Depth Perception
and
Adaptation to Disparity

Ellen Berends

Helmholtz Instituut

School for Autonomous Systems Research

The cover illustration is a picture of Lago Maggiore made by the author.

This thesis was printed by Ponsen & Looijen BV.

ISBN: 90-393-2753-X

Depth Perception and Adaptation to Disparity

Het waarnemen van diepte en adaptatie aan dispariteiten
(met een samenvatting in het Nederlands)

Proefschrift
ter verkrijging van de graad van doctor
aan de Universiteit Utrecht
op gezag van de Rector Magnificus,
Prof. Dr. W.H. Gispen,
ingevolge het besluit van het College voor Promoties
in het openbaar te verdedigen
op woensdag 13 juni 2001 des middags te 12.45

door

Ellen Marian Berends
Geboren op 11 september 1972, te Arnhem

promotor: Prof. Dr. C.J. Erkelens
Helmholtz Instituut
Faculteit Natuur- en Sterrenkunde
Universiteit Utrecht

Contents

Chapter 1

General introduction

1.1 Introduction

Humans have two eyes at the front of the head. Because the eyes are at the same height but at different positions there is a large overlap between the two retinal images, but a slight difference in the viewing point. The differences between the retinal images, which are called retinal disparities, enable us to derive a three-dimensional percept from the two two-dimensional retinal images in combination with the eye positions. This ability is called stereovision or stereopsis. Not only humans but also primates and most predators have stereovision. Those animals that do not have the capacity for stereovision reconstruct a 3D-percept from their surroundings by means of other information sources, like perspective, occlusions, shadows and the relative size of objects. Stereovision improves the monocular 3D-reconstruction. Stereovision gives many predators large advantages in hunting, because it is more accurate than monocular 3D-reconstruction for distances between 50 cm and 5 metres. When objects are further away than 5 metres, the differences on the retinas (disparities) are too small for them to derive a three-dimensional percept. Prey animals do not need stereovision, because they have to escape before their enemy, the predator, comes too close. Prey animals with eyes on each side of the head - not at the front - can escape more readily because then they can oversee a large panorama.

Stereovision helps us to navigate in our environment. It enables us to perform precision tasks like threading a needle or filling a glass of water. Stereovision has intrigued many scientists. Scientists wanted to know how the two retinal images and the eye position signals are combined. They developed various expressions for disparity, which have been used in several models for stereoscopic depth perception.

1.2 Types of disparity

Various expressions for disparity have been described in the literature. Retinal disparity is the first type of disparity mentioned. Retinal disparity is the difference between the two retinal positions. Ptolemy and Galen described the differences between these images a very long time ago, namely in the second century (Wade, 1998).

Headcentric disparity was not described until 1998 (Erkelens and Van Ee, 1998). It is the difference between the two headcentric directions. The headcentric directions do not depend on the eye positions. Therefore, headcentric disparity only depends on the position of objects relative to the head. The headcentric direction of an object relative to each eye is computed from the retinal position and the eye position. The major difference between headcentric disparity and retinal disparity is that the eye position signals are included in the headcentric disparity, whereas they are not included in retinal disparity.

Relative retinal disparity in a horizontal plane does not depend on the eye positions either. An example of relative retinal disparity is the horizontal and vertical size ratio (Gillam and Lawergren, 1983; Rogers and Bradshaw, 1993; Rogers and Bradshaw, 1995). The (horizontal or vertical) size ratio was defined as the ratio of the (horizontal or vertical) angular size of an object in one eye to the angular size in the other eye.

Although, we do not know which expression for disparity is used by the visual system, we know that there are differences between horizontal and vertical (defined relative to the head) disparity. Howard and Kaneko (1994) and Kaneko and Howard (1996) reported that vertical disparity is processed regionally or even globally, whereas horizontal disparity operates locally. Locally derived depth from horizontal disparity does not depend on the shape of the horizontal disparity field at other positions of the visual field. Regionally processed vertical disparity means that the vertical disparity is integrated over a large region of the visual field. Therefore, vertical disparity can influence the percept only in a few ways, whereas horizontal disparity can change the percept in an infinite number of ways.

1.3 Models for stereoscopic depth perception

Many models have been developed for stereoscopic depth perception. Scientists have formulated various mathematical descriptions of how the visual system may process stereo-information. Unfortunately, empirical evidence has shown repeatedly that the visual system is organised differently from what was suggested.

Koenderink and van Doorn (1976) were the first investigators to formulate a computational model for stereoscopic depth perception. They decomposed the disparity field into four first-order components, namely expansion, rotation, deformation and shear. These components can be used to determine the slant about the horizontal and the vertical axis of a surface and the eccentricity of the object. According to the model of Koenderink and van Doorn (1976), eye position signals are not used to determine depth.

Mayhew (1982) and Mayhew and Longuet-Higgins (1982) also developed a model in which eye position signals were not required. They showed theoretically that the direction of gaze could be derived from vertical retinal disparity. However, evidence was found that eye position signals are used in depth perception (Collewijn and Erkelens, 1990; Rogers and Bradshaw, 1995; Backus and Banks, 1999). The polar angle disparity model (PAD) (Weinshall, 1990; Liu, Stevenson and Schor, 1994) uses eye position signals and describes disparity in polar co-ordinates.

The disadvantage of the above-mentioned models is that they do not take into account that vertical disparity is processed regionally or globally (Howard and Kaneko, 1994; Kaneko and Howard, 1996; Van Ee and Erkelens, 1995). Therefore, Gårding, Porrill, Mayhew and Frisby (1995) developed the regional disparity correction model (RDC), in which vertical disparity is integrated over a larger region and eye position signals are used.

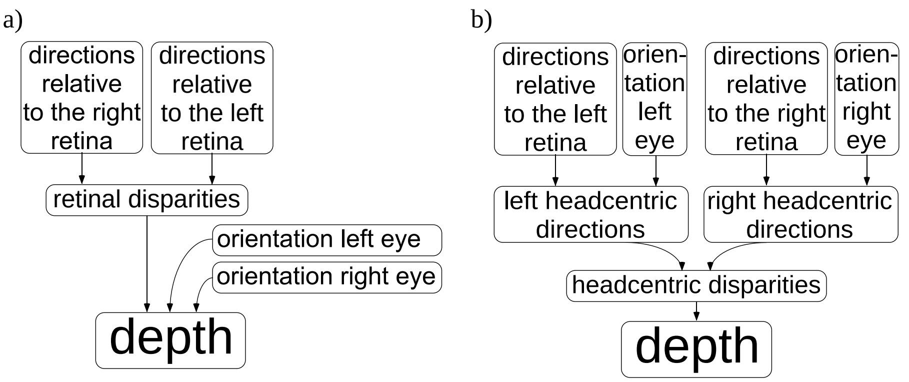

Figure 1.1 - Two methods for processing retinal directions and eye position signals in order to obtain depth. Method a) uses retinal disparities, whereas method b) uses headcentric disparities.

Yet another type of model is the headcentric model developed by Erkelens and Van Ee (1998). This model differs from the above-mentioned models in that it uses headcentric disparities instead of retinal disparities. Consequently, signals are not processed in the same order as in the models that use retinal disparities and eye position signals (PAD and RDC). According to the models that use retinal disparities (Figure 1.1a), retinal horizontal and vertical disparities are first computed by subtracting the retinal directions from corresponding image points. Subsequently, the retinal disparities and the oculomotor signals are combined to obtain depth. According to the headcentric model (Figure 1.1b), the oculomotor signals are involved in an earlier stage of the process. For each eye, the orientation of the eye in the head is combined with the retinal direction of an image point in order to calculate the headcentric direction, i.e. the direction of the image point relative to the head at the location of the eye. Subsequently, the headcentric disparities are computed by subtracting the headcentric direction of the left eye from that of the right eye. Depth follows directly from a simple relationship between headcentric disparity and headcentric distance. Until now, it has not been clear at what stage of depth perception eye position signals are involved.

Many experiments show that depth estimations from disparity alone are not veridical (for instance Van Ee and Erkelens, 1995; Van Ee and Erkelens, 1996; Howard and Kaneko, 1994; Kaneko and Howard, 1996). Underestimation or overestimation of depth has been attributed to conflicts between disparity and other depth cues (Johnston, Cumming and Landy, 1991; Johnston, 1993). Generally, subjects estimate depth induced by disparity alone non-veridically, because different cues signal different depths. Individual differences are explained by assuming that different subjects attach different levels of reliability to different cues. This weighting of different depth cues is described by the weak fusion model (Landy, Maloney, Johnston and Young, 1995) and more specifically by the estimator reliability model (Backus and Banks, 1999; Backus, Banks, van Ee and Crowell, 1999). In the estimator reliability model, the depth derived from horizontal and vertical retinal disparity and the depth derived from the eye position signals in combination with horizontal retinal disparity are weighted.

Probably, evidence will eventually be found that something is lacking in these models and scientists will go on improving models for stereoscopic depth perception.

1.4 Adaptation to disparity

Adaptation experiments are a good way to study stereovision, because experiments of this type teach us something about the flexibility of the visual system. Flexibility of the brain is required to adapt to the present circumstances or to new situations. Adaptation experiments show what signals can change and under what circumstances they change.

The literature reports on many experiments that were carried out to show that perceived depth in a visual stimulus could change. Perceived depth is affected not only by the binocular disparity in the stimulus itself but also by foregoing disparity stimulation. Adaptation may change the percept. Good examples of this effect are the studies by Blakemore and Julesz (1971) and Long and Over (1973). In the studies by these authors, subjects viewed random-dot stereograms in which the centre square was differentially horizontally translated in the two half-images. The subjects perceived the stereogram as a square floating in front of a background. After adaptation to this transformed stereogram, they perceived the central part of an untransformed stereogram to be behind the background. In other words, there was an aftereffect.

The studies by Köhler and Emery (1947) and Ryan and Gillam (1993) and many studies with meridional lenses (for instance Miles, 1948 and Morrison, 1972) show that constant retinal disparity is not required for adaptation.

Although, a great deal of research has been performed on adaptation to disparity, many questions remained unanswered. An important question is at what level in the brain adaptation occurs. Furthermore, the cause of adaptation to disparity has never been investigated although in the literature various causes of adaptation have been suggested (Blakemore and Julesz, 1971; Burian and Ogle, 1945). The question of whether adaptation to disparity can change perceived direction is also interesting. Ebenholtz (1970) suggested that during adaptation to disparity recalibration of the eye position signals occurs and that this changes the perceived direction.

1.5 This thesis

The research reported in this thesis was carried out in order to learn more about stereopsis. The flexibility of stereovision was studied by means of adaptation experiments. Many studies describe how flexible stereovision is (Burian and Ogle, 1945; Köhler and Emery, 1947; Miles, 1948; Blakemore and Julesz, 1971;

Morrison, 1972; Long and Over, 1973; Ryan and Gillam, 1993), but several problems remain unsolved, for instance, what changes during adaptation and why do these changes occur? This thesis deals with various aspects of adaptation to disparity.

The **second chapter** can serve as an introduction to the other chapters in this thesis, although it can also be read as a study on its own. The goal of the second chapter is to compare the strengths of depth effects induced by different types of vertical disparity fields. We determined the ratios between horizontal and vertical disparity that evoke the percept of a fronto-parallel stimulus. We found that the ratios vary according to the type of vertical disparity. These ratios were used in other chapters.

Many adaptation experiments have been mentioned above. These experiments do not tell us anything about the level at which adaptation occurs. Adaptation could occur at the level of slant perception, i.e. it could be driven by conflicts between the binocular and monocular signals related to slant perception. Adaptation could also occur within the binocular system itself. Three types of binocular signals play a role in the perception of random-dot stereograms, namely horizontal disparity, vertical disparity and eye position signals (Rogers and Bradshaw, 1995; Bradshaw, Glennerster and Rogers, 1996; Erkelens and Van Ee, 1998; Backus, *et al.*, 1999). The percept follows from these three signals. In the **third chapter**, we investigate whether adaptation can occur at the level of these signals.

In the **fourth chapter**, we study the cause of adaptation. Two causes of adaptation to disparity are mentioned in the literature. The first cause is fatigue. If neurons are stimulated for a long period, their activity may decrease (Blakemore and Julesz, 1971; Long and Over, 1973; Ryan and Gillam, 1993). The second cause is recalibration due to conflicts between different signals (Epstein and Morgan, 1970; Lee and Ciuffreda, 1983; Burian and Ogle, 1945; Miles, 1948). We tested whether the first cause is the true cause.

In the **fifth chapter**, we look at the relation between perceiving depth and perceiving direction. The same signals can be used for perceiving direction and for perceiving depth, namely retinal signals and eye position signals. Vertical disparity is used to determine eye position for depth perception. We investigate whether vertical disparity is also used for perceiving direction.

The **sixth and last chapter** goes back to the theory. It deals with the headcentric model.

Chapter 2

Strength of depth effects induced by three types of vertical disparity

The goal of the present study is to compare the strengths of depth effects induced by different types of vertical disparity. We use a nulling task, in which the depth effects induced by vertical disparity are nulled by horizontal disparity. The advantage of this method is that it prevents cue conflicts from arising between disparity and other depth cues. The ratios between horizontal and vertical disparity that evoke the percept of a fronto-parallel stimulus vary per type of vertical disparity. The ratios determined for vertical scale and vertical quadratic mix (vertical scale with a horizontal gradient) vary strongly across subjects. The ratios for vertical shear are constant, since all subjects needed the same amount of horizontal and vertical shear to perceive a fronto-parallel plane. In these experiments, one conflict cannot be avoided, namely the conflict between vertical disparity and oculomotor signals. This conflict may cause differential weighting of vertical disparity and oculomotor signals, which could explain the individual differences. The different ratios for different types of vertical disparity suggest that weighting is specific for each type of vertical disparity and the associated oculomotor signal.

2.1 Introduction

Many studies have investigated the strength of depth effects induced by different types of vertical disparity (Ogle, 1938; Ogle, 1939; Gillam, Chambers and Lawergren, 1988; Gillam and Rogers, 1991; Rogers, 1992; Howard and Kaneko, 1994; Kaneko and Howard, 1996; Rogers and Bradshaw, 1995; Adams, Frisby, Buckley, Garding, Hippisley-Cox and Porrill, 1996). In all these studies, the results differ across subjects. The investigators usually studied only one type of vertical disparity and the studies involved different subjects. Therefore, it is not known whether there is a relation between the strengths of depth effects induced by different types of vertical disparities. The goal of the present experiments is to compare the strength of the depth effects induced by three different types of vertical disparity fields. In order to achieve this goal, we used the same subjects, set-up and method for each type of vertical disparity field.

Current work has concentrated on three global vertical fields. Therefore, we investigated three different types of vertical transformations between each eye's image that induce three different types of vertical disparity, namely vertical scale, vertical shear and vertical quadratic mix (vertical scale with a horizontal gradient, see Appendix for further information).

Following Ogle (1938), Ogle (1939), Backus and Banks (1999) and Van Ee, Banks and Backus (1999), we used a nulling method to measure the strength of three types of global vertical headcentric disparity fields. In the literature, different nulling methods have been used to measure the strength of depth effects induced by vertical disparity. In one type of experiments, the depth effects induced by vertical disparity were nulled by all other depth cues (including horizontal disparity; Ogle, 1938; Ogle, 1939; Amigo, 1972). In other experiments, the depth effects induced by vertical disparity were nulled by horizontal disparity (Stenton, Frisby and Mayhew, 1984; Rogers and Bradshaw, 1995; Adams, *et al.*, 1996; Backus, *et al.*, 1999). We used the second method, in which the strength of depth effects evoked by vertical disparity was indicated by the amount of horizontal disparity needed to null the depth effects. The advantage of nulling by horizontal disparity is that the method prevents cue conflicts from arising between disparity and other depth cues. The rationale is as follows. In the experiments, we used stereograms projected on a fronto-parallel screen. When not transformed, the stereogram is perceived as being flat, fronto-parallel plane. The stereogram is also perceived as flat and in the fronto-parallel plane when the horizontal disparity nulls the depth effect elicited by vertical disparity. Other depth cues like perspective, illuminance, blur and accommodation also indicate that the stimulus is flat and fronto-parallel. Therefore, cue conflicts between disparity and these other depth cues are absent when the depth effects induced by vertical and horizontal disparity cancel each other out.

The main difference between our experiments and the above-mentioned nulling experiments is that we investigated three different types of vertical disparity, whereas only one type of vertical disparity was investigated in the other experiments. Another important difference is that we used a forced-choice task and we determined psychometric curves. This enabled us to determine the strength of the depth effects induced by the different types of vertical disparity fields as well as the sensitivity of the subject to vertical disparity.

2.2 Methods

Subjects

Four subjects (aged 18 to 47 years) participated in the experiments. All had normal or corrected-to-normal visual acuity and normal stereoscopic vision. Two of them had experience in psychophysical experiments involving stereoscopic vision (CE, HW) and two subjects were naive (LW, PE).

Apparatus

An anaglyph set-up was used to generate the stereograms (see also Van Ee and Erkelens, 1996). The stimuli were produced by an HP750 graphics computer (frequency = 70 Hz) and back-projected on a fronto-parallel translucent screen by a projection TV (Barco Data 800). The subject was seated 1.50 m from the screen. The left-eye image was projected in red light and the right-eye image was projected in green light. The subject wore glasses consisting of a red filter in front of the left eye and a green filter in front of the right eye. The transmission spectra of the filters (Schott Tiel, The Netherlands) were chosen to correspond as closely as possible to the emission spectra of the projection TV. The measurements were performed in a completely dark room. A random dot pattern of 2500 dots was generated in an array of 900 x 900 pixels. The resolution (the smallest change in disparity possible) was 3.8 minutes of arc. The dots were always circular so that the subject would not use perspective information. We changed their positions without changing their shapes. A small dot size (diameter of 15.3 minutes of arc) was chosen to prevent the shape of the dots from influencing the percept as much as possible. The dots were not anti-aliased. The visual angle of the pattern was 53º x 53º. The sparse random dot pattern was shaped as a jittered square.

During all experiments, the head of the subject was fixated by a chin-rest. No fixation point was provided, so subjects made eye movements as they performed the task.

Procedure for experiment SCALE

Two half-images, which are oppositely scaled in vertical directions, are perceived as slanted about the vertical axis. Half-images which are horizontally scaled relative to each other also induce slant about the vertical axis. In experiment SCALE, we presented different horizontal scales in combination with a specific vertical scale. In a forced-choice task, we determined the horizontal scale required to null the depth induced by the vertical scale. We repeated the experiment for five magnitudes of vertical scale (two in each direction and zero): -0.06, -0.03, 0, 0.03, and 0.06. We used factors to express the magnitudes of all transformations. For vertical scale these factors are equivalent to percentages of magnification of: -6%, -3%, 0%, 3% and 6%. If a subject was unable to fuse vertical scaled stereograms with one of these magnitudes, we used smaller vertical scale factors. In two cases (for subjects CE and PE), the vertical scale factors were reduced to: -0.04, -0.02, 0, 0.02, and 0.04.

Scale, shear and quadratic mix are expressed in dimensionless quantities instead of percentages or degrees (see Appendix). The use of these quantities allows us to draw comparisons between types of vertical disparity.

In order to determine the magnitude of horizontal scale needed to null the slant induced by vertical scale, we used the method of constant stimuli in a forced-choice task. The forced-choice question put to the subject was: "Which is nearer to you - the left side or the right side of the surface?" In pilot experiments, we explored for each magnitude of the vertical scale the range of horizontal scales in which the subject gave inconsistent answers (less than 100% left or right). The relevant range was divided into seven equidistant magnitudes of horizontal scale. Combinations of horizontal and vertical scale were presented in random order distributed over four sessions. Each combination was measured eight times. Psychometric curves (cumulative normal) were fitted to the data. We obtained two fit parameters: the subjective equality, μ and the discrimination threshold, σ. The subjective equality μ is the amount of horizontal scale needed to null the effect of the vertical scale. The discrimination threshold σ is the slope parameter. It indicates how well a subject can distinguish between surfaces slanted to the left and surfaces slanted to the right. We estimated the errors in μ and σ by performing Monte-Carlo simulations on the data sets.

Each stimulus, a specific combination of horizontal and vertical scale, was presented for 30 s whereupon a response-screen appeared. The subjects made their judgements by clicking with the computer mouse the word "left" or "right".

Procedure for experiment SHEAR

In experiment SHEAR, we measured the magnitude of the horizontal shear needed to null the slant evoked by a certain vertical shear. Horizontal shear is used to measure the strength of the depth effect induced by vertical shear, because horizontal and vertical shear evoke the same type of depth effect, namely a slant about the horizontal axis. The procedure for experiment SHEAR is the same as the procedure for experiment SCALE. Five magnitudes of vertical shear were measured: -0.04, -0.02, 0, 0.02, and 0.04. The forced-choice question put to the subject was: "Which is nearer to you - the upper part or the lower part of the surface?"

Procedure for experiment MIX

A vertical quadratic mix transformation and a horizontal quadratic scale transformation (Appendix) are both perceived as a vertical cylinder. In experiment MIX different amounts of horizontal quadratic scale were added to a specific vertical quadratic mix. We determined the strength of the horizontal quadratic scale transformation required to null the depth induced by a vertical quadratic mix transformation. Five magnitudes of vertical quadratic mix were measured: -0.16, -0.08, 0, 0.08, and 0.16. The forced-choice question put to the subject was: 'Is the surface convex or concave?' The rest of the procedure is the same as described in the procedure for experiment SCALE.

Procedure for experiment TIME

Experiment TIME was conducted to investigate whether the results of the experiments MIX, SCALE and SHEAR depended on the presentation time. Van Ee and Erkelens (1996) showed that slant induced by horizontal scale or shear develops to a stable level in about 10 s. Allison, Howard, Rogers and Bridge (1998) found that both horizontal and vertical scale and shear build up with the same speed during 30 s. To examine the time characteristics of depth induced by vertical and horizontal disparity, experiment MIX was repeated with only one vertical quadratic mix factor (0.08) and different presentation times (5 s, 10 s, 15 s, 20 s, 30 s, 40 s). Stimuli with different presentation times were presented in random order and distributed over three sessions.

2.3 Results

Experiment SCALE

The results of experiment SCALE are depicted Figure 2.1. The amount of horizontal scale needed to null the slant induced by the applied vertical scale (the μ value) is plotted against the vertical scale for each subject. The magnitudes of the estimated errors in μ are generally small relative to μ, which means that the psychometric curves fitted well to the data. A linear relation (least squares) was fitted to the μ values for each subject (Table 2.1). The slopes fit very well (R^2 = 0.93). The fitted slopes differ strongly between the four subjects. The slopes are 0.5, 0.6, 0.9 and 1.2, respectively (see Table 2.1). The offsets do not differ significantly from zero ($p > 0.05$). Thus, for each subject there is a specific ratio between horizontal and vertical scale which is perceived as fronto-parallel.

