).[2] The systematic errors in condition B are smaller than those in condition M. The results of subjects JH and MI are different from those of subject DL, as in experiment 1.

For subjects JH and MI (and PT), both the systematic and the within-subject standard deviations were dramatically reduced in condition B, when compared to condition M. The results in conditions CB and PB generally fell between those of the other conditions. The large within-subject standard deviations which sometimes occur in condition PB are due to the fact that there the settings can be split up into two groups: one pointing forward and one pointing backward. This is consistent with the Necker-cube-like instability reported by subject JH in this condition. The subgroup of set pointer orientations pointing correctly forward or backward (indicated by the extra lines with listed standard error of the means in figure 11) have a within-subject standard deviation and systematic error that are very similar to those in condition CB, ie close to the systematic errors in condition B, but with a slightly larger within-subject standard deviation than in condition B.

[2] We performed a control experiment, which was as condition M but with a different starting position, and the pointer was presented monocularly to either the right or the left eye (subject ES). The results revealed that the recorded average setting of approximately 90° was not due to laziness on the part of the subject. The results were not significantly different for the two eyes.

The systematic errors made by subject DL (and ES) were smallest in condition B, but the improvement was much less than for subjects JH and MI (and PT). In condition B subject DL set the pointer at an orientation which was even closer to an orientation with the pin in the frontoparallel plane than in the practice trials and the previous experiment. The standard deviations of subject DL remained approximately constant throughout the four series. Although she seemed to make little use of the binocular information of the pointer, it must be remembered that her stereopsis was good.

Figure 12 is a similar plot to figure 11, but this time for the tilt. For all subjects, the systematic and within-subject standard deviations in the tilt remained approximately constant throughout all conditions. In other words, the increase in binocular information had no measurable effect on the setting of the tilt.

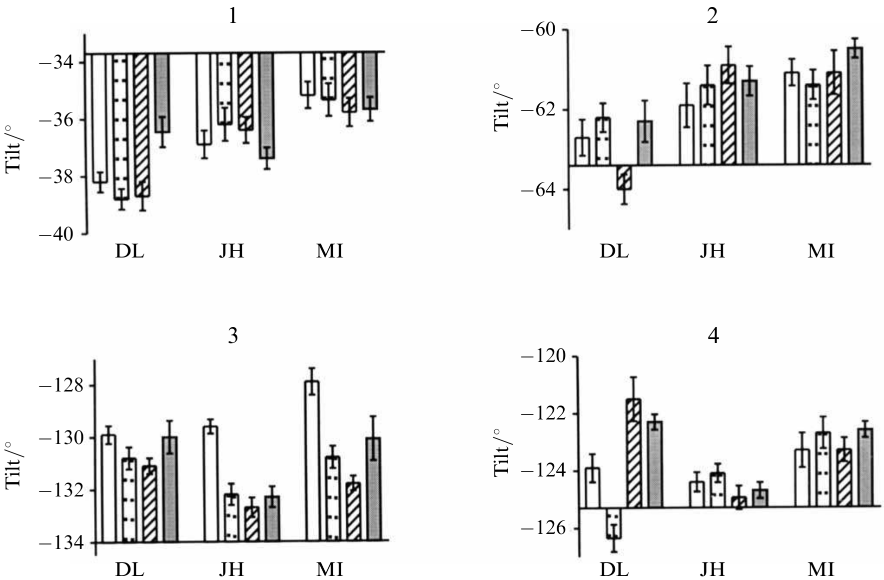

Figure 12. A similar graph to figure 11, this time for the tilt.

3.4 *Discussion*

The results of this second experiment suggest that the tilt is judged solely on monocular information, since adding binocular information did not change the set tilts in any way. The amount of binocular information did influence the set slants for all subjects. Only the extent to which this binocular information was used varied between subjects; JH, MI, and PT seemed to use binocular information from both the ring and the pin of the pointer, while subjects DL and ES seemed to rely mainly on monocular depth information. This subject-dependent use of binocular information is probably one reason why there were such large differences in the slant results in experiment 1.

The idea that the amount of depth information influences the results can be found in the literature. Luneburg (1947) formulated a theory which fitted the results of experiments, done in darkness, with a few luminous objects at eye level (Blumenfeld 1913; Hillebrand 1929). However, this theory can not explain the results of Wagner (1985) and Koenderink and van Doorn (1998), who did experiments under full-cue conditions, nor the results of Ellis et al (1991), who found an influence of reference lines seen from an oblique top view.