The σ values indicate the sensitivity of the subjects to slant judgements. They are a measure of the differences in scales for which subjects can distinguish between slants to the left or the right. Figure 2.4 shows the σ value of each subject averaged over the σ's measured at the five vertical scales. The σ's are scattered widely, especially for subject PE. There is a high correlation between the magnitude of σ and the nulling ratios (R^2 = 0.86).

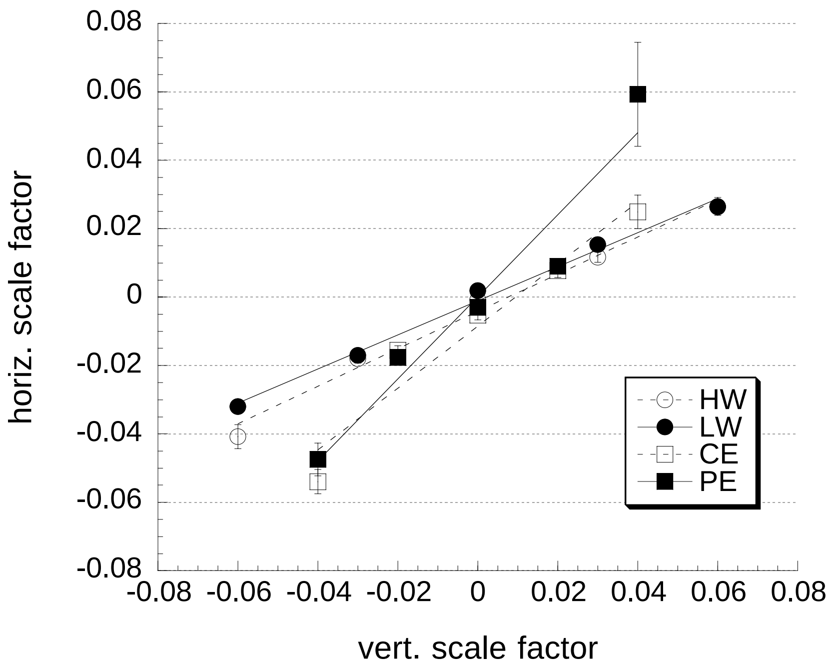

Figure 2.1 - The results of experiment SCALE. The μ values are plotted against the applied vertical scale. The μ values are the amounts of horizontal scale needed to null the effect of the vertical scale used. Different symbols represent different subjects. The errors (± 1 SD) are estimated by a Monte Carlo simulation. Sometimes the error bars are too small to be visible. The lines represent the least square fits for the different subjects. Note that the slopes differ strongly between subjects.

Experiment SHEAR

Figure 2.2 shows the amount of horizontal shear needed to null the slant induced by a specific vertical shear (the μ value) for each subject and different vertical shears. The amount of shear is expressed in shear factor, which is equal to the tangent of the shear angle. The estimated errors in μ are small relative to μ. We carried out a linear regression (least squares) on the μ values for each subject. The slopes fit very well ($R^2 \geq 0.99$) and they are all about -1 (see Table 2.1). Only one slope (PE) differs significantly from -1 ($p < 0.05$). The offsets do not differ significantly from zero ($p > 0.05$).

The σ values indicate the differences in shears for which subjects can distinguish between upward- and downward-slanted surfaces. Figure 2.4 shows a positive correlation between average σ's in experiment SCALE and average σ's in experiment SHEAR. In experiment SHEAR, there is no correlation between the nulling ratios and magnitude of the average σ's, because the ratios are all about -1.

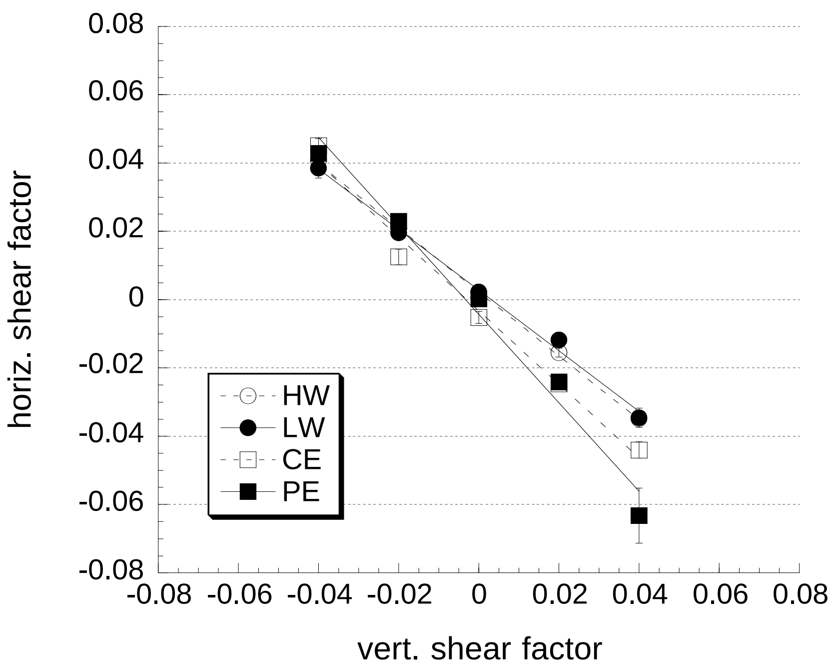

Figure 2.2 - Same as Figure 2.1, but for experiment SHEAR. Note that the slopes are very similar for all subjects.

Experiment MIX

Figure 2.3 shows the results of experiment MIX. The magnitude of μ, which is the amount of horizontal quadratic scale that nulls the effects of a particular vertical quadratic mix, is plotted against the vertical quadratic scale for each subject. The magnitudes of the estimated errors in μ are mostly small relative to μ. In a few cases (CE vertical quadratic mix factor, vqm = 0.08, LW vqm = 0.16, PE vqm = 0.16) the psychometric curves did not fit well (estimated errors in μ and σ > 0.02).

We fitted a linear relation (least squares) to the μ values for each subject (Table 2.1). The slopes fit very well ($R^2 > 0.93$). The slopes differ strongly between subjects, namely between 0.31 and 1.15. The offset is significantly different from zero ($p < 0.05$) for only one subject (LW). Apparently, for this subject perceived flatness is not the same as real flatness.

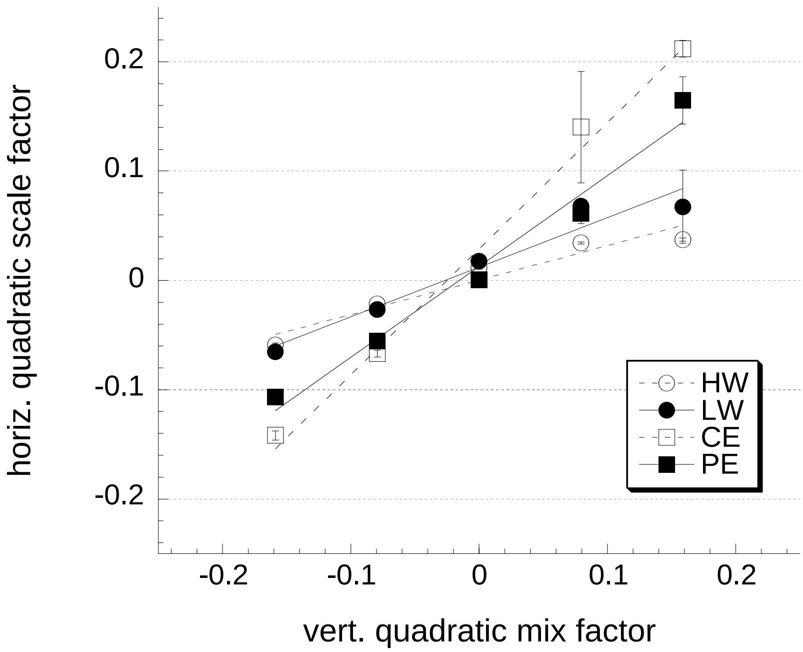

Figure 2.3 - Same as Figure 2.1, but for experiment MIX. Note that the slopes differ strongly between subjects.

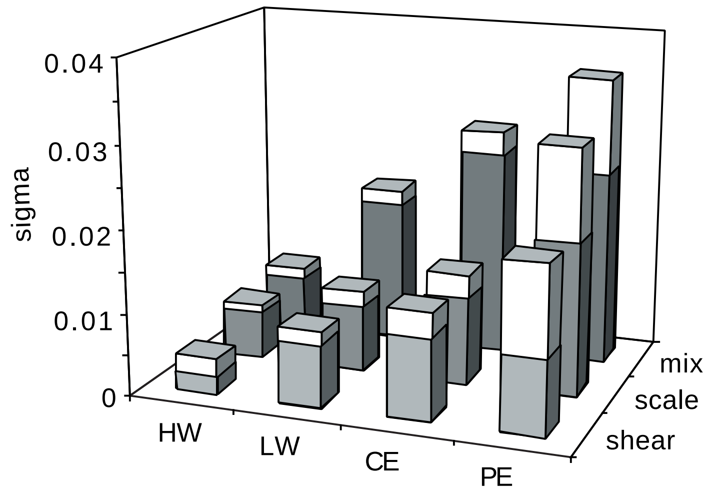

Figure 2.4 - The average of σ for each type of vertical disparity and each subject. The grey bars represent the averages over five σ values, namely the σ values of the five different amounts of a specific type of vertical disparity for one subject. The white bars on top of the grey bars represent the standard errors of the averages.

The σ values indicate how well subjects can distinguish between convex and concave surfaces. Figure 2.4 shows that subjects, who are better at distinguishing between directions of slants, are also better at distinguishing between convex and concave surfaces. Thus, some subjects are more sensitive than others to changes in disparity. The correlation between the nulling ratios and the σ's is not significant ($p > 0.05$) in experiment MIX.

The quadratic mix transformation was not always perceived as a vertical cylinder. Subjects whose results revealed a low ratio for quadratic mix (HW and LW) reported that they saw a sort of convex or concave mountain instead of a vertical cylinder. This mountain seemed to be more curved in the horizontal direction than in the vertical direction.

Experiment Time

In this experiment, the vertical quadratic mix factor was -0.08. The amount of horizontal quadratic scale necessary to null the effects of the vertical quadratic mix (μ) was determined for six different presentation times. We fitted a linear relation (least squares) to the μ values. The slopes did not differ significantly from zero ($p \gg 0.05$). Thus, time did not have a significant effect.

		HW	LW	CE	PE
Expt SCALE	slope	0.55*	0.50*	0.91*	1.20*
	offset	-0.004	-0.001	-0.008	0.000
	R^2	0.99	0.99	0.93	0.93
Expt SHEAR	slope	-0.94	-0.89	-1.08	-1.12*
	offset	0.001	0.001	-0.002	0.001
	R^2	0.999	0.995	0.99	0.998
Expt MIX	slope	0.31*	0.45*	1.15	0.83
	offset	0.001	0.029*	-0.006	0.013
	R^2	0.93	0.95	0.98	0.98

Table 2.1 - The linear fit parameters for experiment SCALE, SHEAR and MIX. The offset marked with an asterisk differs significantly from zero ($p < 0.05$). The slopes marked with an asterisk differ significantly from the slope expected from the headcentric model ($p < 0.05$).

2.4 Discussion

We quantified the depth induced by three types of vertical disparity. We compared the strength of these depth effects by measuring the amount of horizontal disparity needed to null the effects of the vertical disparity fields. Nulling ratios were determined for each subject and each type of vertical disparity field (Table 2.1). The nulling ratio is defined as the ratio between horizontal and vertical disparity, for which the stimulus is perceived as flat and fronto-parallel. The ratios varied slightly for the shear transformations. Only one shear ratio differed significantly from -1 ($p > 0.05$). By contrast, the ratios differed strongly between subjects for scale and quadratic mix transformations (a factor 2.4 for scale and 3.7 for quadratic mix). The main conclusion to be drawn from our study is that the ratios differed per type of vertical disparity and across subjects.

The sensitivity of the subject to vertical disparity is shown in Figure 2.4. It seems that some subjects are more sensitive to vertical disparity than others. This effect is almost significant (two-factor ANOVA with replication, $p = 0.052$).

Past and present results

The shear ratios were about -1 in all four subjects (Table 2.1). A ratio of -1 implies that subjects judged pure rotations of the half-images (also called curl transformations) as a fronto-parallel plane. This agrees with the findings of Howard and Kaneko (1994) and it partly agrees with the findings of Van Ee and Erkelens (1996). Four of their subjects also perceived a rotation as a fronto-parallel plane, whereas two other subjects perceived a rotation as a slanted surface. Gillam and Rogers (1991), on the other hand, found different results. They found that curl evoked a somewhat smaller slant than that induced by horizontal shear alone, which implies a ratio that is closer to zero than to one. The differences between Gillam and Rogers's results on the one hand and Howard and Kaneko's and our results on the other hand may be explained by the fact that Gillam and Rogers used a small screen (visual angle 10º), which was probably too small to measure a global vertical field. Furthermore, a reference was visible. Van Ee and Erkelens (1995) showed that in the presence of a visual reference, slant perception is based solely on horizontal shear and horizontal scale transformations.

We found that the scale ratios varied from 0.5 to 1.2 (Table 2.1) and those magnitudes are consistent with previous observations in the literature. Stenton, *et al.* (1984) and Kaneko and Howard (1996) found average ratios that were a little smaller than one and Backus, *et al.* (1999) reported ratios of 0.64 to 0.89.

Rogers and Bradshaw (1995) studied the depth induced by the vertical quadratic mix field. They presented combinations of vertical quadratic mix and horizontal quadratic scale on the screen. The subject had to alter the amount of horizontal quadratic scale until the stimulus looked flat. We converted their results into nulling ratios. The ratios determined from Rogers and Bradshaw's experiments are 0.59, 0.62 and 0.68 for the different subjects (screen distance 57 cm, viewing angle 70º). These ratios are within the range we determined (between 0.31 and 1.15, Table 2.1). Adams, *et al.* (1996) also studied the depth effects induced by the vertical quadratic mix field. The depth effects they found were comparable in size to those found by Rogers and Bradshaw (1995) in their experiments.

In conclusion, our results agree with the results reported by various authors.

Weighting of vertical disparity and oculomotor signals in depth estimation

Underestimation or overestimation of depth has been attributed to conflicts between disparity and other depth cues (Johnston, *et al.*, 1991; Johnston, 1993). Generally, subjects estimate depth induced by disparity alone non-veridically, because different cues signal different depths. Individual differences are explained by assuming that different subjects attach different levels of reliability to different cues.

Our experimental method prevented conflicts from arising between disparity and other depth cues, like perspective, illuminance, blur or accommodation. Still, there were two disparity-based depth estimates that were not in agreement with each other in our experiments, namely depth derived from horizontal disparity scaled by vertical disparity and depth from horizontal disparity scaled by eye position. We suggest that both vertical disparity and eye position signals are used differently by the subjects causing the observed individual differences for each type of vertical disparity field. This idea of weighting agrees with the findings of Gillam, *et al.* (1988), Backus and Banks (1999) and Backus, *et al.* (1999) for scale and the findings of Rogers and Bradshaw (1995) for the mixed transformation. However, Gillam et al. did not carry out a nulling experiment.

The fact that we found hardly any individual differences in experiment SHEAR suggests that for this vertical disparity field weighting of the depth estimates based on vertical disparity and oculomotor signals is identical for all subjects. The fact that the ratio is equal to -1 indicates that only vertical disparity is used. Cyclovergence signals are the type of oculomotor signals that are related to vertical shear. Thus, the visual system may consider cyclovergence signals to be very unreliable, whereas it considers vertical disparity to be very reliable. It is possible that cyclovergence signals are not used in depth perception at all.

In conclusion, we suggest that the present results are due to weighting of vertical disparity and eye position signals. The fact that the ratios depend on the type of vertical disparity indicates that the visual system weights these signals differently for each type of vertical disparity.

Weighting in different models

Weighting of different depth cues is described by the weak fusion model (Landy, *et al.*, 1995) and more specifically by the estimator reliability model (Backus and Banks, 1999; Backus, *et al.*, 1999). In the estimator reliability model, the depth derived from horizontal and vertical retinal disparity and the depth derived from the eye position signals in combination with horizontal retinal disparity are weighted. So far the estimator reliability model has been applied to stereoscopic slant about the vertical axis. It predicts the results of experiment SCALE well. If this model is applied to slants about the horizontal axis and curvature, it should predict the results of experiment SHEAR and experiment MIX too. The weak fusion model does not demonstrate clearly how depth is derived from stereo, but it can explain all of our results.

According to the weak fusion model and the estimator reliability model, weighting occurs at the level of depth maps. However, a model in which weighting occurs at the level of disparity and oculomotor signals may also predict the present results. Weighting at an earlier stage than weighting of depth maps is often called interaction between depth cues. This type of weighting is described by the strong fusion model (Landy, *et al.*, 1995) and also by the regional disparity correction model (RDC) (Gårding, *et al.*, 1995). The RDC model combines pictorial cues, oculomotor cues and vertical disparity in both stages of the model, namely disparity correction and disparity normalisation.

The estimator reliability model is based on oculocentric co-ordinates and thus on retinal disparities, but a model based on headcentric co-ordinates may also use weighting of disparity and oculomotor signals. We propose a modification of the headcentric model (Erkelens and Van Ee, 1998). In the original headcentric model, it is assumed that retinal signals are more accurate than oculomotor signals. The model uses vertical disparity as an error signal. If an error in the oculomotor signals occurs, then the vertical headcentric disparity is non-zero. A corrective term, which is related to vertical disparity and depends on the type of error, is added to the horizontal headcentric disparity in order to correct for the oculomotor error. Thus, the original headcentric model relies entirely on the retinal signals. However, a non-zero vertical headcentric disparity field may also be caused by a retinal error. Thus, the visual system may not rely entirely on the retinal signals. It is feasible that the visual system weights the oculomotor signals and the retinal signals according to their reliability. This weighting can be realised by multiplying the different correction terms by weighting factors given by the ratios that we measured. Each type of vertical disparity field has its own correction term and its own weighting factor. The fact that the three weighting factors differ from each other within individual subjects suggests that the three vertical disparity fields are processed separately. Each vertical disparity field, signalling a certain type of error in the oculomotor signal, has its own weighting factor; this indicates that the visual system assigns different levels of reliability to different oculomotor signals.

Summarising, we suggest that weighting of disparity and eye position signals occurs. Weighting depends on the type of vertical disparity. The present results do not tell us whether disparity is of retinal or headcentric nature. Furthermore, these results do not tell us whether weighting occurs at the level of depth maps or at the level of disparity and oculomotor signals.

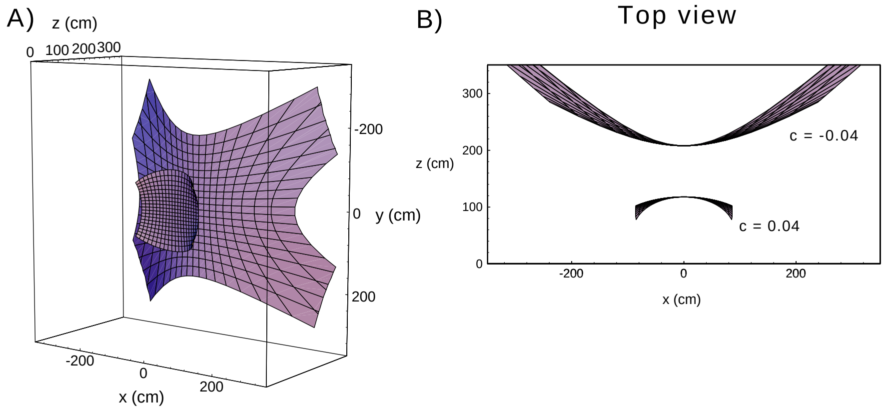

Figure 2.5 - A) The percept, according to the model of Erkelens and Van Ee (1998), when a vertical quadratic mix transformation (factor 0.04 or -0.04) is presented to a subject who has a weighting factor of 0.3. The model assumes that depth estimation by horizontal disparity is veridical. The subject is positioned with his cyclopean eye at the origin and watches a fronto-parallel screen at a distance of 150 cm. B) Top view of Figure 2.5 A.

Deviation from the cylinder percept

We found that two subjects did not perceive the quadratic mix transformation as a vertical cylinder, but they perceived it as a sort of hill or valley. The hill or valley was perceived as more curved in the horizontal direction than in the vertical direction. Adams, *et al.* (1996) mentioned the same effect. They did not offer an explanation. We will show here that the effect is explained by the modification of the headcentric model suggested in the previous section. The subjects in our study, who reported the effect (HW and LW), had low ratios in experiment MIX (Table 2.1). An interpretation in terms of the modified headcentric model is that the vertical disparity is given a low weighting relative to the oculomotor signals. To show the validity of this interpretation we performed the following simulation with the help of the headcentric model.

Percepts, as predicted by the model of Erkelens and Van Ee (1998), were computed for two vertical quadratic mix transformations (factor 0.04 and -0.04). The correction term based on vertical disparity indicates how large the correction for oculomotor errors should be. The subject would perceive a fronto-parallel plane if the visual system used this correction in a proper way. By multiplying the correction term by a small weighting factor (0.3 in this simulation) the vertical disparity becomes underweighted. Figure 2.5 shows the reconstructed surfaces. The surfaces are curved in two directions. They are more curved in the horizontal direction than in the vertical direction, just as the subjects reported. The curvature of the surfaces in the horizontal direction is less in the middle of the surface than at the upper and the lower part of the surface.

2.5 Appendix

Expression of vertical quadratic mix transformation

We used a vertical transformation of the left and right eye's image on a screen, which induces an elevational headcentric disparity field identical to the field evoked by a horizontal vergence signal error. We will refer to this transformation as quadratic mix. Rogers and Bradshaw (1995) and Adams, *et al.* (1996) also used this transformation. They designed a transformation, which scales the vertical retinal disparity. Such stimulus depends on the fixation point. Only when the fixation point is straight ahead, the scaling of vertical retinal disparity agrees with the vertical quadratic mix transformation on the screen. To avoid confusion we refer to our transformation as quadratic mix.

In order to obtain the expression for quadratic mix, we considered a vertical scale with a magnification of b first (Figure 2.6):

$$\begin{cases} y_L = y + \tfrac{1}{2} \cdot b \cdot y \\ y_R = y - \tfrac{1}{2} \cdot b \cdot y \end{cases} \qquad (2.1)$$

If the co-ordinate systems are chosen as described by Erkelens and Van Ee (1998), this transformation results in a vertical disparity field identical to the field evoked by a horizontal version signal error (with a gradient in the vertical direction).

Secondly, a vertical shear over an angle β (tan(β) = c) was considered (Figure 2.6):

$$\begin{cases} y_L = y + \tfrac{1}{2} \cdot c \cdot x \\ y_R = y - \tfrac{1}{2} \cdot c \cdot x \end{cases} \qquad (2.2)$$

This transformation on the screen induces a vertical disparity field identical to the field evoked by a cyclovergence signal error (with a gradient in the horizontal direction).

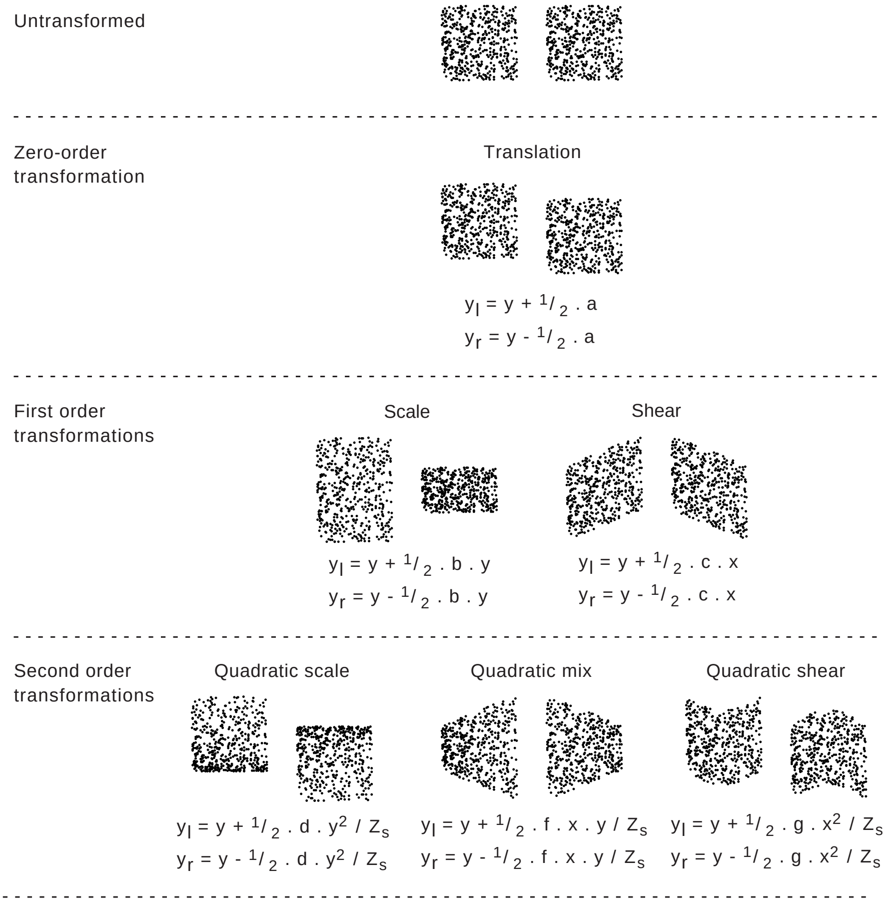

Figure 2.6 - Different types of vertical transformations of stereograms on a fronto-parallel screen. The transformations can also be performed in the horizontal direction or in both the horizontal and the vertical direction. Zero and first-order transformations of the two half-images are commonly used in studies of stereoscopic depth perception. The second and higher order transformations are rarely used. a, b, c, d, f and g are constants. x and y are the points in the untransformed stereogram. $x_l = x_r = x$ *in all vertical transformations.*

The expression found for the vertical quadratic mix transformation is straightforward. This transformation can be considered as a vertical scale (a transformation depending on the y-co-ordinate) which depends on the horizontal (x) co-ordinate. Thus, the expression is obtained by multiplying x by y:

$$\begin{cases} y_L = y + \tfrac{1}{2} \cdot f \cdot x \cdot y / z_s \\ y_R = y - \tfrac{1}{2} \cdot f \cdot x \cdot y / z_s \end{cases} \qquad (2.3)$$

Dividing f·x·y by the screen distance (z_s) renders the constant f dimensionless.

This transformation is a second-order transformation. There are three second-order transformations possible (Figure 2.6). Firstly, a quadratic scale transformation is a non-linear scale, which depends on the vertical distance (y). Secondly, a quadratic shear transformation is a non-linear shear, which depends on the horizontal distance (x). Thirdly, quadratic mix is a transformation that lies in between quadratic scale and quadratic shear.

Expression of a quadratic horizontal scale

The expression for horizontal quadratic scale is analogous to the expression for vertical quadratic scale in which y is replaced by x:

$$\begin{cases} x_L = x + \tfrac{1}{2} \cdot h \cdot x^2 / z_s \\ x_R = x - \tfrac{1}{2} \cdot h \cdot x^2 / z_s \end{cases} \qquad (2.4)$$

A horizontal quadratic scale induces an ellipse or a hyperbola, depending on the sign of the quadratic scale factor, h.

Chapter 3

Adaptation to disparity but not to perceived depth

The purpose of the present study was to investigate whether adaptation can occur to disparity per se. The adapting stimuli were large random-dot patterns of which the two half-images were transformed such that the depth effects induced by the vertical transformations were nulled by horizontal transformations. Thus, the adapting stimuli were perceptually the same, whereas the disparity fields differed from each other. The adapting stimuli were presented for five minutes. During that period, the percept of a fronto-parallel surface did not change. After the adapting period, subjects perceived a thin untransformed strip as either slanted or curved depending on the adapting transformation. The thin strips provided negligible information about the vertical disparity field. In a forced-choice task we measured the amount of horizontal transformation that was required to null the acquired adaptation. We found that the amounts of horizontal transformation required to perceive the test strip fronto-parallel were significantly different from zero. We conclude that the visual system can adapt to disparity signals in the absence of a perceptual drive.

3.1 Introduction

Binocular disparity between the two images on the retinas is an important source of information for the recovery of the three-dimensional layout of the visual environment. Random-dot stereograms have been used to study stereopsis since they were introduced by Julesz (1960). Perceived orientations of planar surfaces are related to linear transformations between the half-images of stereograms. Both horizontal and vertical scale induce a surface slant about the vertical axis. Both horizontal and vertical shear induce a surface slant about the horizontal axis. Perception of non-planar surfaces depends on higher-order transformations between the half-images of stereograms. For example, both a horizontal transformation consisting of a second-order gradient in the horizontal direction and a vertical transformation consisting of a gradient in both the horizontal and the vertical direction induce curvature about a vertical axis.

Perceived depth in a visual stimulus is affected by not only the binocular disparity in the stimulus itself but also by foregoing disparity stimulation. Adaptation may change the percept. For example, it has been shown that subjects perceived a non-transformed stereogram as not being fronto-parallel, if they first viewed a stereogram of which one half-image is horizontally transformed relative to the other for a prolonged period of time (Köhler and Emery, 1947; Blakemore and Julesz, 1971; Long and Over, 1973; Mitchell and Baker, 1973; Ryan and Gillam, 1993). In other experiments, meridional lenses have been used to show adaptation to horizontal scale (Burian, 1943; Miles, 1948; Epstein and Morgan, 1970; Epstein, 1971; Epstein, 1972a; Epstein and Morgan-Paap, 1974). Adaptation to vertical scale has also been shown by using meridional lenses. Miles (1948) and Morrison (1972) investigated adaptation that lasted for several days. Subjects perceived distortion of space when they started to wear the lens. The distortion, in this case slant about the vertical axis, decreased during the experiment, but never disappeared, not even after 28 days. Lee and Ciuffreda (1983) found adaptation that lasted one to four hours. They showed that the decrease of slant started within half an hour. In a pilot experiment, we too studied adaptation to a vertically transformed half-images. Subjects looked at vertically scaled random-dot stereogram for long periods ranging from 5 to 30 minutes. They reported that after a few minutes the slant started to decrease and that after about ten minutes the surface looked fronto-parallel.

The above mentioned adaptations do not tell us anything about the level at which adaptation occurs. Adaptation could occur at the level of slant perception, i.e. it could be driven by conflicts between the binocular and monocular signals related to slant perception. Adaptation could also occur within the binocular system itself. Three types of binocular signals play a role in the perception of random-dot stereograms, namely horizontal disparity, vertical disparity and eye position signals (Rogers and Bradshaw, 1995; Bradshaw, *et al.*, 1996; Erkelens and Van Ee, 1998; Backus, *et al.*, 1999). The percept follows from these three signals. The goal of this study was to find out whether adaptation could occur at the level of any one or a combination of these signals.

To reach our goal we pursued the following approach. We carried out experiments in which we presented three types of vertical disparity fields. Horizontal disparities were added such that all stimuli were perceived as a fronto-parallel plane. These three types of stimuli were perceived the same. We investigated whether adaptation was specific to the type of disparity field. If this were the case, adaptation would be related to specific combinations of disparity signals and not to perceived depth.

Adaptation can cause different types of perceptual phenomena. Firstly, the strength of the percept can decrease during prolonged presentation of the stimulus. Secondly, adaptation can induce after-effects after removal of the adapting stimulus. We explored both phenomena.

3.2 Methods

In the present experiments, subjects adapted to a specific combination of horizontal and vertical transformation of one half-image of a stereogram relative to the other. The combination of horizontal and vertical transformation was chosen such that each subject perceived the adapting stimulus as a fronto-parallel surface. In a stereogram, many depth cues, like perspective, illuminance, blur and accommodation indicate that the surface is projected on a fronto-parallel screen, whereas disparity may indicate different orientations. In our experiments, the adapting stimulus was a vertically transformed stereogram. A horizontal transformation was added to the vertical transformation, so that subjects perceived the adapting stimulus as a fronto-parallel surface. Thus horizontal disparity nulled the depth effects induced by the vertical transformations. Therefore, disparity by itself also indicated that the surface was fronto-parallel. Thus, disparity was not in conflict with most of the other depth cues (see also Backus and Banks, 1999; Backus, *et al.*, 1999; Berends and Erkelens, 2001b).

Current work has concentrated on three types of global vertical disparity fields. The following vertical transformations induce the three types of vertical disparity fields (see also Berends and Erkelens (2001b). Firstly, vertical scale induces a vertical disparity field with a gradient in the vertical direction. Horizontal scale can null the slant about a vertical axis evoked by vertical scale (Ogle, 1938, Ogle, 1939; Amigo, 1972; Stenton, *et al.*, 1984; Backus, *et al.*, 1999; Backus and Banks, 1999). Secondly, vertical shear elicits a vertical disparity field with a gradient in the horizontal direction. Vertical shear evokes slant about a horizontal axis, which can be nulled by horizontal shear (Ogle and Ellerbrock, 1946). Thirdly, a vertical transformation called vertical quadratic mix induces a vertical disparity field with a gradient in both the horizontal and vertical direction. The curvature evoked by vertical quadratic mix can be nulled by horizontal quadratic scale (Rogers and Bradshaw, 1995; Adams, *et al.*, 1996).

We investigated whether the strength of the percept changes during prolonged presentation of the stimulus and whether an after-effect occurs after removal of the adapting stimulus.

In a pilot experiment we asked subjects how they perceived the adapting stimulus during prolonged presentation. They answered that the surface remained fronto-parallel, even after they had viewed it for 15 minutes. We checked the validity of their opinion in a forced-choice experiment (experiment. FLAT). After adaptation, we measured again how much horizontal transformation had to be added to the vertical transformation in the adapting stimulus to perceive the stimulus as a fronto-parallel surface. That amount of horizontal transformation was compared with the amount that was needed before adaptation.

The after-effect was measured by means of thin strips. Subjects judged the directions of slant or curvature (convex or concave) of these strips (experiment SCALE, SHEAR and MIX).

Subjects

Four subjects (aged 20 to 48 years) participated in the experiments. All had normal or corrected-to-normal visual acuity and normal stereoscopic vision. One of them knew about the purpose of the experiment (CE) and three subjects were naive (LW, PD and ME).

Apparatus

Red-green anaglyphic stereograms were generated at a frequency of 70 Hz and back-projected onto a fronto-parallel translucent screen by a CTR projector (Barco Data 800). The resolution (the smallest change in disparity possible) was 3.8 minutes of arc. The subject was seated 1.50 m from the screen. The measurements were performed in a completely dark room. The head of the subject was fixed by a chin rest. There were no instructions given where to fixate; subjects were free and even encouraged to look around.

Stimuli

In all experiments, two types of stimuli were presented in succession, i.e. an adapting stimulus and a test stimulus. The adapting stimulus was always large (53º x 53º). It was a random dot pattern of 2500 dots. In the FLAT experiment, the test stimulus had the same size as the adapting stimulus, whereas the test stimuli were thin strips (0.64º x 45º) in the after-effect experiments (SCALE, SHEAR and MIX). The test strips were random dot patterns containing 150 dots. The strips had to be thin so that they would not to provide information about the vertical disparity field. The thin test strip was oriented horizontally or vertically depending on the type of disparity field that was being tested. In two experiments, the test strip was oriented horizontally. Then, the strip was less than 1º high, so vertical disparities were difficult or perhaps impossible to measure reliably. In one experiment, the test strip was oriented vertically. Then the narrow strip was presented in the head's median plane. Therefore, again vertical disparities should have been unreliable. Thus, the strips contained horizontal disparity but very little vertical disparity. We found that subjects perceived the test strip after prolonged viewing of the full-field vertical and horizontal transformations differently from before prolonged viewing.

The shape of the dots themselves were not transformed, but the dots were small (0.25º diameter) so their perceived shape have little effect on the percept. The dots were not anti-aliased.

Procedure for experiment FLAT

In experiment FLAT we investigated how the adapting stimuli were perceived after a presentation period of five minutes.

The adapting stimulus was transformed horizontally and vertically in such a way that the subject perceived it as a fronto-parallel surface before adaptation. In previous experiments (Berends and Erkelens, 2001b), we determined which combinations of horizontal and vertical transformation subjects perceived as fronto-parallel surfaces. We found a specific ratio of horizontal to vertical transformation for each type of vertical transformation. The ratios determined for vertical scale and vertical quadratic mix varied strongly across subjects. The ratios for vertical shear were constant, namely -1 for all subjects, This agrees with the findings of Howard and Kaneko (1994). They showed that rotation does not induce slant. Therefore, the ratio of horizontal to vertical shear in the adapting stimulus was set to -1. The other two ratios were measured. Therefore, the previous experiments (Berends and Erkelens, 2001b) were carried out for the new subjects. The experiments were shortened by using a shorter presentation time (10 seconds) and by measuring four instead of five magnitudes of vertical scale or vertical quadratic mix.

Experiment FLAT was subdivided into three sessions. In each session, we measured adaptation to one type of vertical transformation. One magnitude of each type of vertical transformation was measured, namely 0.03 (3%) for scale, 0.03 (1.7º) for shear and 0.08 for quadratic mix. At the beginning of each session the large adapting stimulus was presented for 5 minutes, whereupon the large test stimulus was presented for 10 seconds. The amount of vertical transformation in the test stimulus was the same as in the adaptation stimulus. After the presentation of the test stimulus, the screen became black and subjects judged the direction of slant or curvature by clicking on the left or right button of the computer mouse (a forced-choice task). After the first judgement of the measurement session, each following trial consisted of twenty seconds presentation of the adapting stimulus, 10 seconds testing and a judgement. The change in percept of the adapting stimulus after a presentation period of five minutes was measured from slant or curvature judgements of the test stimulus.

The amount of horizontal transformation in the test stimulus was varied during a session, whereas the amount of vertical transformation was fixed. The amount of horizontal transformation needed to perceive the test stimulus as fronto-parallel was determined by an adaptive method. We wanted to estimate both the shift and the slope of the psychometric curve, because the slope indicates whether the adaptation effect is significant or not. We used the MUEST method (Snoeren and Puts, 1997), which estimates multiple parameters (shift α and slope β). This method is an extension of the QUEST method of Watson and Pelli (1983), which estimates only one parameter (shift α). The psychometric function was assumed to be a logistic function, which is a good approximation of a cumulative Gauss (Treutwein, 1995). A fixed number of trials, namely 50, were used as stop criterion.

Procedure for experiment SCALE

In experiment SCALE we investigated adaptation to a combination of horizontal and vertical scale. The adapting stimulus was scaled horizontally and vertically in such a way that the subject concerned perceived it as a fronto-parallel surface.

Experiment SCALE was subdivided into five sessions. In each session, we measured adaptation to one magnitude of vertical scale. Five magnitudes of vertical scale were measured: -0.06, -0.03, 0, 0.03 and 0.06 (equivalent percentages of magnification: -6%, -3%, 0%, 3% and 6%). These magnitudes covered the range that could be fused by subjects.

At the beginning of each session (see Figure 3.1) the adapting stimulus was presented for 5 minutes, whereupon the thin horizontal test stimulus was presented for 10 seconds. Subsequently, the screen became black and the subjects judged whether the test stimulus was slanted towards the left or towards the right by clicking on the left or right button of the computer mouse (a forced-choice task). After the first judgement of the measurement session, each following trial consisted of twenty seconds adaptation, 10 seconds testing and a judgement (see Figure 3.1).

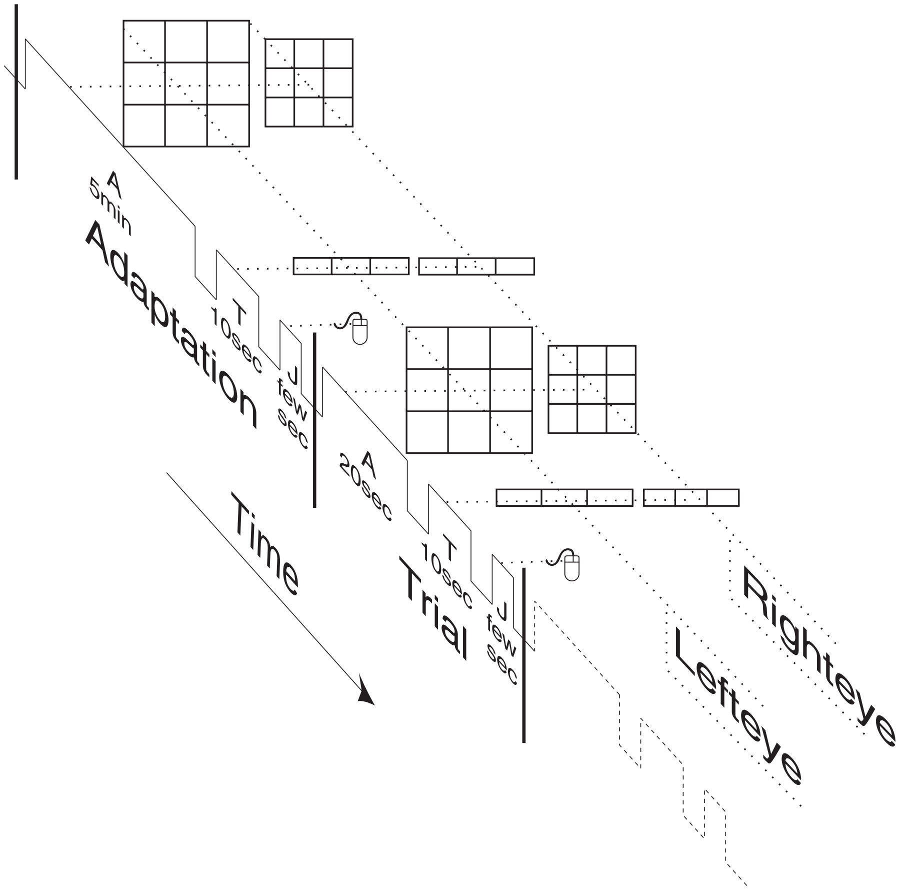

Figure 3.1 - Measurement scheme for experiment SCALE. The stimuli are shown schematically as grids. A measurement session started with five minutes presentation of the adapting stimulus (A), whereupon a test stimulus was presented (T) for ten seconds. After the test stimulus the subject had to judge (J) whether the test stimulus was slanted towards the left or towards the right. Each following trial consisted of a period of twenty seconds adaptation (A), 10 seconds testing (T) and a judgement (J). The amount of horizontal scale in the test stimulus was adjusted every trial.

The presentation time of the adapting stimulus was limited to 20 seconds, because the test stimulus hardly contained any information about vertical disparity. Therefore, we assumed that adaptation was maintained during inspection of the test stimulus.

Similar to experiment FLAT, the amount of horizontal scale in the test stimulus was varied during a session. The amount of horizontal scale needed to perceive the test stimulus as fronto-parallel was determined by an adaptive method, namely the MUEST method (Snoeren and Puts, 1997). A fixed number of trials, namely 50, were used as stop criterion.

Procedure for experiment SHEAR

In experiment SHEAR we investigated adaptation to a combination of vertical and horizontal shear that also was perceived as a fronto-parallel surface. We measured the magnitude of the horizontal shear in the test stimulus that was perceived as a fronto-parallel strip. The procedure was the same as in exp. SCALE. We measured adaptation to five magnitudes of vertical shear: -0.06, -0.03, 0, 0.03 and 0.06 (equivalent shear angle can be computed by taking the arc tangent of the shear factor: -3.4º, -1.7º, 0º, 1.7º and 3.4º). The thin test stimulus was oriented vertically so that subjects could discern slant about the horizontal axis.

Procedure for experiment MIX

In experiment MIX we investigated adaptation to a combination of vertical quadratic mix and horizontal quadratic scale. We measured the magnitude of the horizontal quadratic scale in the test stimulus that was needed to perceive the test strip as being fronto-parallel. The procedure was the same as in exp. SCALE. The adapting stimulus was a combination of horizontal quadratic scale and vertical quadratic mix. The combination was chosen such that each individual subject perceived the stimulus as a fronto-parallel surface. In each session of experiment MIX, we measured adaptation to one magnitude of vertical quadratic mix. In all, five magnitudes of vertical quadratic mix, which covered the range that could be fused by subjects, were measured: -0.16, -0.08, 0, 0.08 and 0.16. The thin test stimulus was oriented horizontally so that subjects could discern curvature in the horizontal direction.

3.3 Results

Experiment FLAT

In experiment FLAT, we investigated whether the adapting stimuli were still perceived fronto-parallel after a presentation period of five minutes.

First, we determined the combination of horizontal and vertical transformation that subjects perceived as being fronto-parallel before adaptation. For subjects CE and LW, the ratios are known from previous experiments (Berends and Erkelens, 2001b). For subject ME, we also carried out those measurements. For subjects CE, LW and ME, the ratios for scale are 0.91, 0.50 and 0.76, respectively. For quadratic mix, the ratios are 0.58, 0.74 and 0.45, respectively. These ratios were used to compute the amount of horizontal transformation needed to perceive the adapting stimulus fronto-parallel before adaptation (see Figure 3.2). The errors were computed by using the errors in the fit of the ratio.

The MUEST method was applied to find the amount of horizontal transformation needed to perceive the large test stimulus as being fronto-parallel (μ or α) after adaptation. Monte Carlo simulations were performed to estimate the error in μ. This error indicates how well the model (psychometric curve) fits the data (see Figure 3.2). Figure 3.2 shows that the differences between 'before' and 'after' are smaller than the errors for each subject and each type of vertical disparity field. Thus, the adaptation stimulus is perceived the same, namely fronto-parallel, before and after adaptation.