There are two factors which might influence the set orientations of the pointer that have not yet been mentioned. First, the dark circular band that occluded the straight edges of the computer screen was visible, because it was darker than the screen. Although it could not be used as a reference for orientation, it could have been used as a reference in depth. It is not clear what kind of effect this had on the results. The possible role of a reference is not mentioned in existing models of visual space (Luneburg 1947; Wagner 1985). However, Eby and Braunstein (1995) have shown that a frame around a 3-D scene can reduce the perceived depth within the scene. This is not supported by the results of subjects JH, MI, and PT in the B condition. The second factor concerns the possible influence of prior assumptions made by the subjects. Although they were given no information about the pointer and target locations which were used, they may have assumed that they could recognise a pattern in the locations where the pointer appeared. This seems unlikely, because it implies that the subjects could also orient the pointer in depth in the M condition. The results indicate otherwise.

4 General discussion and conclusions

Two experiments have been described, in which subjects had to perform an exocentric pointing task in all three dimensions. The results clearly demonstrated that the deviations from the veridical could be split up into two independent components—tilt, which can be set monocularly, and slant, which also needed binocular information. The extent to which binocular information was used varied between subjects.

The within-subject standard deviations measured were small for both tilt and slant. For slant, the standard deviations correspond to a change in relative disparity of about 0.25 min of arc. This is less than would be expected on the basis of hyperacuity depth-detection thresholds reported in the literature (Blakemore 1970).

For the systematic errors, at least three possible explanations exist, because there are three possible sources of error in perception in the task. First, there could be an error (or bias) in the perception of the orientation of the pointer. Second, there could be an error (or bias) in locating the target and the pointer. Third, a straight line that could connect objects in visual space could represent a curved line in physical space. These experiments cannot exclude any of these three possibilities.

The results of the second experiment suggest that an error in perceived locations is likely. The depth difference between the target and the pointer, as indicated by the relative disparities, cannot be retrieved from the monocular depth cues. Experiment 2 showed that some subjects rely mainly on monocular depth cues and make little use of the binocular cues. The depth at which these subjects saw the pointer is not known. The weak monocular depth cue of the accommodation of the eyes is in conflict with all other depth cues in our setup, and indicates that the pointer is at approximately the same depth as the target (the accommodation cue leads to a depth-difference-detection threshold of 5 cm at a distance of 1.5 m, according to Piéron 1927). This would suggest that the more subjects rely on the accommodation of the eyes as a cue for depth the more likely they are to perceive the pointer too close to the target. However, this hypothesis does not explain all the systematic errors found in depth.

The large differences between subjects make it difficult to fit them into a single theory. Existing theories about the relationship between visually perceived space (or visual space) and physical space generally assume that one transformation exists as a general property of the visual system (Luneburg 1947; Wagner 1985). Moreover, these theories of visual space assume that the difference between visual space and physical space occurs solely through a systematic misperception of the distance between the subject and any point in space as a function of that distance. The results of subjects CE, JH, and MI do not disagree with this assumption. The results of subjects JN and DL suggest a misperception of depth with respect to the target (or computer screen) which does not affect the perceived size and shape of the pointer. The results of subject MA are better explained by an apparent frontoparallel plane being perceived as slanting backwards, as shown by Cogan (1979).

In terms of the measured within-subject standard deviations, the quality of performance of exocentric pointing in 3-D space was high. With the target in a horizontal or vertical direction in projection onto a frontoparallel plane, the standard deviations were extremely small, less than 1 min of arc. Under oblique angles the standard deviations were about twice as large. This was an impressive performance, if one takes into account the fact that empty space over a 58 deg visual angle had to be bridged. Also, the task was not restricted to the foveal boundaries. The slant performance was equally impressive. Here, relative disparities of less than 1 min of arc appear to be detectable and interpretable as differences in direction, while the pointing task also extended over many minutes of arc in depth.

Both the systematic errors and the observed variances indicate that they can be split into two independent components. Thus, visual space is not isotropic. This has consequences for the generalisation of the results measured within a single plane. The difference in results observed by Indow and Watanabe (1984) between parallel and equidistant alleys in the frontoparallel plane and those on a horizontal plane at eye-height may be a consequence of these two independent components: in the frontoparallel plane only the tilt component is present and in a horizontal plane only the slant component is present. The similarity between the results in the tilt component and the results of Sittig and de Graaf (1994, see above) suggests that the physical presence of a plane is of little consequence.

To summarise, there are two important conclusions to be drawn from these results. First, it would appear that in abstract visual space relative directions are accurately recognised, since less than 1 min of arc change in disparity can be interpreted as a change in direction. Within the tilt component, the horizontal and vertical direction are recognised with particular accuracy, with standard deviations corresponding to 0.5 min of arc. Second, visual space is not isotropic. It is split into two independent components (see figure 1). One component uses only monocular information, the other component needs also binocular information. Thus, the result of judging a direction in 3-D space depends on how this direction is oriented in relation to the two components.

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