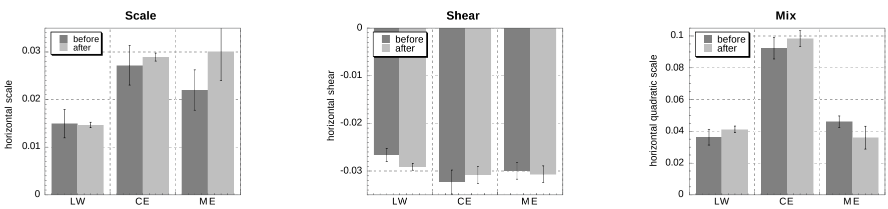

Figure 3.2 - The results of experiment FLAT. The amounts of horizontal transformation needed to perceive the adapting stimuli fronto-parallel before adaptation (dark grey bars) and after adaptation (light grey bars).

Experiment SCALE

The MUEST method was applied to find efficiently the amount of scale that was needed to null the effect of adaptation. The MUEST method provides a shift, α and slope, β. The terms α and β were converted into the more commonly used values μ and σ ($\mu = \alpha$, $\sigma = 1.7 / \beta$) (Treutwein, 1995). The shifts (μ values) are the amounts of horizontal scale needed to perceive the test strip as fronto-parallel. The σ values are the thresholds. Monte Carlo simulations were performed to estimate the errors in μ and σ.

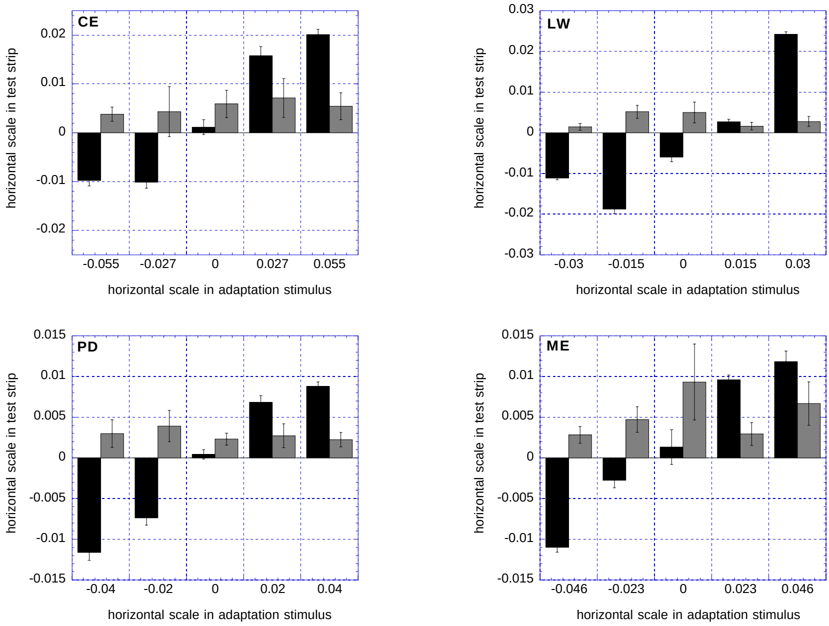

Figure 3.3 - The results of exp. SCALE. Adjacent pairs of black and grey bars represent a measurement session. The black bar is the μ value, which is the amount of horizontal scale needed to null the after-effect. The grey bar is the σ value, which is the threshold. The error bars in μ and σ indicate the accuracy of the measurements and the goodness of fit of the model (psychometric curve) to the data. Note that the scales on the horizontal and vertical axes differ from each other and differ in the various panels.

The results are shown in Figure 3.3. The fact that most σ values are much smaller than the accompanying μ values is an indication that the after-effect is significant. Furthermore, the errors in μ are small relative to the μ values. A linear relation (least squares) was fitted between the amount of scale in test strip and in the adapting stimulus of each subject (Table 3.1). The slopes these fits differ significantly from zero ($p < 0.05$), showing that the after-effects are significant in all subjects. The offsets do not differ significantly from zero ($p > 0.05$), as expected.

Experiment SHEAR

The results of exp. SHEAR are shown in Figure 3.4. We fitted a linear relation (least squares) between the amount of shear in test strip and in the adapting stimulus of each subject (Table 3.1). All the slopes of these fits differ significantly from zero ($p < 0.05$). This indicates that the after-effect is significant. Surprisingly, three offsets (of subjects CE, LW and ME) differ significantly from zero ($p < 0.05$).

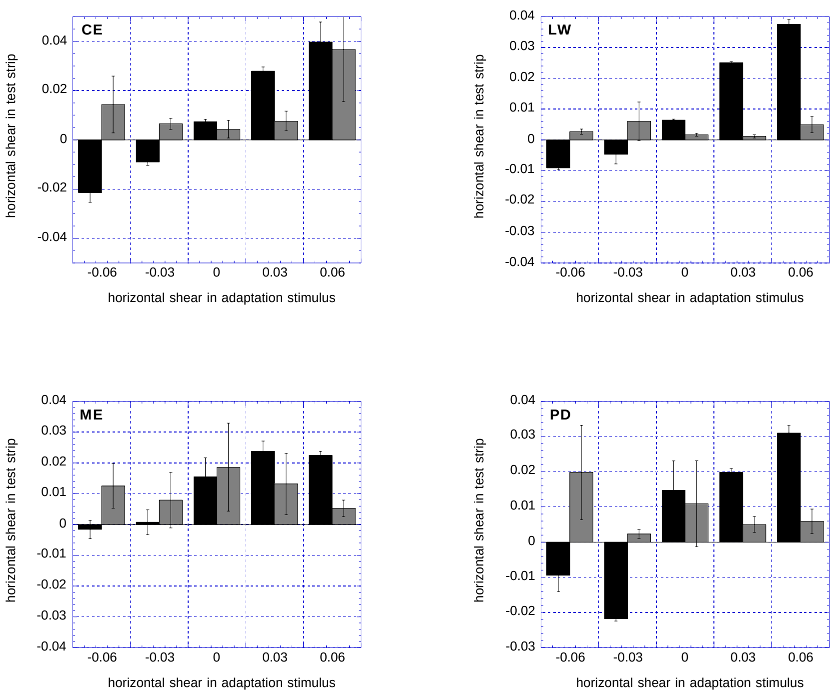

Figure 3.4 - Same as Figure 3.3, but for experiment SHEAR.

Experiment MIX

The results of exp. MIX are depicted Figure 3.5. We fitted a linear relation (least squares) between the amount of scale in test strip and in the adapting stimulus of each subject (Table 3.1). All the slopes of these fits differ significantly from zero ($p < 0.05$). Thus, we found a significant after-effect in exp. MIX. Only one offset (of subject ME) differed significantly from zero ($p < 0.05$).

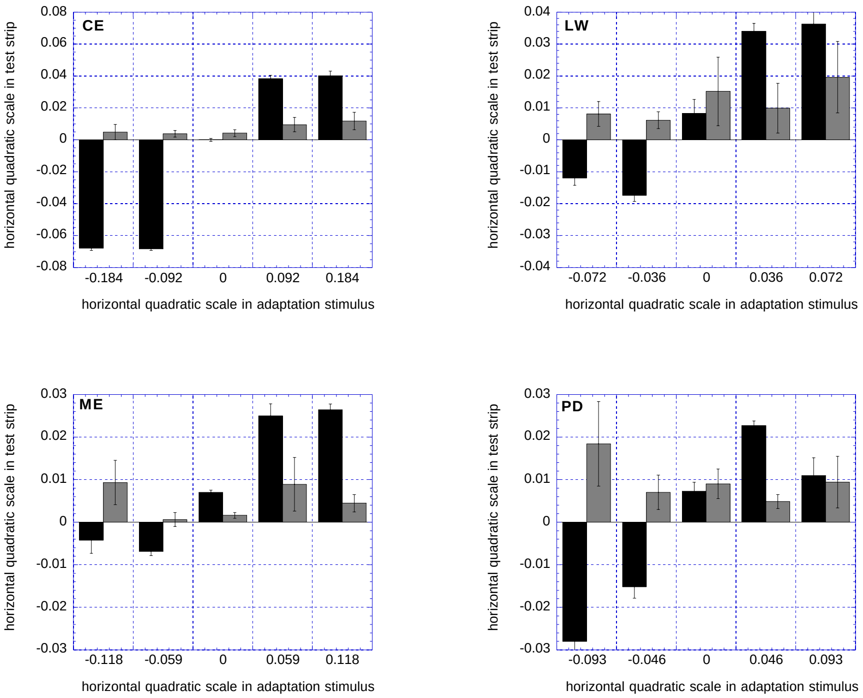

Figure 3.5 - Same Figure 3.3, but for experiment MIX.

		CE	LW	ME	PD
SCALE	ratio	0.91	0.50	0.76	0.67
	slope	0.31*	0.61*	0.25*	0.27*
	offset	0.0034	-0.0018	0.0018	-0.0006
	R^2	0.92	0.78	0.97	0.97
SHEAR	ratio	-1	-1	-1	-1
	slope	0.53*	0.41*	0.24*	0.41*
	offset	0.0089*	0.0111*	0.0122*	0.0069
	R^2	0.99	0.96	0.89	0.79
MIX	ratio	1.15	0.45	0.74	0.58
	slope	0.35*	0.41*	0.16*	0.25*
	offset	-0.0115	0.0099	0.0095*	-0.0004
	R^2	0.89	0.87	0.88	0.79

*Table 3.1 - The ratios of horizontal transformation to vertical transformation in the adapting stimulus and the linear fit parameters for exp. SCALE, SHEAR and MIX. The offsets and the slopes marked with a * differ significantly from zero ($p < 0.05$).*

3.4 Discussion

Adaptation to disparity, not to perceived depth

We investigated whether adaptation to disparity can occur in the absence of a perceptual drive. We found that the percept did not change during prolonged viewing of combinations of vertical and horizontal transformations. The adapting stimulus was always perceived as a fronto-parallel plane. We found stimulus-specific after-effects after removal of the adapting stimulus. We concluded that adaptation occurred to disparity signals and not to perceived depth.

There are two possible explanations for the fact that the percept did not change during adaptation. One explanation is that the visual system did not adapt. This explanation is not correct because we found an after-effect. The other explanation is that the visual system adapted, but that adaptation was not revealed by the adapting stimulus. Three signals that may be adapted play a role in these experiments, namely horizontal retinal disparity, vertical retinal disparity and oculomotor signals. Adaptation may imply that the relationship has been changed between perceived depth and these three signals separately without affecting the relationship between depth and the three signals in combination. In the present experiments, at least two of these three signals adapted else the adapting stimulus could not remain fronto-parallel during adaptation. The present experiments do not give a decisive answer which of these three signals adapted and whether adaptation involved two or three signals.

The main conclusion to be drawn from this paper is that a percept of slant or curvature is not required for adaptation to disparity. The visual system did not adapt to the percept, because it was found to adapt differently to the three adapting stimuli although these stimuli were perceptually indistinguishable. The adapting stimuli were always perceived as a fronto-parallel plane. Each disparity field induced a particular after-effect, namely slant about the horizontal axis, slant about the vertical axis and curvature of the surface. So, the visual system adapted to disparity in these experiments.

Present and past experiments

The present results for SHEAR are comparable to the results obtained by Mack and Chitayat (1970). They exposed subjects to a binocular prism system that induced 5º, opposite rotation of the visual fields in the two eyes. They measured the after-effect after 5 and after 20 minutes. They used a small vertical line element to measure the after-effect in order to prevent subjects from using depth cues other than stereo. They found an after-effect after 5 minutes of adaptation that was somewhat smaller than the one we found (viz. they found slopes about 0.1 and we found slopes between 0.24 and 0.53, see Table 3.1. The difference may be caused by the fact that Mack and Chitayat did not use a nulling method.

Eye movements may explain the results of experiment SHEAR. A combination of horizontal and vertical shear induces cyclovergence (Ogle and Ellerbrock, 1946; Howard and Kaneko, 1994). This kind of eye movements may have affected the percept of the subsequently presented stimuli. However, Mack and Chitayat (1970) measured eye movements and they found that cyclotorsion did not occur. Furthermore, Howard and Kaneko (1994) showed that cyclotorsion could not explain our results, because their measurements of cyclovergence revealed a strong asymmetry for incyclorated and excyclorotated stimuli, whereas they did not find this asymmetry in the percepts.

Explanations for the disparity adaptation

Adaptation has been explained in two different ways in the literature. The first explanation is that adaptation was caused by a signal that remains constant over a long period of time. The second explanation is that adaptation is a response of the visual system to conflicts between different signals. The following paragraphs deal with the second explanation, but first of all we will discuss the explanation that adaptation is caused by a constant disparity signal. Blakemore and Julesz (1971), Long and Over (1973) and Mitchell and Baker (1973) supported this explanation. They carried out experiments in which subjects adapted to horizontally transformed stereograms. Their subjects had to maintain steady fixation. Therefore, retinal disparity was constant during adaptation. One can imagine that they attributed the after-effect to the adaptation of disparity-specific neurones. In the experiments of Ryan and Gillam (1993) and in our present experiments the subjects were free to look around. Thus, retinal disparity varied during the adaptation phases. Nevertheless, we found adaptation. Therefore, it is unlikely that the visual system adapted to retinal disparities. Both headcentric disparity and relative retinal disparity (e.g. horizontal size ratio) were constant in all the above-mentioned adaptation experiments. Thus, if adaptation was caused by a signal that was constant over a long period of time, the visual system must have adapted to headcentric disparity or to relative retinal disparity, not to absolute retinal disparity.

In the following paragraphs, we discuss how cue conflicts can explain the measured adaptation in the present experiments. Young, Landy and Malony (1993), Turner, Braunstein and Andersen (1997) and Jacobs and Fine (1999) argued that conflicts between different signals are involved in depth adaptation. Mack and Chitayat (1970) and Epstein and Morgan (1970) explained the adaptation in terms of recalibration of the relationship between retinal disparity and perceived depth. Burian (1943), Epstein (1971); Epstein (1972a), Morrison (1972), Epstein and Morgan-Paap (1974) and Lee and Ciuffreda (1983) offered the following explanation. Adaptation is the recalibration of erroneous binocular depth cues (disparity) due to the presence of veridical monocular depth cues and due to memory experiences and tactile information. In the present experiments, there were only conflicts between vertical disparity and eye position signals. Thus, according to this explanation, both vertical disparity signals and eye position signals should have been recalibrated.

An example of how recalibration of the eye position signals may explain the adaptation is given with the help of the headcentric model developed by Erkelens and Van Ee (1998). According to this model, vertical headcentric disparity is usually zero unless an error occurs in the oculomotor signals. A change in the oculomotor system (e.g. eye muscle damage or damage to a nerve) can also cause a non-zero vertical disparity field. Then, recalibration is desired. Within the concept of headcentric disparity, adaptation to vertical disparity can be interpreted as the recalibration of a specific oculomotor signal, namely recalibration to horizontal version (SCALE), to cyclovergence (SHEAR) and to horizontal vergence (MIX). Recalibration of the oculomotor signals would affect not only vertical headcentric disparity but also horizontal headcentric disparity. Therefore, this interpretation explains why perceived depth did not change during presentation of the adapting stimuli.

Chapter 4

Stereoscopic viewing of an unslanted stimulus can induce a slant aftereffect even if the disparities change continuously

We have recently demonstrated that prolonged viewing of a fronto-parallel plane can induce a slant aftereffect (adaptation). Here we test the hypothesis that such adaptation is caused by disparity that is constant over a relatively long period of time (fatigue). For this we used an adaptation stimulus that contained both a fixed ratio of horizontal and vertical disparity gradients and, additionally, oscillating horizontal and/or vertical disparities. Subjects perceived the continuously changing curvature evoked by the oscillating disparity but the stimulus remained unslanted. After 5 minutes of adaptation, subjects were presented with a thin horizontally elongated test strip (negligible vertical disparity). Subjects had to decide whether the left or the right end of the strip was closer. Using a nulling-technique, we measured the horizontal disparity gradient that subjects needed to perceive the strip unslanted. We found that the stimulus induced a clear and stable slant aftereffect. Thus, we found that adaptation to disparity can be caused by a signal that changes continuously. Therefore, we reject the above-mentioned hypothesis. We suggest that adaptation is probably a response to conflicts between different signals.

4.1 Introduction

Binocular disparity between the two retinal images is an important source of information for the recovery of the three-dimensional layout of the visual environment. Perceived depth of a visual stimulus is affected not only by the binocular disparity of the stimulus itself but also by foregoing disparity stimulation. For example, if the visual system is in an "adapted state", it has become less sensitive to disparity in a stimulus (Blakemore and Hague, 1972; Mitchell and Baker, 1973). We are interested in the factors that play a role in disparity adaptation. There is a considerable body of literature on the subject and various explanations have been given for adaptation to disparity. The explanations can be divided into two groups.

The first explanation is that adaptation is caused by a signal that remains constant over a long period. If neurons are stimulated for a longer period, their activity may decrease (fatigue) (Blakemore and Julesz, 1971; Long and Over, 1973). In the studies by these authors, subjects viewed random-dot stereograms in which the centre square was differentially horizontally translated in the two half-images. They perceived the stereogram as a square floating in front of a background. After adaptation to this transformed stereogram, they perceived the central part of an untransformed stereogram to be behind the background. In other words, there was an aftereffect. During these experiments, retinal disparity was constant, because subjects had to maintain steady fixation. These authors suggested that disparity-specific neurons adapted to constant retinal disparity. Köhler and Emery (1947) and Ryan and Gillam (1993) also found an aftereffect in their experiments, in which subjects were free to look around, which means that adaptation also occurs when retinal disparities vary. Therefore, Ryan and Gillam (1993) concluded that subjects adapt not to a constant disparity but to a constant disparity gradient. This conclusion supports the explanation that adaptation is caused by a signal that remains constant.

Another explanation has been derived from experiments in which subjects adapted as a result of wearing a meridional lens in front of one eye. Meridional lenses have been used to study adaptation to horizontal scale (Burian, 1943; Burian and Ogle, 1945; Miles, 1948; Epstein and Morgan, 1970; Epstein, 1972a; Epstein, 1972b; Morrison, 1972; Epstein and Morgan-Paap, 1974; Adams, Banks and Van Ee, 1999) and to vertical scale (Miles, 1948; Epstein, 1972b; Morrison, 1972; Lee and Ciuffreda, 1983). In these experiments, subjects wore the meridional lens for periods varying between ten minutes and thirty days. During these periods, the perceived distortion (i.e. slant) induced by the lens vanished. At the end of the period, when the lens was removed, subjects again perceived the environment to be slanted, but the slant direction was opposite to that perceived during the adaptation period. All investigators have explained adaptation in terms of recalibration of the mapping between disparity and perceived depth. Two types of recalibration have been described. First, adaptation was explained in terms of a change in bias in the relationship between retinal disparity and perceived depth (Epstein and Morgan, 1970; Lee and Ciuffreda, 1983; Adams, *et al.*, 1999). The second explanation was that adaptation was due to a change in the weighting factors of different cues (Burian, 1943; Burian and Ogle, 1945; Miles, 1948; Morrison, 1972).

A forthcoming study by Berends and Erkelens (2001a) constitutes the basis for the present study. It shows that the visual system adapts to specific disparities but not to the perceived depth induced by these disparities. Subjects adapt to large random-dot patterns of which the two half-images are transformed such that the depth effects induced by the vertical transformations are nulled by those induced by horizontal transformations. After a period of adaptation, in which the perceived surface remains flat and unslanted, an untransformed thin strip is perceived as either slanted or curved depending on the adapting transformation. We suggest that adaptation is caused by recalibration of the eye position signals. Our view is based on the fact that in our experiments the only possible cue conflicts are those between vertical disparity and eye position signals.

Summarising, the literature reports two different mechanisms that explain adaptation to disparity. Either adaptation is caused by the prolonged presence of a constant signal (fatigue), or adaptation is recalibration, i.e. the response of the visual system to conflicts between different signals. The purpose of the present study is to test the first hypothesis, namely, that adaptation to disparity is caused by the prolonged presence of a constant signal.

To reach our goal we adopt the following approach. We investigate whether adaptation occurs when the disparity signal is not constant. In our experiments, disparity varies as a function of time. If we find that adaptation occurs when disparity varies, the prolonged presence of a constant signal is not required for adaptation to disparity.

Our adapting stimuli consist of a constant transformation and an oscillating transformation. The constant transformation is a combination of horizontal and vertical scale, which subjects perceive as a fronto-parallel plane. Three types of oscillating transformations are studied, namely a varying horizontal transformation, a varying vertical transformation and a variation of both. Whereas subjects perceived the oscillations in depth caused by the oscillating transformations, they perceived the adapting stimulus to remain unslanted.

4.2 Methods

Subjects

Four subjects with corrected-to-normal visual acuity participated. CE and RE knew about the purpose of the experiment.

Apparatus

Red-green anaglyphic stereograms were generated at a frequency of 70 Hz and back-projected onto a fronto-parallel translucent screen by a projector (JVC DLA-G11E). The resolution (the minimum step in disparity) was 3.8 minutes of arc. The subject was seated 1.50 m from the screen. The measurements were performed in a completely dark room. The head of the subject was fixed by a chin rest. Subjects were free to look around.

Stimuli

Two types of stimuli were presented: first an adapting stimulus and then a test stimulus. The adapting stimuli were large stereograms (visual angles of 57º x 57º). The test stimuli were thin horizontal strips (visual angles of 40º x 0.7º) which did not provide substantial information about any vertical disparity gradient. The adapting stimulus and the test stimulus were random dot patterns of 2500 and 37 dots, respectively. The 'dots' were always small squares (15.2 arcmin diameter; not anti-aliased). Monocular flatness cues were minimised.

Oscillating disparity

The adapting stimuli consisted of a constant transformation and an oscillating transformation. The constant transformation was the same as in one of our other experiments (Berends and Erkelens, 2001a), namely a combination of horizontal and vertical scale. The constant transformation was scaled horizontally and vertically in such a way that the subject perceived it as a fronto-parallel surface. The combination was different for each subject (Van Ee and Erkelens, 1998; Backus, *et al.*, 1999; Berends and Erkelens, 2001b). Three types of oscillating transformations were added to this combination. An adaptation stimulus, in which horizontal disparity oscillated, is shown in Figure 4.1. The oscillation and the spatial modulation were both sine-shaped. The subjects perceived half a cylinder (with a horizontal axis) that changed continuously from convex to concave and vice versa. The amplitude of modulation was 1.04° and the frequency of oscillation was 0.1 Hz.

We studied adaptation to both oscillating horizontal disparity and to oscillating vertical disparity for the following reason. The aftereffect following adaptation to a combination of horizontal and vertical scale can be induced by several signals (Berends and Erkelens, 2001a), namely the vertical disparity signal, the horizontal disparity signal or the combination of both signals. If adaptation is induced by prolonged presentation of a constant vertical disparity signal and if horizontal disparity varies, then adaptation will still occur.

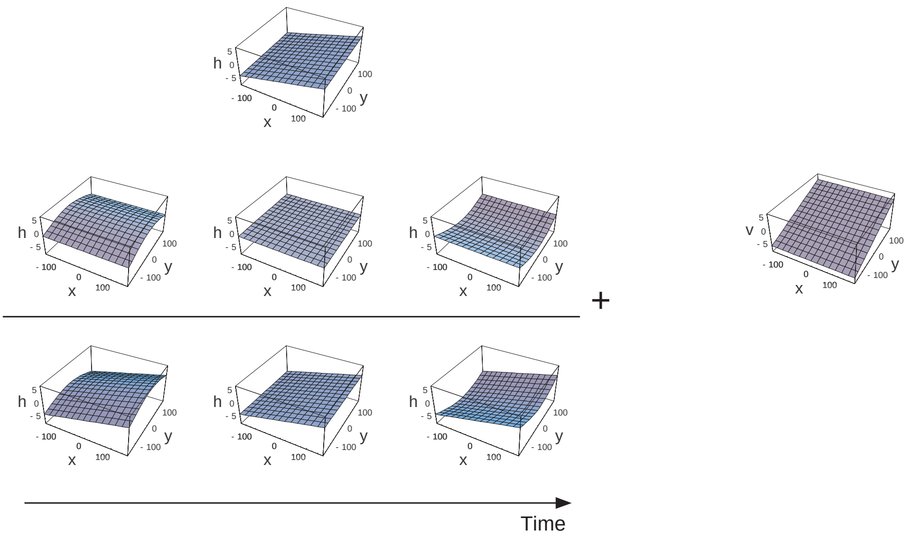

Figure 4.1 - The amount of transformation in the horizontally modulated adaptation stimulus. The amount of horizontal transformation (h) is depicted on the left and the amount of vertical transformation (v) is depicted on the right. The vertical transformation is a constant vertical scale. Two horizontal transformations were added to this stimulus. The first transformation was a horizontal scale (first row). This transformation was also constant over time. The size of the horizontal scale was chosen such that the combination of horizontal and vertical scale was perceived as a fronto-parallel plane. The second transformation is a sine-shaped horizontal transformation, one half period (second row). The sine is positioned vertically; the horizontal translation in the middle is larger than on the top and the bottom of the stimulus. The amplitude of the sine depended on time. The sine-shaped transformation is shown at three different points of times. The adaptation stimulus, shown in the third row, consists of the constant transformation plus the oscillating transformation in the other two rows.

The same holds if adaptation is induced by constant horizontal disparity and vertical disparity oscillates. If adaptation occurs in response to oscillating horizontal disparity and to oscillating vertical disparity, then we can rule out a constant signal as the cause for adaptation.

The vertical disparity oscillation differed in two ways from the horizontal disparity oscillation. The direction of modulation differed and the modulation amplitude was smaller for the vertical disparity modulation, namely 0.84º. Although the modulation was also sine-shaped, subjects perceived a flat surface at all times, because vertical disparity operates globally (Van Ee and Erkelens, 1995; Howard and Kaneko, 1994; Kaneko and Howard, 1996).

We also designed a stimulus in which the global gradient of the disparity varied, because Ryan and Gillam (1993) argued that the visual system adapts to a constant global disparity gradient. Furthermore, according to Erkelens and Van Ee (1998), the global gradient in the vertical disparity field is important in binocular vision, because vertical disparity processing is based on the global gradient. To produce a stimulus in which the global gradient of the disparity varied we oscillated the amount of both vertical and horizontal scale. We varied the amounts of vertical and horizontal scale such that subjects perceived the adaptation stimulus to be fronto-parallel at all times. Therefore, we prevented subjects from adapting to the percept. The amplitude of the oscillation was 3% vertical scale and the frequency was 0.1 Hz. If we found that subjects adapted to a combination of oscillating horizontal and vertical disparity, the two experiments in which we measured adaptation to either oscillating horizontal or vertical disparity would be superfluous. However, in the experiment in which both horizontal and vertical disparity varied, the range in which we were able to measure was very small.

Procedure

The experiments were subdivided into twelve sessions. In each session, we measured adaptation to one magnitude of vertical scale and to one type of oscillation. Five magnitudes of vertical scale were measured: -6%, -3%, 0%, 3% and 6%. These magnitudes covered the range that could be fused by all subjects. The three types of modulation were modulation of horizontal disparity, modulation of vertical disparity and modulation of both. In case of modulation of both, only two magnitudes of vertical scale were measured: -3% and 3%.

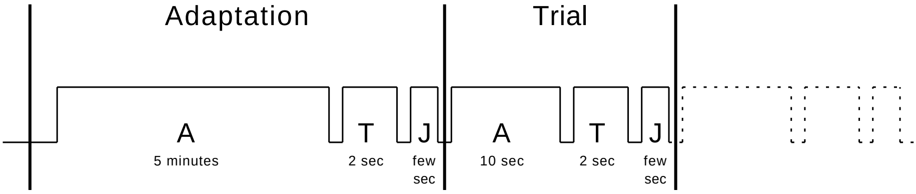

Figure 4.2 - Time series. A session started with five minutes of adaptation to the adapting stimulus, whereupon a test stimulus was presented for two seconds. After the test stimulus, the subject had to judge whether the test stimulus was slanted towards the left or towards the right. Each following trial consisted of ten seconds of adaptation, two seconds of testing and a judgement.

Each session (see Figure 4.2) started with the presentation of an adapting stimulus for 5 minutes. Then a thin test strip was presented for 2 seconds. Subsequently, the screen became black and the subjects judged whether the test stimulus had been slanted towards the left or towards the right by clicking on the left or right button of the computer mouse (a forced-choice task). After the first judgement of the measurement session, each following trial consisted of 10 seconds of adaptation, 2 seconds of testing and a judgement. The presentation time was chosen such that exactly one period of the disparity oscillation was shown. The adapting stimulus was concave at the start of half of the trials (and convex at the start of the remaining trials).

Adaptation was measured from judgements regarding the slant of the test stimulus. The amount of horizontal scale in the test stimulus was varied during the sessions. The amount of horizontal scale needed to perceive the test stimulus as fronto-parallel was determined by an adaptive method, called MUEST (Snoeren and Puts, 1997). After 50 repetitions, the session was terminated.

4.3 Results

In previous experiments, we determined which combinations of horizontal and vertical scale subjects perceived as fronto-parallel surfaces (Berends and Erkelens, 2001b). For subjects CE and LW, the ratios are 0.91 and 0.50, respectively. The same experiment was carried out for subjects LD and RE. The ratios for subjects LD and RE are 0.61 and 0.40, respectively.

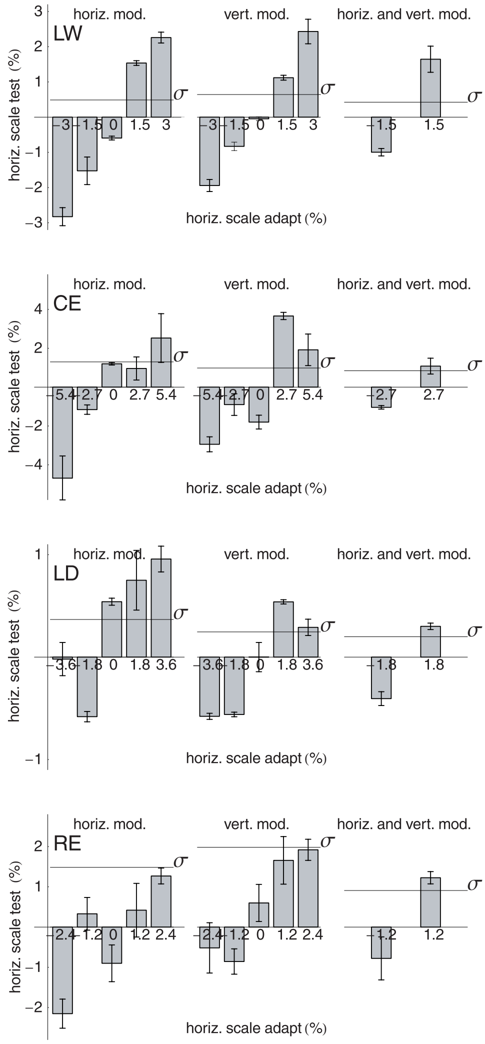

Figure 4.3 - The results. Each panel shows the results for one subject and one type of oscillation. The results for one subject are depicted next to each other such that they are easy to compare. In each panel, the values on the x-axis represent the amount of horizontal scale in the adaptation stimulus. The heights of the bars represent the amount of horizontal scale in the test stimulus needed to see the test stimulus as fronto-parallel (the μ value). The error bars in μ indicate the accuracy of the measurements and the goodness of fit of the model (psychometric curve) to the data. The solid line represents the average σ value that indicates the sensitivity of the subject. Note that the scales on the horizontal and vertical axes differ from each other for different subjects.

The MUEST method was applied to find out how much scale that was needed to null the effect of adaptation. Psychometric curves (cumulative normal function) were fitted to the data. We obtained two fit parameters: μ, the amount of horizontal scale needed to perceive the test strip as fronto-parallel and σ, the slope parameter. Monte Carlo simulations were performed to estimate the errors in μ and σ. These errors indicate how well the model (psychometric curve) fits the data. The results are depicted in Figure 4.3 for all three types of modulations. The aftereffects, μ, are larger than the estimated errors in μ. This implies that adaptation occurred in all three cases. There is no significant difference between adaptation to the three types of oscillations (ANOVA between regression lines, $p > 0.05$ for each subject).

Linear relations (least squares) were fitted between the amounts of scale in test strips and adaptation stimuli for each subject and each type of modulation (Table 4.1). Most slopes of these fits differ significantly from zero ($p < 0.05$), showing that the aftereffects are significant in all subjects and with two types of modulation. Three slopes are not significantly different from zero, namely LD ($p = 0.08$) and RE ($p = 0.09$) both for the horizontal modulation and CE for the vertical modulation. The offsets do not differ significantly from zero ($p > 0.05$), as expected. For the modulation in two directions, it is impossible to give the goodness of fit of the line, because we measured only two points.

		LW	CE	LD	RE
ratio		0.50	0.91	0.61	0.40
horizontal disparity oscillated	slope	0.88*	0.60*	0.18	0.58
	offset	-0.23	-0.23	0.33	-0.21
	R^2	0.98	0.86	0.69	0.67
vertical disparity oscillated	slope	0.71*	0.52	0.15*	0.62*
	offset	0.15	-0.01	-0.06	0.56
	R^2	0.99	0.68	0.80	0.88
horizontal and vertical disparity oscillated	slope	0.88	0.39	0.19	0.83
	offset	0.32	0.02	-0.05	0.22

*Table 4.1- The ratios of horizontal transformation to vertical transformation in the adapting stimulus and the linear fit parameters for experiments with three types of oscillation. The offsets and the slopes marked with a * differ significantly from zero (p < 0.05).*

4.4 Discussion

Our key finding is that stereoscopic viewing of an unslanted stimulus can induce a slant aftereffect even if both horizontal and vertical disparities oscillate continuously. This finding has a bearing on existing explanations for disparity adaptation.

Adaptation to constant disparity versus oscillating disparity

Blakemore and Julesz (1971) and Long and Over (1973) suggested that adaptation is caused by a disparity signal that remains constant over a long period. In other words, neuron activity decreases after prolonged stimulation (fatigue). Ryan and Gillam (1993) also found adaptation if subjects were allowed to make eye movements. They concluded that subjects adapted to a constant disparity gradient. However, as we have reported, we found that adaptation occurred when either horizontal disparity or vertical disparity or both oscillated. Thus, neither constant disparity nor a constant disparity gradient is required for adaptation to disparity. The main conclusion of this paper is that constant signals are not necessary for adaptation to disparity. We found no significant difference between the results for the different types of oscillations.

Integration over time

The choice of the oscillation frequency is relevant. If the frequency is high, the visual system will integrate the disparity over time and it will perceive no difference between the oscillating stimuli used in the present experiments and the constant stimuli used in previous experiments (Berends and Erkelens, 2001a). Thus, a low oscillating frequency is required in our experiments.

Therefore, we looked at integration times reported in the literature. Patterson, Cayko, Short, Flanagan, Moe, Taylor and Day (1995) used the following criterion for temporal integration of disparity. The integration time is the presentation time that subjects need to perceive a random-dot stereogram (duration threshold). They found duration thresholds lower than 90 msec. Beverly and Regan (1974) used a similar criterion for integration time. According to these authors, temporal integration occurred, when the oscillation frequency was increased so much, that subjects were unable to perceive changes in depth. We used this criterion for the horizontal disparity oscillations. Subjects were clearly able to perceive the horizontal disparity oscillations of 0.1 Hz. This means that the choice of a frequency of 0.1 Hz was suitable for examining the adaptation that occurred in our study. This criterion cannot be used for the adaptation stimuli in which vertical disparity oscillated or in which both horizontal and vertical disparity oscillated, because these oscillations did not have perceptual correlates. However, Allison, *et al.* (1998) found that percepts induced by horizontal and vertical disparities developed over the same period of time. Therefore, we assumed that the integration time for vertical disparity is the same as for horizontal disparity.

Recalibration

The literature provides two explanations for adaptation to disparity. Either adaptation is caused by a signal that remains constant over a relatively long period (fatigue) or adaptation is a response of the visual system to conflicting cues. If the latter is true, adaptation can be interpreted as a recalibration of the signals involved in depth perception. Our experiments show that the first explanation can be ruled out. Our experiments are consistent with the second explanation, but they do not prove conclusively that this is the only possible explanation.

4.5 Conclusion

Stereoscopic viewing of an unslanted stimulus can generate the perception of a slant aftereffect even if both horizontal and vertical disparities oscillate continuously (generating perception of continuously changing curvature). We therefore reject the hypothesis that such adaptation is caused by a signal that remains constant over a prolonged period.

Chapter 5

Differing roles for vertical disparity in the perception of direction and depth

In binocular vision, retinal signals and extra-retinal eye position signals are available for perceiving both depth and direction. It has been experimentally shown that vertical disparities and extra-retinal eye position signals alter perceived depth. We investigated whether vertical disparities can alter perceived direction. We dissociated the common relationship between the vertical disparity field and the stimulus direction by applying a vertical magnification to one eye's image (vertical scale). We used a staircase paradigm to measure whether perceived straight-ahead depends on the amount of vertical scale in the stimulus. Subjects judged whether a test dot was flashed to either the left or the right side of straight-ahead. The test dot was flashed during the presentation of a vertically scaled random-dot stereogram that was larger than the visual field (therefore, the stereogram edges could not be used in the estimation of straight-ahead). We found that perceived straight-ahead did indeed depend on the amount of vertical scale but only after subjects adapted (5 minutes) to vertical scale (and only in five out of nine subjects). Thus, the role of vertical disparity in perceiving direction is different from its role in perceiving depth. Our results suggest that vertical disparity is a factor in the calibration of eye position signals.

5.1 Introduction

Retinal signals and extra-retinal eye position signals can be used for perceiving both depth and direction. Although it is not known how the processes of perceiving direction and perceiving depth are related, some kind of relationship seems likely because both processes use the same input signals. The literature proposes various methods for determining depth from retinal signals and extra-retinal eye position signals. Depth can be derived from a combination of horizontal and vertical disparity (Rogers and Bradshaw 1995; Backus et al 1999) and it can also be derived from horizontal disparity and eye position signals (Foley 1980; Collett et al 1991; Cumming et al 1991; Sobel and Collett 1991; Rogers and Bradshaw 1995; Backus et al 1999). The fact that vertical disparity affects depth does not necessarily imply that it is used for perceiving direction. The goal of the present research was to find out whether vertical disparity can alter perceived direction.

We used a stimulus in which we dissociated the common relationship between the vertical disparity field and the stimulus direction. In order to understand the essence of the method used, consider an object that is located straight-ahead of an observer. Such an object has the same size (visual angle) in both eyes. However, if the object is magnified vertically (scaled vertically) in the left eye, then the retinal vertical disparity corresponds to the disparity of an object, which under normal viewing conditions is located to the left of the observer. If an image is vertically magnified in one eye, the direction specified by vertical disparity differs from the direction specified by eye position signals. Therefore, we dissociated the directions specified by vertical disparity and by eye position signals by scaling vertically one half-image of a stereogram relative to the other half-image. We investigated whether perceived straight-ahead depended on the amount of vertical scale in the stimulus that was presented. The predicted change in perceived straight-ahead, based on the assumption that straight-ahead is determined entirely by vertical disparity, is rather large, namely 27° and 64° to the right for 3% and 6% vertical magnification of the image in the left eye, respectively (calculated for a screen distance of 100 cm and a inter-ocular distance of 6.5 cm). If we assume that only the eye position signals are used to perceive direction, then the predicted change in perceived straight-ahead is zero.

If the outcome of our experiment is that scaling the stimulus vertically causes a change in perceived straight-ahead, then the actual vertical disparity is used directly to determine perceived direction. If vertical scaling does not cause this change, this does not imply that vertical disparity and perceived direction are fully independent. Then, adaptation to vertical disparity might still be associated with a change in perceived direction. This idea is not new: Ebenholtz (1970) predicted that prolonged wearing of a magnifying lens in front of one eye would change the perceived direction. He reasoned that the dissociation between vertical disparity and eye position signals causes a conflict between direction specified by vertical disparity and direction specified by the eye position signals. Therefore, Ebenholtz forecasted that recalibration of the eye position signals should occur. Berends and

Erkelens (2001a) found such a result with respect to depth perception. They reported that adaptation to a combination of horizontal and vertical scale is caused by the recalibration of the eye position signals.

In our study, we used a purely visual task to measure changes in perceived direction. A manual task is not suitable because then one may also measure changes in the proprioceptive system of the arm (visuo-motor calibration). Thus, a change measured by a manual task does not necessarily indicate a change in the visual system.

Summarising, we investigated whether a vertical scale changes the perceived direction immediately and whether adaptation to a vertical scale causes a change in perceived direction. If perceived direction changes immediately, then vertical disparity affects perceived direction in a direct fashion. If perceived direction changes only after an adaptation period, then vertical disparity is probably used to recalibrate the eye position signals. If perceived direction does not change even after adaptation, then vertical disparity does not influence perceived direction.

5.2 Methods

Subjects

Nine subjects participated in the experiments. All had normal or corrected-to-normal visual acuity. Four of them knew about the purpose of the experiment (EB, LD, CE and RE) and five subjects were naive (JB, MB, SH, RV and LW).

Apparatus

An anaglyph set-up was used for the generation of stereograms. The stimuli were generated by an HP750 graphics computer (frequency = 70 Hz) and back-projected on a fronto-parallel translucent screen by a D-ILA projector (JVC DLA-G11E). The resolution (the minimum step in disparity) was 5.7 minutes of arc. The subject was seated 1 m from the screen. A subject was not allowed to wear normal anaglyph glasses in this experiment, because the frame of the glasses would be a frame of reference. Therefore, the red and green filters were fixed to the subject’s head by means of tape, so that the subject could not see the edges of the filters. If a subject wore corrective glasses, the red and green filters were taped behind his/her own glasses. The measurements were performed in a completely dark room. Nothing was visible apart from the stimuli. The head of the subject was fixed by a chin rest and a bite-board. Subjects were free to look around. A fixation point was not used because it might have served as a reference. Furthermore, a fixation point is not necessary because the direction in which one perceives an object is not affected by the direction in which the eyes are pointing (Hill 1972).

Stimuli

The stimuli were large stereograms (visual angles of 98° x 86°), such that subjects could not see the edges of the stimuli. The stimuli were sparse random dot patterns containing 1250 dots. The dots were small (22.8 arcmin diameter), always circular and not anti-aliased. Monocular flatness cues were minimised. A larger test dot (68.4 arcmin diameter) was used to measure perceived straight-ahead. The test dot was always placed at eye height, but its horizontal position was varied.

Procedure for experiment DIRECT

Experiment DIRECT was subdivided into four sessions. In each session, we measured the difference in perceived straight-ahead when a certain amount of scale was presented and when an untransformed stimulus was presented. We used a visual task in order to test changes in the visual system.

Four magnitudes of vertical scale were measured: –6%, -3%, 3% and 6%. These magnitudes covered the range that could be fused by all subjects. An amount of horizontal scale was added to the vertical scale so that subjects perceived the adaptation stimulus as being fronto-parallel. Therefore, there were no conflicts between horizontal disparity and monocular depth cues (Rogers and Bradshaw 1995; Backus et al 1999; Berends and Erkelens 2001b).

Each session consisted of fifty trails of untransformed stimuli and fifty trails of scaled stimuli. The trails were presented in random-order. The series of untransformed trails was used to measure what a subject perceived as straight-ahead under normal circumstances, i.e. when there are no conflicts between vertical disparity and eye position. This was necessary because perceived straight-ahead depends on the subject and on how the subject is positioned in the set-up.

During each trail, either the untransformed stimulus or the scaled stimulus was presented. After 1 sec, the test dot was flashed for 100 msec. Then subjects had to judge whether the test dot was presented to their left or to their right by clicking on the left or right button of the computer mouse (a forced-choice task). Then the next trail started with a new random-dot pattern. The horizontal position of the test dot was varied during the session. The horizontal positions which subjects perceived as straight-ahead when the scaled stimulus was presented and when an untransformed stimulus was presented were determined by an adaptive method, namely the MUEST method (Snoeren and Puts 1997).

Procedure for experiment ADAPTATION

The experiment ADAPTATION was subdivided into five sessions. In each session, we measured the change in perceived straight-ahead induced by adaptation to a combination of horizontal and vertical scale. Five magnitudes of vertical scale were measured: –6%, -3%, 0%, 3% and 6%. The magnitudes of horizontal scale were chosen such that subjects perceived the stimulus as being fronto-parallel.

At the beginning of each session we determined what subjects perceived as being straight-ahead before adaptation. In the middle of a session, subjects adapted for five minutes to a combination of horizontal and vertical scale, which they perceived as being fronto-parallel. Then, we determined what subjects perceived as being straight-ahead after adaptation.

We used the same procedure for determining straight-ahead as in the DIRECT experiment. The ADAPTATION experiment differed only in three aspects from the DIRECT experiment. First, the trials were not presented in random order in the ADAPTATION experiment, but the untransformed trials were presented first and then the scaled trials. Second, in the ADAPTATION experiment, a scaled stimulus was presented as an adaptation stimulus between the untransformed and the scaled trials. The adaptation stimulus was scaled as much as in the scaled trials that were presented later in the session. Third, the ADAPTATION experiment consisted of five instead of four sessions. During the fifth session, we measured an extra condition, namely 0% vertical scale.

5.3 Results

In a previous experiment, we determined which combination of horizontal and vertical scale subjects perceived as a fronto-parallel surface. We found a specific ratio of horizontal to vertical scale for each individual subject (Berends and Erkelens 2001b). The same experiment was carried out to determine the ratios of horizontal scale to vertical scale used in the adaptation stimuli. The resulting ratios are shown in Table 5.1.

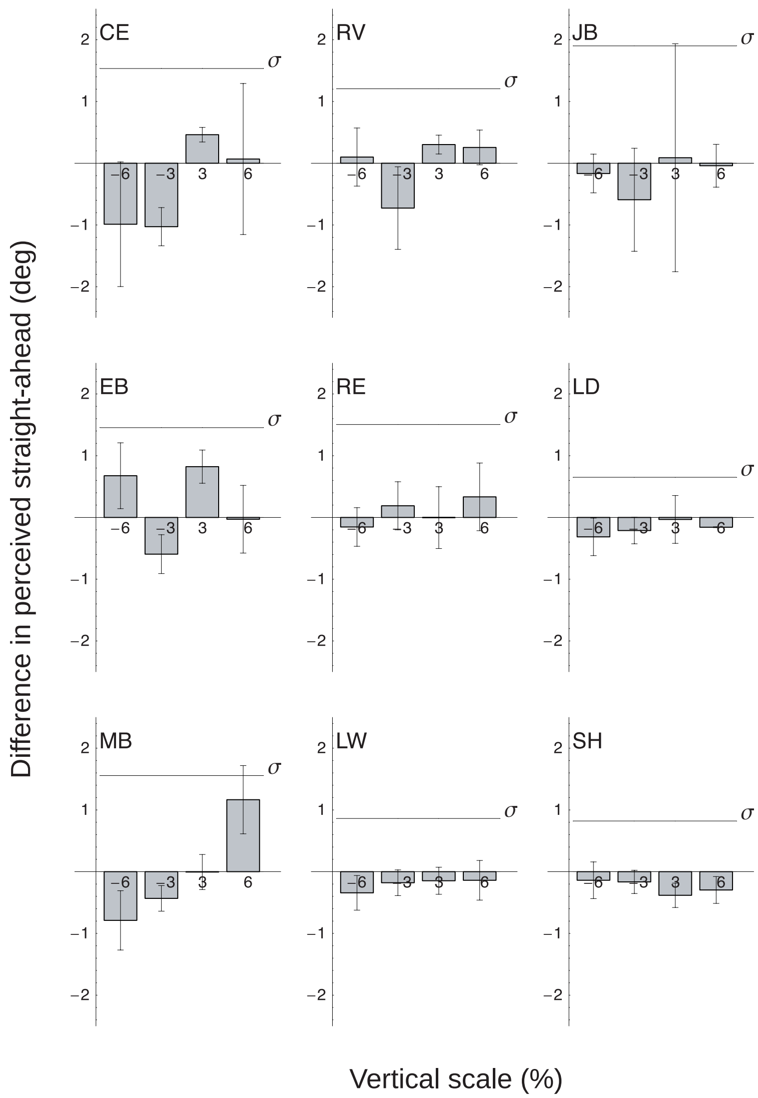

Figure 5.1 - The results of experiment DIRECT. Each panel shows the results for one subject. In each panel, the values on the x-axis represent the amount of vertical scale in the adaptation stimulus in percentages. The heights of the bars represent the change in perceived straight-ahead (μ_{after} - μ_{before}) in degrees. The error bars indicate the accuracy of the measurements and the goodness of fit of the model (psychometric curve) to the data. The solid line represents the average of the sum of the sigma values (μ_{after} + μ_{before}). It indicates the sensitivity of the subject.

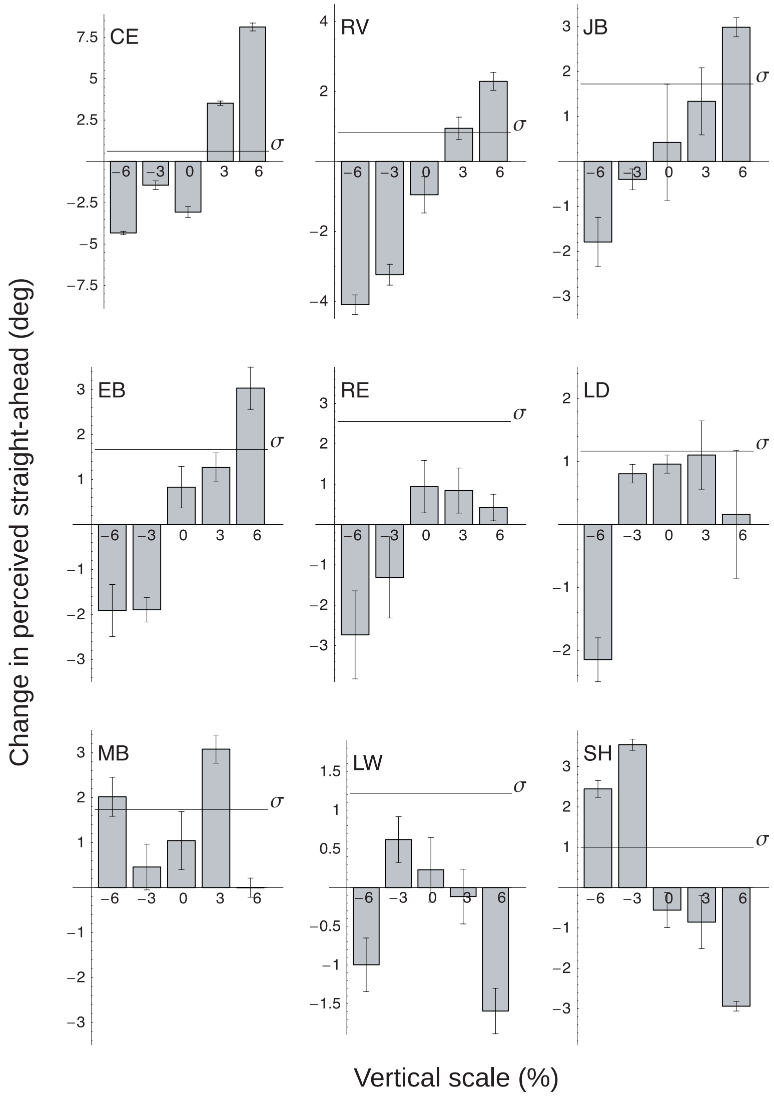

Figure 5.2- Same as Figure 5.1, but for experiment ADAPTATION. Note that the scales on the vertical axes differ for different subjects.

Experiment DIRECT

The MUEST method was applied to find the straight-ahead direction during viewing of a transformed or an untransformed background. Psychometric curves (cumulative normal function) were fitted to the data. We obtained two fit parameters: μ indicates the position on the screen that a subject perceived as lying in the straight-ahead direction and σ indicates how accurately a subject estimated this direction. Monte Carlo simulations were performed to estimate the errors in μ and σ. These errors indicate how accurately the model (psychometric curve) fits the data. The results are depicted in Figure 5.1. The differences in perceived straight-ahead (μ_{after} - μ_{before}) are mainly smaller than the estimated errors (error in μ_{after} + error in μ_{before}), which implies that there was no difference between perceived straight-ahead during viewing of the scaled stimuli and this direction during viewing of the untransformed stimuli.

Linear relations (least squares) were fitted between the differences in perceived straight-ahead and the amounts of vertical scale in the adaptation stimuli for each subject (Table 5.1). None of the slopes of these fits differs significantly from zero ($p > 0.05$), showing that the differences in perceived straight-ahead are not significant in any subjects. Very few of the offsets (for subjects LW and SH) do not differ significantly from zero ($p > 0.05$).

Experiment ADAPTATION

The MUEST method was applied to find the straight-ahead direction before and after adaptation. The processing of the data of experiment ADAPTATION was the same as in experiment DIRECT. The results are shown in Figure 5.2. The changes in perceived straight-ahead (μ_{after} - μ_{before}) are often larger than the estimated errors (error in μ_{after} + error in μ_{before}).

Linear relations (least squares) were fitted between the changes in perceived straight-ahead and the amounts of vertical scale in the adaptation stimuli for each subject (Table 5.1). For five subjects (CE, RV, EB, JB and SH), the slopes of these fits differ significantly from zero ($p < 0.05$), showing that the change in perceived straight-ahead is significant in these subjects. These results show that adaptation to a combination of horizontal and vertical scale can change perceived straight-ahead. In one subject (RE), the slope is significantly different from zero at a slightly lower level of confidence ($p = 0.07$). For subjects CE, RV, EB, JB and RE, the slopes are positive, whereas for SH, the slope is negative. For the other subjects, the slope did not differ significantly from zero. For most subjects, the offsets do not differ significantly from zero ($p > 0.05$).

Two subjects (CE and EB) reported that a group of dots, which appeared straight-ahead at the beginning of the adaptation period, appeared more to the left or more to the right after some time. However, the subjects did not experience any movement. Thus, it seems that the change in perceived direction built up slowly. This agrees with the results of experiment DIRECT.

		Experiment DIRECT Fit			Experiment ADAPTATION Fit		
subject	Ratio	R^2	Slope significant	Offset significant	R^2	Slope significant	Offset significant
CE	0.91	0.76	-	-	0.83	+	-
CE	0.91	0.76	-	-	0.83	+	-
RV	1.10	0.26	-	-	0.98	+	+
EB	0.74	0.00	-	-	0.93	+	-
JB	0.93	0.33	-	-	0.98	+	+
RE	0.40	0.45	-	-	0.70	-	-
LW	0.50	0.70	-	+	0.11	-	-
LD	0.61	0.59	-	-	0.10	-	-
MB	0.71	0.86	-	-	0.03	-	-
SH	0.41	0.72	-	+	0.83	+**	-

*Table 5.1 - The ratios and the fits. All significant slopes are positive, except the slope marked **.*

5.4 Discussion

Conclusion

Our main finding is that perceived straight-ahead did depend on the amount of vertical scale in the stimulus but only after subjects adapted for five minutes (and only in five out of nine subjects).

In experiment DIRECT, we found no significant difference between the perceived straight-ahead directions when subjects viewed scaled and untransformed stimuli. In conclusion, vertical disparity has no immediate influence on perceived direction. This conclusion agrees with the conclusion drawn from the observations of Gillam and Lawergren (1983) and Frisby (1984). They pointed out that vertical magnification of one eye’s image does not change the apparent direction of the stimulus. The explanation given for this negative result is that perceived direction is estimated from eye position signals alone rather than from vertical disparity in combination with other signals (see also Backus et al 1999).

In experiment ADAPTATION, we found that the direction of perceived straight-ahead changed significantly in five out of nine subjects after adaptation to scaled stimuli. Thus, an adaptation period is required to change perceived straight-ahead. We suggest that the sustained presence of unnatural vertical disparity is used to recalibrate the eye position signals.

In the perception of direction, vertical disparity does not alter perceived direction in a immediate fashion. In depth perception, on the other hand, vertical disparity affects perceived depth immediately (Ogle 1938, 1939; Backus et al 1999; Rogers and Bradshaw 1995). Thus, the role of vertical disparity in the perception of direction is different from its role in the perception of depth.

Visually induced change in perceived direction

It is known that perceived direction can change after a period of adaptation. Helmholtz (1911) showed that visually perceived direction could change after prolonged wearing of wedge prisms. After Helmholtz (1911), many researchers investigated adaptation to prisms (see Harris 1965). Many of them used a pointing task in which the hand was visible (for instance Held and Freedman 1963; Welch and Rhoades 1969; Warren 1975). The use of a pointing task involves the measurement of changes in both the proprioceptive system of the arm and the visual system. Therefore, in these experiments it is not clear what was changed. Hay and Pick (1966), Kalil and Freedman (1966), McLaughlin (1967), Craske (1967) and Pick et al (1969) performed a visual test in order to measure the changes in the visual system. They found that adaptation to prisms changed the perceived direction. However, in their task, the hand was visible. Therefore, the conflict between the visual information and the proprioceptive information from the hand may have caused the adaptation.

Ono and Angus (1974) also carried out adaptation experiments in which the perceived direction changed. They measured the change in the felt position of the hand when subjects had closed one eye for a longer period. Thus, in their experiments too, both the change in the proprioceptive system of the arm and the change in visually perceived direction were measured.

In all the above-described adaptation experiments, the proprioceptive system of the hand was involved in the adaptation. In our experiments, on the other hand, subjects could only see the stimulus. Therefore, the origin of adaptation may have been purely visual. However, it is also possible that our results were due to adaptation of the oculomotor system. Kapoula et al (1995) and Van der Steen and Bruno (1995) found that the amplitudes of horizontal and vertical saccades are adapted after presentation of a combination of horizontal and vertical scale. It is likely therefore, that adaptation in the oculomotor system also occurred in our experiments.

There are two types of eye position signals which could be adapted. The first possibility is that the efferent copy of the eye muscle control signal was adapted. If this occurred, then adaptation was solving a conflict between the efferent copy and the vertical disparity. Then, the origin of adaptation must have been purely visual and the adaptation of the oculomotor system must have been a separate phenomenon. The other possibility is that the proprioceptive afferent information of the eye muscle was adapted. If so, then the efferent signals and the amplitudes of saccades must have been adapted via the feedback of the oculomotor system.

Independent data streams?

In stereovision, two methods are used to determine depth (Rogers and Bradshaw 1995; Backus et al 1999;). First of all, depth is determined directly from the combination of horizontal disparity and eye position signals. Secondly, depth is determined from the combination of horizontal disparity and vertical disparity. The weak fusion model (Landy et al 1995) and the estimator reliability model (Backus and Banks 1999) suggest that eye position signals and vertical disparity signals are processed in separate data streams. However, the present results indicate that eye position signals and vertical disparity signals are not independent; one type of signal influences the other. Thus, in stereovision, eye position signals and vertical disparity are not processed as two independent sources of information about depth. Interaction between these two signals occurs at an earlier stage than depth estimation. This is suggested by several models including the strong fusion model (Landy et al 1995) and the headcentric model (Erkelens and Van Ee 1998).

Results versus predictions

In experiment ADAPTATION, we found a change in perceived straight-ahead. In this section, we compare the direction and the magnitude of the change in perceived straight-ahead with our predictions. We can deduce the predicted direction of the effect as follows. A stimulus that is positively scaled has a larger half-image in the left eye than in the right eye. If a subject looks straight-ahead at this stimulus, then vertical disparity indicates that he/she is looking to the left. Likewise, if he/she looks to the right, then vertical disparity indicates that he/she is looking straight-ahead. The conflict between the oculomotor signals and vertical disparity may cause recalibration of the eye-position signals that are used for perception of direction: perceived straight-ahead may move to the right. In four subjects, we did indeed find that adaptation to a positive scale induced a change in perceived straight-ahead to the right. In one subject, we found a change in the opposite direction.

The maximum predicted change in experiment ADAPTATION is equal to the difference between the direction specified by eye position and the direction specified by vertical disparity. This value is the same as the maximum predicted changes in experiment DIRECT (see Introduction), namely 27° and 64° for 3 and 6% vertical scale, respectively. The measured changes in perceived straight-ahead are much smaller than the predicted ones and in some subjects the measured changes in perceived straight-ahead are even zero. Several reasons can be given for this difference. The first reason may be that the maximum adaptation was not be reached yet due to the limited adaptation time (5 minutes). The second reason may be the presence of visual references. For instance, we found that the frame of the anaglyph glasses affected the results in some subjects. We removed this reference, but there were references that could not be removed, for instance the nose and the eyebrows. Different sensitivities of individual subjects to these visual references may explain the differences between subjects. The third reason is that there might be other signals in the brain, which are able to recalibrate the eye position signals. If these signals agree with the eye position signals before adaptation, they will resist adaptation.

An adaptation experiment similar to ours, but with one important difference

Epstein and Daviess (1972) investigated whether perceived straight-ahead changed after subjects had adapted to a meridional size lens. They found no change in perceived direction. The task that their subjects performed was very similar to our task. However, there was an important difference between their experiments and ours. The axis of their lens was vertical. Thus, the lens induced only a horizontal scale. We conclude that vertical scale must be responsible for the change in perceived direction, because horizontal scale alone did not cause a change in perceived direction.

Chapter 6

A re-examination of the headcentric model of stereoscopic depth perception

In this chapter, we re-examine the headcentric model of Erkelens and Van Ee (1998). The model uses correction terms which change the relation between disparity and distance if errors in the eye position signals occur. Erkelens and Van Ee did not derive the correction terms analytically. We do this in the first part of this chapter. One of the three correction terms turns out to be slightly different from the one that was derived from simulations by Erkelens and Van Ee. The effects of this difference were shown by simulations. The second part of the chapter describes simulations that show that the headcentric model can explain many of the results used as evidence for regionally processed vertical disparity. According to the headcentric model, vertical disparity is a global phenomenon. Thus, it is not clear whether vertical disparity is processed regionally or globally.

6.1 Introduction

In this chapter, the model developed by Erkelens and Van Ee (1998) is re-examined. Their model is based on headcentric disparities, which are the differences between the headcentric directions towards an object from the two eyes. In this model, depth follows directly from a simple relationship between headcentric horizontal disparity and headcentric distance. Headcentric vertical disparity is zero unless an error occurs in the oculomotor signals. The headcentric model is able to correct for oculomotor signal errors, because the gradients in the vertical disparity indicate the type and the size of the error. The gradients are used to compute a correction term which is added to the horizontal disparity.

There were various reasons for re-examining the headcentric model. For instance, it seems strange that the headcentric model and the retinal models

(Mayhew and Longuet-Higgins, 1982; Mayhew, 1982; Weinshall, 1990; Liu, *et al.*, 1994; Gårding, *et al.*, 1995) predict different amounts of slant if a stereogram is presented, of which one half-image is vertically scaled relative to the other (Berends and Erkelens, 2001b). It would be interesting to check whether the correction terms were derived accurately. Erkelens and Van Ee determined the correction terms by simulations. In the first part of the present chapter, we derive the correction terms analytically.

Another interesting point is that the headcentric model assumes that vertical disparity is processed globally, whereas several experimental results have been used to demonstrate that vertical disparity is processed regionally (Rogers and Koenderink, 1986; Cagenello and Rogers, 1990; Rogers, 1992; Kaneko and Howard, 1996; Kaneko and Howard, 1997a; Kaneko and Howard, 1997b). Erkelens and Van Ee (1998) showed that their model gives qualitatively correct predictions for globally sheared and scaled images. Berends and Erkelens (2001b) demonstrated that the expectations of the headcentric model agree qualitatively with experimental results. However, it is not certain whether the model can predict the experimental results that indicate that vertical disparity is processed regionally. The percepts induced by these experiments are simulated in the second part of this chapter.

6.2 Part I: The correction terms derived analytically

The headcentric model

The headcentric model (Erkelens and Van Ee, 1998) is described in Helmholtz co-ordinates (Helmholtz, 1911): azimuthal angle (μ), elevational angle (λ) and headcentric distance (r). The azimuthal and elevational angles in both eyes (μ_l, μ_r, λ_l and λ_r) are known. The azimuthal disparity is defined as the difference between the azimuthal components of the two headcentric directions of a specific point in space: $\delta_\mu = \mu_l - \mu_r$. The elevational disparity is defined as the difference between the elevational components of the two headcentric directions: $\delta_\lambda = \lambda_l - \lambda_r$. The depth, which is the headcentric distance, can be determined by the use of the azimuthal disparity (δ_μ). The elevational disparity (δ_λ) is zero if no oculomotor errors occur.

The Helmholtz co-ordinates can be converted into Cartesian co-ordinates and vice versa:

$$\mu = \arctan\left(\frac{x}{\sqrt{y^2+z^2}}\right) \qquad x = r\cdot\sin\mu$$

$$\lambda = \arctan\left(\frac{-y}{z}\right) \qquad y = -r\cdot\cos\mu\cdot\sin\lambda \qquad (6.1)$$

$$r = \sqrt{x^2+y^2+z^2} \qquad z = r\cdot\cos\mu\cdot\cos\lambda$$

The origins of the left and right eye co-ordinate systems are positioned to the left and right of the central origin:

$$x_l = x + \tfrac{1}{2}e \text{ and } x_r = x - \tfrac{1}{2}e \qquad (6.2)$$

The exact relationship between the azimuthal headcentric disparity (δ_μ) and the distance (r) is derived below:

$$\delta_\mu = \mu_l - \mu_r = \tan^{-1}\tan(\mu_l - \mu_r) = \tan^{-1}\frac{\tan\mu_l - \tan\mu_r}{1+\tan\mu_l\cdot\tan\mu_r} =$$

$$\tan^{-1}\frac{e\cdot\sqrt{y^2+z^2}}{x^2+y^2+z^2-\frac{1}{4}e^2} = \tan^{-1}\frac{e\cdot r\cdot\cos\mu}{r^2-\frac{1}{4}e^2} \quad . \qquad (6.3)$$

Often, the approximation for the azimuthal disparity, δ_μ is used:

$$\delta_\mu \approx \frac{e\cdot\cos\mu}{r}. \qquad (6.4)$$

According to the headcentric model, three types of vertical disparity fields are relevant for stereoscopic depth perception, namely the vertical disparity fields induced by errors in the horizontal vergence, in the horizontal version and in the cyclovergence signals. These types of oculomotor errors evoke a gradient in the vertical disparity field. The direction of the gradient depends on the type of oculomotor error. The other three types of oculomotor errors (i.e. errors in vertical version and vergence and cycloversion signals) do not induce a gradient in the vertical disparity field. The correction terms are derived analytically in the sections below. Four approximations are used frequently in the derivations:

I. The error in the eye position signal, α is small. Small angle, α. Then $\sin^2\alpha \approx 0$, $\cos\alpha \approx 1$ and $\sin\alpha \approx \alpha$.

II. $\alpha\cdot e << z$. Thus, $\alpha\cdot e$ is neglected.

III. $\sqrt{1+\varepsilon} \approx 1+\tfrac{1}{2}\varepsilon$ for small ε.

IV. The small baseline approximation: $e^2 << r^2$. Thus, e^2 is neglected.

Horizontal vergence signal error

If the vergence signals are not passed on accurately to the visual system, a horizontal vergence signal error occurs. This means that the horizontal headcentric directions in both eyes have an error of the same size but in the opposite direction. Thus, the headcentric directions of both eyes are rotated about the y-axis in opposite directions. This results in the following Cartesian co-ordinates:

$$\begin{aligned} x_l &= (x+\tfrac{1}{2}e)\cdot\cos\alpha + z\cdot\sin\alpha & x_r &= (x-\tfrac{1}{2}e)\cdot\cos\alpha - z\cdot\sin\alpha \\ y_l &= y & y_r &= y \\ z_l &= z\cdot\cos\alpha - (x+\tfrac{1}{2}e)\cdot\sin\alpha & z_r &= z\cdot\cos\alpha + (x-\tfrac{1}{2}e)\cdot\sin\alpha \end{aligned} \qquad (6.5)$$

If there is an error in the horizontal vergence signal, elevational disparity is not zero:

$$\delta_\lambda \approx \frac{\tan\lambda_l - \tan\lambda_r}{1+\tan\lambda_l\cdot\tan\lambda_r} = \frac{y_l\cdot z_r - y_r\cdot z_l}{y_l\cdot y_r + z_l\cdot z_r} = \frac{-2\cdot y\cdot x\cdot\sin\alpha}{y^2 + (z\cdot\cos\alpha - \frac{1}{2}e\cdot\sin\alpha)^2 - x^2\cdot\sin^2\alpha}. \qquad (6.6)$$

The formula for elevational disparity can be simplified for small horizontal vergence signal errors, α (approximation I and II) and the fact that x and y have the same order of magnitude. Thus, $\delta_\lambda \approx 2\cdot\alpha\cdot\tan\mu\cdot\sin\lambda$. The full-field gradients in the elevational and the azimuthal directions are equal to zero, but the second-order full-field gradient is not:

$$E_{\mu\lambda} = 2\cdot\alpha\,. \qquad (6.7)$$

The azimuthal disparity is more complicated in the presence of oculomotor errors. If a horizontal vergence signal error occurs, the azimuthal disparity is:

$$\delta_\mu \approx \frac{\tan\mu_l - \tan\mu_r}{1+\tan\mu_l\cdot\tan\mu_r} = \frac{x_l\cdot\sqrt{y_r^{\,2}+z_r^{\,2}} - x_r\cdot\sqrt{y_l^{\,2}+z_l^{\,2}}}{x_l\cdot x_r + \sqrt{y_l^{\,2}+z_l^{\,2}}\cdot\sqrt{y_r^{\,2}+z_r^{\,2}}}\,. \qquad (6.8)$$

Approximations I and III are used to reduce the square roots. The approximated roots are:

$$\begin{aligned} \sqrt{y_l^{\,2}+z_l^{\,2}} &\approx r\cdot\cos\mu - \alpha\cdot\cos\lambda\cdot\left(r\cdot\sin\mu + \tfrac{1}{2}e\right) \\ \sqrt{y_r^{\,2}+z_r^{\,2}} &\approx r\cdot\cos\mu + \alpha\cdot\cos\lambda\cdot\left(r\cdot\sin\mu - \tfrac{1}{2}e\right)\ . \end{aligned} \qquad (6.9)$$

The approximation that the horizontal vergence signal error is small is applied to both x_l and x_r. Then, the azimuthal disparity is further simplified by the use of approximations I, II and IV.

$$\delta_\mu = \frac{e\cdot\cos\mu}{r} + 2\cdot\alpha\cdot\cos\lambda\,. \qquad (6.10)$$

The correction term is the difference between the azimuthal disparity in the absence of an oculomotor error and the azimuthal disparity in the presence of a horizontal vergence signal error:

$$\delta_c = \frac{e\cdot\cos\mu}{r} - \left(\frac{e\cdot\cos\mu}{r} + 2\cdot\alpha\cdot\cos\lambda\right) = -2\cdot\alpha\cdot\cos\lambda\,. \qquad (6.11)$$

The correction term in terms of gradients is:

$$\delta_c = -E_{\mu\lambda} \cdot \cos\lambda . \tag{6.12}$$

The analytically derived correction term agrees with the one derived by Erkelens and Van Ee (1998).

Horizontal version signal error

If the version signals are not passed on accurately to the visual system, an error occurs in the horizontal version signal. Then, the horizontal headcentric directions in both eyes will have an error of the same size and in the same direction. Thus, the headcentric directions of both eyes are rotated about the y-axis in the same direction. The viewing direction also has an error of about the same size. Therefore, the central co-ordinate system, which has its origin in the cyclopean eye, rotates over about the same angle:

$$\begin{aligned} x_n &= x \cdot \cos\alpha + z \cdot \sin\alpha = r \cdot \sin\mu \\ y_n &= y = -r \cdot \cos\mu \cdot \sin\lambda \\ z_n &= z \cdot \cos\alpha - x \cdot \sin\alpha = r \cdot \cos\mu \cdot \cos\lambda \end{aligned} \tag{6.13}$$

This results in the following Cartesian co-ordinates for the left and right eye:

$$\begin{aligned} x_l &= (x + \tfrac{1}{2}e) \cdot \cos\alpha + z \cdot \sin\alpha = x_n + \tfrac{1}{2}e \cdot \cos\alpha \\ y_l &= y = y_n \qquad\qquad (left) \\ z_l &= z \cdot \cos\alpha - (x + \tfrac{1}{2}e) \cdot \sin\alpha = z_n - \tfrac{1}{2}e \cdot \sin\alpha \\ x_r &= (x - \tfrac{1}{2}e) \cdot \cos\alpha + z \cdot \sin\alpha = x_n - \tfrac{1}{2}e \cdot \cos\alpha \\ y_r &= y = y_n \qquad\qquad (right) \\ z_r &= z \cdot \cos\alpha - (x - \tfrac{1}{2}e) \cdot \sin\alpha = z_n + \tfrac{1}{2}e \cdot \sin\alpha \end{aligned} \tag{6.14}$$

The elevational disparity is not zero if an error occurs in the horizontal version signal:

$$\delta_\lambda \approx \frac{\tan\lambda_l - \tan\lambda_r}{1 + \tan\lambda_l \cdot \tan\lambda_r} = \frac{y_l \cdot z_r - y_r \cdot z_l}{y_l \cdot y_r + z_l \cdot z_r} = \frac{y_n \cdot e \cdot \sin\alpha}{{y_n}^2 + {z_n}^2 - \frac{1}{4}e^2 \cdot \sin^2\alpha} . \tag{6.15}$$

If formula 6.13 is substituted in formula 6.15, the elevational disparity induced by errors in the horizontal version signal turns out to depend on the visual scene (r):

$$\delta_\lambda \approx \frac{y_n \cdot e \cdot \sin\alpha}{{y_n}^2 + {z_n}^2 - \frac{1}{4}e^2 \cdot \sin^2\alpha} \approx \frac{-\sin\lambda \cdot e \cdot \sin\alpha}{r \cdot \cos\mu} . \tag{6.16}$$

Therefore, the gradients depend on the situation. If a subject watches a fronto-parallel screen at distance z_s, then:

$$\delta_\lambda \approx \frac{-e \cdot \alpha \cdot \sin\lambda \cdot \cos\lambda}{z_s} . \tag{6.17}$$

If formula 6.17 is substituted in formula 6.16 and approximation I is applied (small horizontal version signal error), the elevational disparity is:

$$\delta_\lambda \approx \frac{-e \cdot \alpha \cdot \sin\lambda \cdot \cos\lambda}{z_s}. \quad (6.18)$$

The gradient in the elevational direction is

$$E_\lambda = -e \cdot \alpha / z_s. \quad (6.19)$$

If a horizontal version signal error occurs, the azimuthal disparity is:

$$\delta_\mu \approx \frac{x_l \cdot \sqrt{y_r^2 + z_r^2} - x_r \cdot \sqrt{y_l^2 + z_l^2}}{x_l \cdot x_r + \sqrt{y_l^2 + z_l^2} \cdot \sqrt{y_r^2 + z_r^2}} = \frac{e \cdot \alpha \cdot \sin\mu \cdot \cos\lambda + e \cdot \cos\mu}{r}. \quad (6.20)$$

Approximations I, III and IV were used to obtain this result. The r in this formula belongs to a co-ordinate system which is rotated over an angle α (see formula 6.13).
We determine the correction term for a special case where the subject watches a fronto-parallel screen. The relation between r and the screen distance, z_s is:

$$r = \frac{z_s}{\cos\mu \cdot \cos\lambda + \alpha \cdot \sin\mu}. \quad (6.21)$$

Substituting r in the azimuthal disparity gives:

$$\delta_\mu \approx \frac{e \cdot \cos^2\mu \cdot \cos\lambda + e \cdot \alpha \cdot \sin\mu \cdot \cos\mu \cdot \left(\cos^2\lambda + 1\right)}{z_s}. \quad (6.22)$$

The azimuthal disparity in the absence of an oculomotor error is:

$$\delta_\mu = \frac{e \cdot \cos^2\mu \cdot \cos\lambda}{z_s}. \quad (6.23)$$

The correction term is the difference between the azimuthal disparity in the absence of an oculomotor error and the azimuthal disparity in the presence of a horizontal version signal error:

$$\delta_c = -\frac{e \cdot \alpha \cdot \sin 2\mu \cdot \left(1 + \cos^2\lambda\right)}{2z_s} = \tfrac{1}{2} \cdot \sin 2\mu \cdot \left(1 + \cos^2\lambda\right) \cdot E_\lambda. \quad (6.24)$$

The analytically derived correction term differs slightly from the correction term derived by Erkelens and Van Ee (1998). Their correction term is:

$$\delta_c = \sin 2\mu \cdot \cos\lambda \cdot E_\lambda \quad (6.25)$$

The correction terms for horizontal version signal errors can only be used in special cases (fronto-parallel surfaces).

The error in the depth percept is repaired by means of the correction, but the error in the viewing direction still exists after using the correction term. It is possible that the visual system corrects for this error because the error in the viewing direction, α, is known (from E_λ and $\delta_\mu(\mu = 0, \lambda = 0)$). The correction might consist of a rotation of the headcentric co-ordinate system over an angle −α. However, we (Berends, Van Ee and Erkelens, 2001) found that perceived straight-ahead did not depend on the amount of scale in the stimulus. In that paper, we concluded that a vertical disparity field with a gradient in the vertical direction does not influence the perceived direction. Thus, if a horizontal version error occurs, then the perceived depth is corrected, but the perceived direction is not.

Cyclovergence signal error

We derived the correction term induced by cyclovergence signal errors only for the case where the fixation point is at infinity and straight ahead. The fixation point was chosen at this location because it is not known how the visual system transforms retinal co-ordinates into headcentric co-ordinates. The transformation consists of three rotations, namely horizontal and vertical rotations and a rotation around the visual axis. The rotations are not commutative and it is not known in which order they are processed by the visual system. However, we assume that the transformation of retinal to headcentric co-ordinates is not dependent on eye position. Then, an error in the cyclovergence signals is related to a rotation around the z-axis, i.e. the visual axis when the fixation point lies at infinity and straight-ahead. The headcentric co-ordinate systems of both eyes are rotated about the z-axis in the opposite direction if an error occurs in the cyclovergence signal. This results in the following Cartesian co-ordinates:

$$\begin{aligned} x_l &= (x+\tfrac{1}{2}e)\cdot\cos\alpha + y\cdot\sin\alpha & x_r &= (x-\tfrac{1}{2}e)\cdot\cos\alpha - y\cdot\sin\alpha \\ y_l &= y\cdot\cos\alpha - (x+\tfrac{1}{2}e)\cdot\sin\alpha & y_r &= y\cdot\cos\alpha + (x-\tfrac{1}{2}e)\cdot\sin\alpha \\ z_l &= z & z_r &= z \end{aligned} \qquad (6.26)$$

The elevational disparity is not zero if the cyclovergence signal is incorrect:

$$\begin{aligned} \delta_\lambda &\approx \frac{y_l\cdot z_r - y_r\cdot z_l}{y_l\cdot y_r + z_l\cdot z_r} = \frac{-2\cdot z\cdot x\cdot\sin\alpha}{z^2+(y\cdot\cos\alpha-\tfrac{1}{2}e\cdot\sin\alpha)^2 - x^2\cdot\sin^2\alpha} \\ &\approx \frac{-2\cdot z\cdot x\cdot\alpha}{z^2+y^2} = -2\cdot\alpha\cdot\tan\mu\cdot\cos\lambda \quad . \end{aligned} \qquad (6.27)$$

Approximations I and II and the fact that x and y have the same order of magnitude are used to obtain this result. The gradient in the azimuthal direction is non-zero, whereas the other two gradients are zero.

$$E_\mu = -2\alpha \qquad (6.28)$$

If a cyclovergence signal error occurs and if approximations I, II, III and IV are applied, then the azimuthal disparity is:

$$\delta_\mu \approx \frac{x_l\cdot\sqrt{{y_r}^2+{z_r}^2} - x_r\cdot\sqrt{{y_l}^2+{z_l}^2}}{x_l\cdot x_r + \sqrt{{y_l}^2+{z_l}^2}\cdot\sqrt{{y_r}^2+{z_r}^2}} \approx \frac{e\cdot\cos\mu}{r} + 2\cdot\alpha\cdot\sin\lambda\,\cdot \qquad (6.29)$$

The correction term is the difference between the azimuthal disparity in the absence of errors and the azimuthal disparity in the presence of a cyclovergence signal error:

$$\delta_c = \frac{e \cdot \cos\mu}{r} - \left(\frac{e \cdot \cos\mu}{r} + 2 \cdot \alpha \cdot \sin\lambda\right) = -2 \cdot \alpha \cdot \sin\lambda = E_\mu \cdot \sin\lambda \,. \tag{6.30}$$

The analytically derived correction term agrees with the one derived by Erkelens and Van Ee (1998).

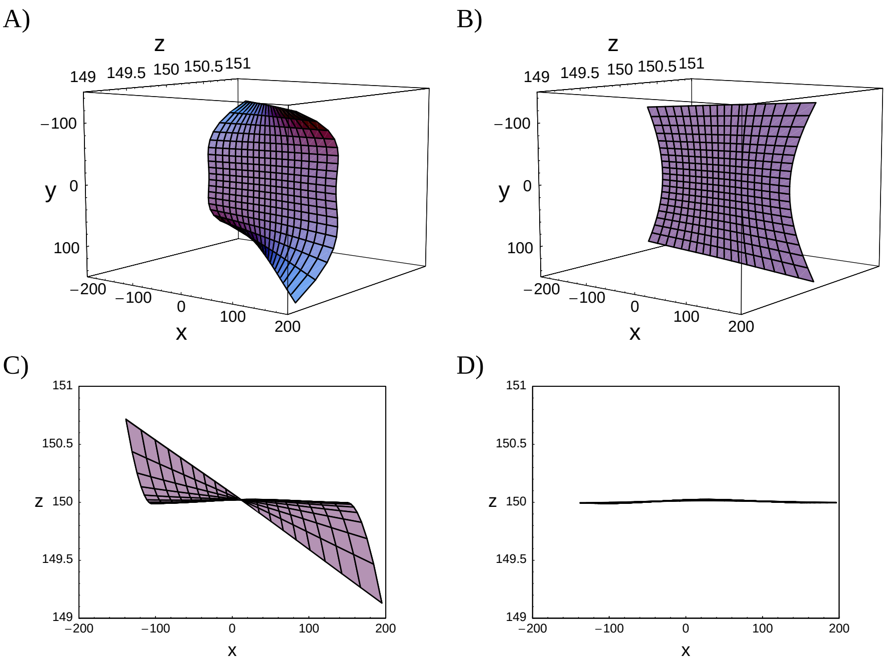

Figure 6.1 - The reconstructed percepts of a fronto-parallel surface if a horizontal version error of 5 degrees occurs. Panels A and B show the reconstructed surfaces computed by the past and the present correction term, respectively. Panels C and D are the top views of panels A and B respectively. The surface is at a distance of 150 cm. The inter-ocular distance is 6.5 cm. x, y and z are expressed in cm. Note that the z-axis scale differs from the x- and y-axis scale.

Effects of the difference between the earlier and the current derivation

One analytically derived correction term differs from the correction term derived by Erkelens and Van Ee (1998), namely, the correction term for gradients in the elevational direction (formulas 28 and 29). In everyday life, a vertical disparity field with a gradient in the elevational direction can be induced by an error in the horizontal version signal. In an experimental set-up, such a vertical disparity field can be evoked by one vertically scaled image. We show the impact of the difference between the two correction terms for these two cases. Two simulations were carried out. Firstly, an error in the horizontal version signals of 5 degrees was simulated. The reconstructed percepts were computed of a fronto-parallel surface at a distance of 150 cm with the help of the present and the earlier correction terms (Figure 6.1). The percept computed by means of the present correction term deviates only slightly from flat, namely by 0.001 cm (Figure 6.1B and D), whereas the percept computed by means of the earlier correction term is more curved (Figure 6.1A and C). The maximum deviation from a flat surface is 0.9 cm for these parameters.

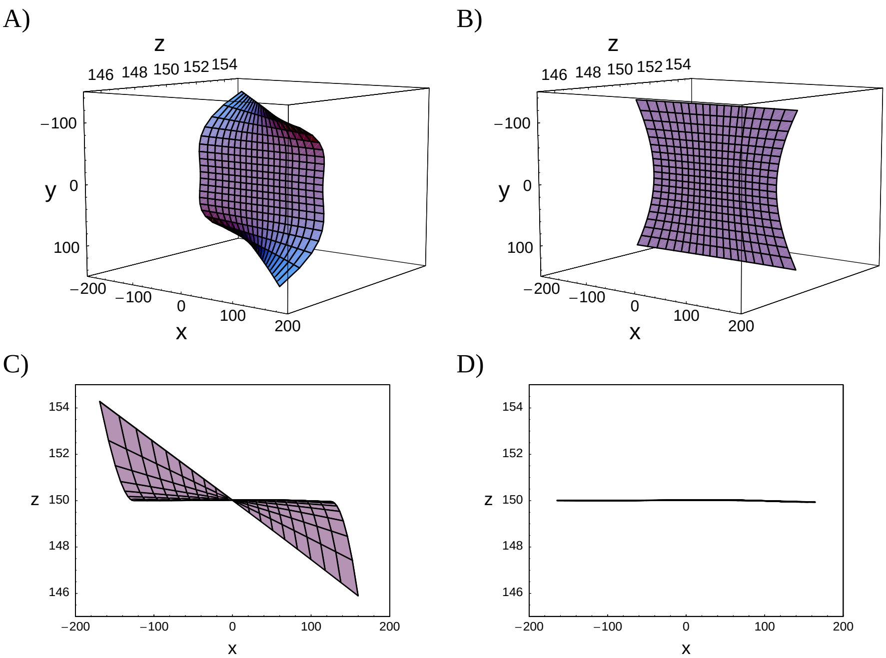

Figure 6.2 - Same as Figure 6.1, but for the reconstructed percepts of a fronto-parallel stereogram which is both horizontally (4%) and vertically (2%) scaled.

Secondly, a stereogram that was both vertically (2%) and horizontally scaled (4%) was simulated. The reconstructed percepts were computed of a fronto-parallel stereogram at a distance of 150 cm by means of the present and the past correction terms (Figure 6.2). The present correction term results in an almost flat surface (Figure 6.2B and D), whereas the past correction term results in a surface that is more curved (Figure 6.2A and C). For these amounts of scale, the maximum deviation from a flat surface is 0.07 cm and 4.27 cm for the present and earlier correction term, respectively.

In conclusion, the effects induced by the differences between the earlier and the current derivation of the correction term relating to the vertical disparity field with a gradient in the elevational direction are small. The reconstructed percepts differ from each other only slightly (by a few centimetres). Probably the improved model is more accurate than the visual system itself.

6.3 Part II: Evidence for regionally processed vertical disparity?

Introduction

In studies about retinal disparity, slant caused by vertical scale is considered to be a regional effect (Rogers and Koenderink, 1986; Gårding, *et al.*, 1995; Kaneko and Howard, 1996; Kaneko and Howard, 1997a). Regional means that at each location of the visual field, slant is influenced by the vertical disparity in a retinal region around this location. Here, it will be shown that various effects which have been regarded as proof that vertical disparity evoked by vertical scale is a regional effect can be explained by the headcentric model of Erkelens and Van Ee (1998). It might well be that vertical disparity processing is not a regional phenomenon but purely a global phenomenon after all.

The effects that have been used as evidence for regional vertical disparity processing can be subdivided into two groups. First of all, there are the effects that can be attributed to one of the vertical disparity fields induced by oculomotor errors, namely the field with a gradient in both horizontal and vertical direction. Secondly, there are the effects that can be explained by horizontal disparity alone. In the headcentric model, the co-ordinate system is not orthogonal. Therefore, a vertical transformation on the screen evokes also some change in the horizontal disparity field.

Depth effects induced by a vertical disparity field with a gradient in two directions

A stimulus is perceived as a vertical cylinder if the horizontal disparity field is related to a fronto-parallel plane and the vertical disparity field has a gradient in both the horizontal and vertical direction (Rogers and Bradshaw, 1993; Rogers and Bradshaw, 1995; Adams, *et al.*, 1996; Berends and Erkelens, 2001b). Perceiving a cylinder is very like perceiving two opposite slants about the vertical axis that are located next to each other with a fluent transition in between.

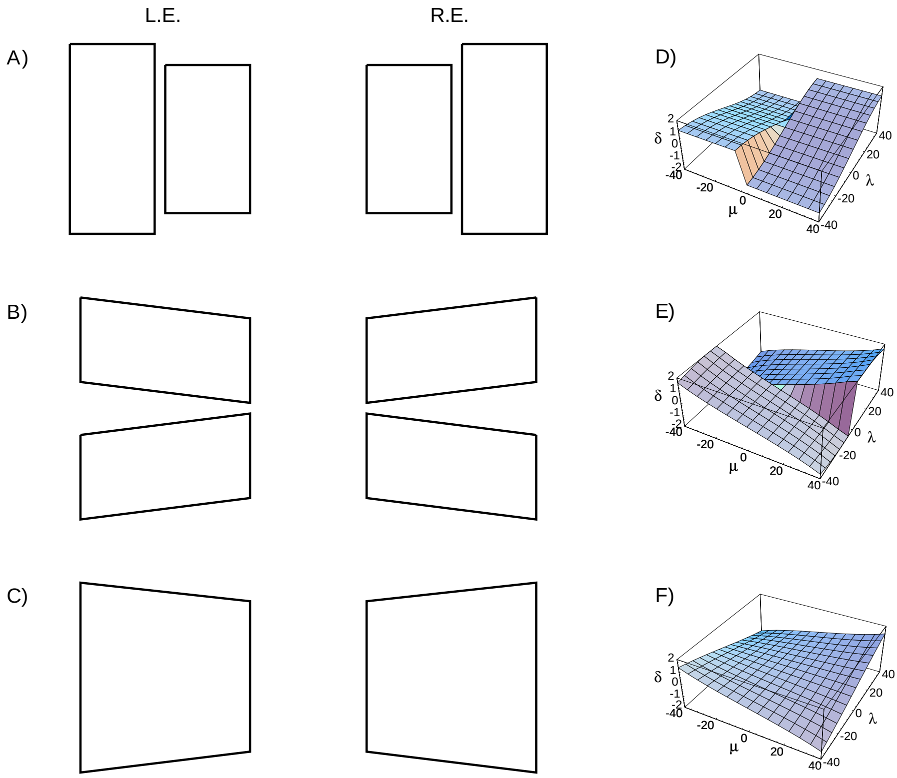

Figure 6.3 - A: Stimulus used in experiments where an opposite vertical scale has been applied in the left and right part of the visual field. Below L.E. the left eye half image is shown and below R.E. the right eye half image is shown. - B: Stimulus where an opposite shear has been applied in the top and bottom part of the visual field. - C: Stimulus used in the present experiments, i.e. the vertical quadratic mix field - D, E and F: The vertical disparity (δ) fields of the stimulus shown in A, B and C respectively. The azimuthal angle (μ), the elevational angle (λ) and δ are expressed in degrees.

Rogers and Koenderink (1986) and Kaneko and Howard (1996) divided the image on the screen into a left and a right half-field. The two half-fields were vertically scaled in opposite directions (Figure 6.3A). Rogers and Koenderink (1986) reported that both half-fields were slanted about the vertical axis in opposite directions. Kaneko and Howard (1996) measured the amount of slant about the horizontal axis which was induced by the oppositely scaled half-fields. The subjects of their experiment reported that the border between the two abutting areas did not look sharp. These results become comprehensible if we compare the vertical disparity fields which were induced by the stereogram they used (Figure 6.3A and D) with the field induced by a quadratic mix transformation (Figure 6.3C and F). The vertical disparity fields are quite similar, particularly, if vertical disparity is considered to be processed globally. Figure 6.3B shows a third stereogram, which is oppositely sheared in the top and bottom half-fields. The vertical disparity field elicited by this stereogram (Figure 6.3E) is rather similar to the other two disparity fields and should evoke the same percept.

Conclusion

Both the vertical headcentric disparity field induced by two opposite vertical scales next to each other and by two opposite shears below each other are very similar to the disparity field induced by the vertical quadratic mix transformation. Therefore the experiments of Rogers and Koenderink and Kaneko and Howard do not prove that vertical disparity is processed regionally.

Experiment

It is difficult to distinguish between the two different theories of vertical disparity processing, namely the regional and the global headcentric theory. According to the regional theory, the quadratic mix stimulus consists of several regional vertical scale stimuli next to each other with different scale factors. Therefore, the regional theory predicts a high correlation between the strengths of the depth effects induced by scale and quadratic mix.

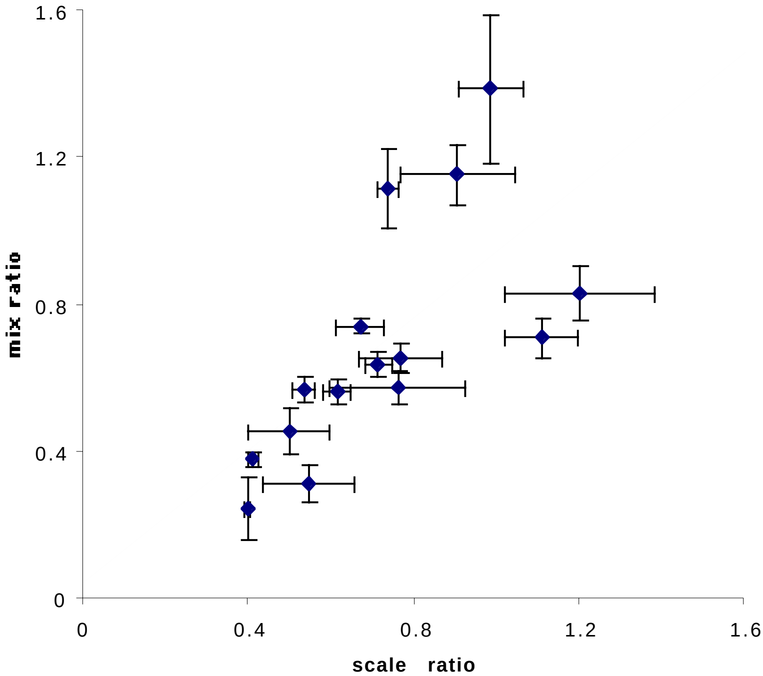

Figure 6.4 - The quadratic mix ratios plotted against the scale ratios. Each point represents one subject.

The headcentric model, on the other hand, predicts that the strengths of the depth effects induced by scale and quadratic mix are uncorrelated, because the vertical disparity fields induced by the both types of stimuli are related to different oculomotor signals. We (Berends and Erkelens, 2001b) measured the strengths of the depth effects induced by both vertical disparity fields in four subjects by means of a nulling method. We found that the nulling ratios depend on the subject and on the type of disparity field. The determination of a correlation coefficient between the quadratic mix and the scale ratios requires a large number of subjects. Therefore, we repeated these experiments for fifteen subjects. Figure 6.4 shows the results of this experiment. The correlation is rather high (R^2 = 0.46) and significant ($p < 0.01$). This result indicates that the vertical disparity fields induced by vertical scale and the quadratic mix field are not independent. Thus, we conclude that there is some evidence to support the view that vertical disparity processing is regional.

Depth effects that can be interpreted by horizontal headcentric disparity alone

The following sections deal with the second type of depth effects, which are considered as evidence for regionally processed vertical disparity, namely depth effects that can be interpreted by horizontal headcentric disparity alone. In the headcentric model, the co-ordinate system is not orthogonal. Therefore, a purely vertical transformation on the screen of one half-image relative to the other one not only induces a change in vertical disparity, but also evokes some change in the horizontal disparity field. Consequently, vertical transformations that do not induce a vertical disparity field with a global gradient can still evoke some depth effects. Some of these depth effects were used as evidence that vertical disparity is processed regionally. We subdivided these effects into three types. Below we describe three simulations which show that these effects can be explained by horizontal disparity alone.

The first simulation involves depth effects induced by vertical scale. Kaneko and Howard (1996) applied an opposite vertical scale to the top and the bottom part of an image. Subjects perceived this as a different slant about the vertical axis in the top and bottom part with a very smooth transition in between. According to their theory, vertical scale works regionally. We used the headcentric model to reconstruct the percept induced by opposite vertical scale in the top and bottom half-field of the visual field (Figure 6.5A). The simulation was carried out as follows. The headcentric horizontal and vertical disparity fields were calculated (Figure 6.5A1 and A2). Figure 6.5A2 shows that the global gradients in vertical disparity are zero in each direction. Therefore, according to the headcentric model, vertical disparity does not contribute to the depth percept and the reconstructed percept depends on the horizontal disparity only. The predicted percept (Figure 6.5A3 and A4) is a saddle figure, which can also be described as two opposite slants about the vertical axis in the top and bottom part of the image with a very smooth transition in between.

The second simulation was performed to examine depth effects elicited by vertical shear. Cagenello and Rogers (1990) designed a stimulus with equal and opposite vertical shears in different parts of the visual field. It is not clear whether these parts were depicted next to each other or below each other. Anyway, a slight differential slant was perceived. Rogers (1992) presented two half images next to each other with an opposite shear using a very small view angle (12 degrees per half-image). A small difference in slant about the horizontal axis between the two half-images was still measured. Probably these view angles were too small for the perception of any effect of vertical disparity.

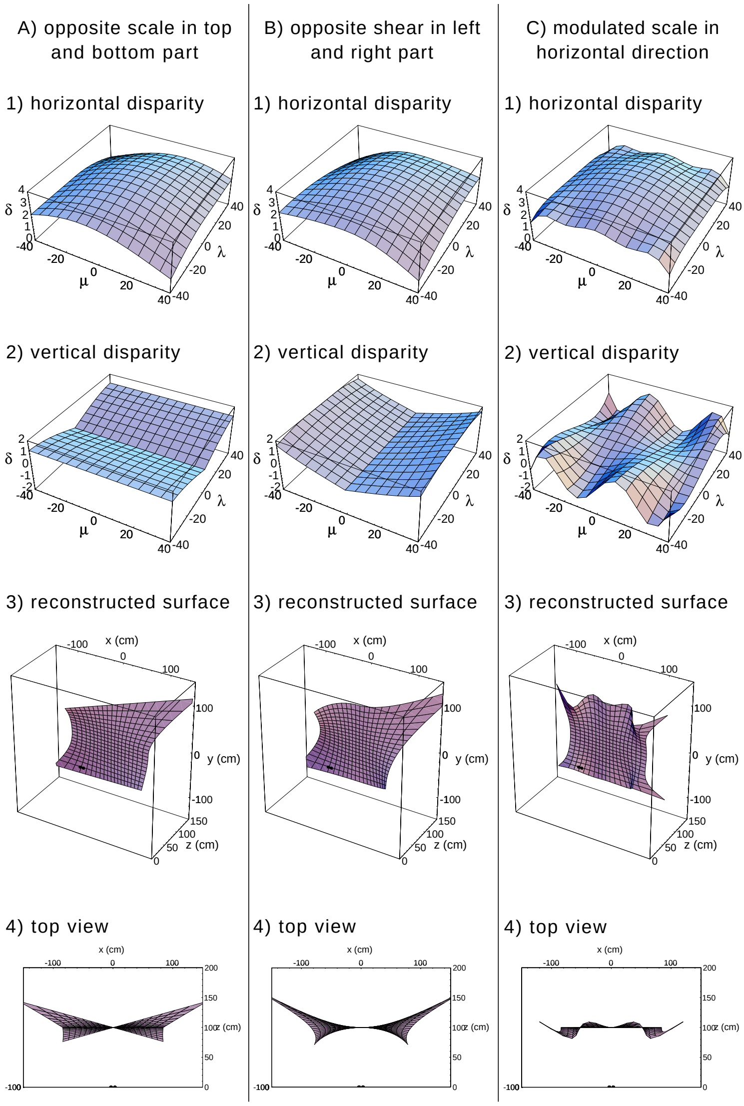

Figure 6.5 - The results of the three simulations. Each column shows the horizontal disparity (1), the vertical disparity (2) of which the global gradient is zero, the percept (3) which has been reconstructed based purely on the horizontal disparity, a top view of the percept (4). Simulation A demonstrates an opposite vertical scale in the top and bottom part of the image. Simulation B demonstrates an opposite vertical shear in the left and right part of the image. Simulation C demonstrates a sinusoidal modulated vertical scale in the horizontal direction. Disparity (δ), azimuthal angle (μ) and elevational angle (λ) are expressed in degrees.

We performed a simulation with two opposite shears in the left and right half-field (Figure 6.5B). The horizontal and vertical headcentric disparities were determined (Figure 6.5B1 and B2). The vertical disparity has no overall gradient (Figure 6.5B2). Thus, the reconstructed percept (Figure 6.5B3 and B4) depends purely on horizontal disparity. The expected percept is a saddle figure which can be described as opposite slants about the horizontal axis in the left and right part of the image with a very smooth transition in between.

The third simulation involves depth effects evoked by modulated vertical scale. Kaneko and Howard (1997a) applied a sinusoidal modulation in the horizontal direction of a vertical scale. They compared the percept induced by this vertical transformation with the percept induced by a horizontal sine-shaped transformation. They reported that a waveform elicited by vertical disparity was perceived up to a frequency of 0.04 cycle per degree. We simulated such a modulation Figure 6.5C). Horizontal and vertical headcentric disparity (Figure 6.5C1 and C2) were calculated. The vertical disparity field had no influence on the reconstructed depth percept, because it has no global gradient in any direction. The predicted Figure 6.5C3 and C4) is a wave pattern. The amplitude of this wave pattern depends on the vertical distance. This waveform differs slightly from the waveform that was induced by the horizontal sine-shaped transformation, because that waveform had a constant amplitude.

Conclusions

The simulations show that the above-mentioned experiments cannot be regarded as evidence against the global processing of vertical disparity. The experiments were interpreted as evidence against full-field integration of vertical disparity, because the experimenters assumed that vertical transformations on the screen do not change the horizontal disparity. In other words, horizontal and vertical disparities were assumed to be orthogonal. The validity of this assumption depends on the co-ordinate system. For instance, it does not hold for the Helmholtz co-ordinate system, which is used by the headcentric model.

Other depth effects that can be interpreted by the headcentric model

In the sections above, several examples were given of results that are used to prove that vertical disparity operates regionally, but which can also be described by the headcentric model. According to the headcentric model, these results were explained by one effect. In addition to the given examples, there are results that can be explained by more than one effect. These types of experiments were, for example, performed with stimuli with a vertical transformation in one half of the visual field and no transformation in the other half.

Kaneko and Howard (1997b) applied stimuli with the half-fields next to each other. They applied a vertical shear in one half and no screen disparity in the other half. They measured the perceived slant about the horizontal axis of both halves and found that the slant depended on the position of the shearing axis. The slant did not depend on the half-field. They explained their results by stating that subjects take the average value of vertical shear disparity around the fixation point. According to the headcentric model, the vertical disparity has only a gradient in the horizontal direction. This gradient causes slant about the horizontal axis. Furthermore, in the corners of the visual field horizontal disparity causes some changes in depth, as in the saddle figures (see Figure 6.5A3 and B3). In Kaneko and Howard's experiment, the stimuli were circular. Therefore, the corners were not visible and subjects perceived one slant for both half-fields. If the shearing axis is shifted towards the middle of the sheared half-field, the global gradient decreases; this prediction agrees with the findings of Kaneko and Howard.

Pierce and Howard (1997) performed an experiment in which they applied a vertically scaled half-field below an untransformed half-field. They found different slants in the top and in the bottom part. The headcentric model predicts a saddle figure-shaped percept that is slanted about the vertical axis. The vertical disparity has only a gradient in the vertical direction. This gradient causes slant about the vertical axis. The horizontal disparity induces the saddle figure-shape. Thus, according the headcentric model, the percept induced by the stimulus of Pierce and Howard (1997) is similar to the percept induced by the above-described stimulus of Kaneko and Howard (1997b). The differences in percept between both experiments may be explained by the fact that Pierce and Howard (1997) chose a square-shaped stimulus. Then, the corners influenced the percept.

Howard and Pierce (1998) also performed an experiment with a vertically sheared half-field below an untransformed half-field. This stimulus induces a horizontal gradient in the headcentric vertical disparity. Furthermore, it induces a gradient in both the horizontal and vertical direction. According to the headcentric model, the two gradients induce two effects, namely curvature in the horizontal direction and slant about the horizontal axis. Howard and Pierce measured only the slant about the horizontal axis and they found a small difference in slant. The difference may be explained by the fact that some subjects perceive curvature not only in the horizontal direction but also in the vertical direction when a quadratic mix field is presented (Adams, *et al.*, 1996; Berends and Erkelens, 2001b).

6.4 Discussion

Correction terms derived analytically

Erkelens and Van Ee (1998) proposed a model for stereoscopic depth perception based on headcentric disparity. The headcentric model corrects for oculomotor errors. Erkelens and Van Ee determined the correction terms by simulations. We have been able to derive the correction terms analytically. The analytically derived correction terms for horizontal vergence errors and for cyclovergence errors were found to agree with the correction terms that were determined by simulations. The analytically derived correction term for horizontal version errors, however, is slightly more accurate than the correction term determined by simulations.

Correction term for horizontal version errors for fronto-parallel surfaces only

We derived the correction term for fronto-parallel planes only. For visual scenes other than fronto-parallel planes, horizontal version errors are not corrected exactly by the headcentric model. For slanted surfaces, this is not really a problem, because the inaccurate correction term causes an error of only few centimetres in the percept. Larger problems arise when a visual scene contains large differences in distance. However, when there are large differences in distance, one has to make eye movements in order to see everything sharply. Then, eye movements can be used to solve the problem of the inaccurate correction term.

Adaptation may solve the above-described problem that the correction term is only valid for depth corrections of fronto-parallel planes. The vertical disparity field induced by a horizontal version error causes adaptation of the visual system (Berends and Erkelens, 2001a). We (Berends and Erkelens, 2001a; Berends, *et al.*, 2001) suggested that adaptation means the recalibration of the eye position signals. If recalibration of the eye position signals occurs, then the vertical disparity field and the correction term become zero. Then, the percept becomes correct, because the correction term is no longer involved.

Different scale predictions for headcentric model and other models

If a stereogram is presented, of which one half-image is vertically scaled relative to the other, then the amounts of slant predicted by many retinal models (Mayhew and Longuet-Higgins, 1982; Mayhew, 1982; Weinshall, 1990; Liu, *et al.*, 1994; Gårding, *et al.*, 1995; Backus and Banks, 1999) differ from the amounts of slant predicted by the headcentric model (Erkelens and Van Ee, 1998),. The difference is rather large; for a nulling task, the headcentric model predicts that twice as much horizontal as vertical scale is required to perceive a fronto-parallel plane, whereas the other models predict a ratio of one. We suggested that the correction term for horizontal version errors was not determined accurately. However, the analytical derivation shows that there was only a small error in the correction term. Thus, the reason why the models give different predictions is not due to an error in the correction term. The headcentric model (Erkelens and Van Ee, 1998) is not the only theory that predicts that twice as much horizontal as vertical scale is required to perceive a fronto-parallel plane (Berends and Erkelens, 2001b). The theory of Gillam, *et al.*, 1988) predicts this too. Thus, there must be another reason why different models give different predictions, namely the models must be based on a different principle.

According to the theory of Gillam, *et al.*, 1988), the horizontal disparity of a surface patch determines on which Vieth-Muller circle the patch lies. Vertical disparity determines the eccentricity. If the vertical disparity is adjusted, the surface patch rotates around the centre of the Vieth-Muller circle. In the headcentric model (Erkelens and Van Ee, 1998), the correction term for horizontal version errors also induces rotation around the centre of the Vieth-Muller circle. Thus, these two theories predict the same.

According to the model of Mayhew (1982) and Mayhew and Longuet-Higgins (1982), horizontal disparity determines the amount of slant of a surface patch relative to the normal to the viewing direction (gaze). Vertical disparity determines the gaze. If the vertical disparity is adjusted, the surface patch rotates around the cyclopean eye. The same occurs in the models of Weinshall (1990), Liu, *et al.* (1994), Gårding, *et al.* (1995), Backus and Banks (1999). The difference of the centre of rotation probably causes the difference in the predictions made by the various models.

Global or regional

Our simulations showed that the results of many of the experiments that are used to prove that vertical disparity operates regionally could also be described by the headcentric model. For many experiments, the global headcentric model gives the same predictions as the regional models, for instance the regional disparity correction model (RDC) (Gårding, *et al.*, 1995). Therefore, it is hard to find out whether vertical disparity operates regionally or globally. However, the fact that we found a high correlation between the strength of the depth effects induced by vertical scale and by vertical quadratic mix can be seen as new evidence.

Chapter 7

Summary and conclusions

The goal of this thesis was to learn more about adaptation to disparity. Adaptation experiments have been performed to study the flexibility of the visual system with respect to stereovision. The literature reports on experiments that show perceived depth in a stimulus depends on the disparity in the stimulus, but also on the foregoing disparities (for instance Blakemore and Julesz, 1971 and Long and Over, 1973) and on experiments that show under what circumstances the depth percept can change (for instance various studies of Epstein, 1971, 1972a, 1972b). Although, a great deal of research has been performed on adaptation to disparity, many problems remained unsolved, for instance, what changes during adaptation and why do these changes occur? This thesis deals with various aspects of adaptation to disparity.

The **second chapter** can serve as an introduction to the other chapters in this thesis, although it can also be read as a study on its own. The goal of this chapter is to compare the strengths of depth effects induced by different types of vertical disparity. Three types of vertical disparity fields were investigated, namely vertical disparity fields induced by the following transformations: vertical scale (= vertical magnification of one of the half-images), vertical shear (= shear in the vertical direction of one of the half-images) and vertical; quadratic mix (= a higher order transformation). We measured the strengths of these vertical disparity fields by means of a nulling task. The depth effects induced by vertical disparity were cancelled out by adding horizontal disparity. For example, a stereogram that is vertically scaled is perceived a plane that is slanted about the vertical axis. Horizontal scale can cancel out this depth effect, because it induces also slant about the vertical axis. We measured how much horizontal scale was required to null a certain amount of vertical scale. For each type of disparity, we determined the ratios between horizontal and vertical disparity that evoke the percept of a fronto-parallel stimulus. We found that the ratios vary according to the type of vertical disparity. These ratios were used in other chapters.

The goal of the **third chapter** is to investigate on which level in the brain adaptation to disparity occurs. Adaptation could occur at the level of slant perception, i.e. it could be driven by conflicts between the binocular and monocular signals related to slant perception. Adaptation could also occur within the binocular system itself. Three types of binocular signals play a role in the perception of random-dot stereograms, namely horizontal disparity, vertical disparity and eye position signals (Rogers and Bradshaw, 1995; Bradshaw, Glennerster and Rogers, 1996; Erkelens and Van Ee, 1998; Backus, Banks, van Ee and Crowell, 1999). The percept follows from these three signals. In this chapter, we investigate whether adaptation can occur at the level of these signals. An adaptation stimulus was required to carry out this study in which there is no conflict between the monocular and the binocular depth cues. The monocular depth cues in our set-up always indicate that the stimulus lies in the plane of the screen. Therefore, the binocular depth cues have to indicate that the stimulus is a fronto-parallel plane, which is true if the depth effects induced by vertical disparity are cancelled out by horizontal disparity (see the nulling ratio experiment). Subjects had to adapt (5 minutes) to a combination of horizontal and vertical disparities which they perceived as being fronto-parallel. During that period, the percept of a fronto-parallel surface did not change. After the adapting period, subjects perceived a thin untransformed strip (containing negligible information about the vertical disparity field) as either slanted or curved depending on the type of disparity in the adapting stimulus. Thus, they saw an after-effect. This experiment shows that a certain depth percept is not necessarily required to adapt (the percept was always fronto-parallel) and that adaptation to disparity is possible, because the after-effects depend on the disparity in the adapting stimulus.

In the **fourth chapter**, we study the cause of adaptation. Two causes of adaptation to disparity have been mentioned in the literature. The first cause is fatigue. If neurons are stimulated for a long period, their activity may decrease (Blakemore and Julesz, 1971; Long and Over, 1973; Ryan and Gillam, 1993). The second cause is recalibration due to conflicts between different signals (Epstein and Morgan, 1970; Lee and Ciuffreda, 1983; Burian and Ogle, 1945; Miles, 1948). We tested whether the first cause is the true cause. We investigated whether adaptation occurs if both retinal and headcentric disparity are not constant. We repeated the experiments of chapter 3 with one major difference, namely we added disparity modulations in time to the constant combination of horizontal and vertical disparity that was perceived as being fronto-parallel. We found an after-effect, although disparity varied during the adaptation phase. Thus, adaptation was not caused by a signal that was constant for a long period (fatigue). We suggest that adaptation is probably a response to conflicts between different signals.

In the **fifth chapter**, we look at the relation between perceiving depth and perceiving direction. The same signals can be used for perceiving direction and for perceiving depth, namely retinal signals and eye position signals. Vertical disparity and eye position signals can both alter depth perception (Rogers and Bradshaw, 1995, Backus, *et al.*, 1999). We investigate whether vertical disparity also influences perceived direction. We dissociated the common relationship between the vertical disparity field and gaze direction by applying a vertical magnification to one eye's image (vertical scale). We found that perceived straight-ahead did indeed depend on the amount of vertical scale but only after subjects adapted (5 minutes) to vertical scale (and only in five out of nine subjects). Thus, the role of vertical disparity in perceiving direction is different from its role in perceiving depth. Our results suggest that vertical disparity is a factor in the calibration of eye position signals.

The **sixth and last chapter** goes back to the theory. We re-examine the headcentric model of Erkelens and Van Ee (1998). The model uses correction terms which change the relation between disparity and distance if errors in the eye position signals occur. The correction terms were not analytically derived. We derived them analytically in the first part of this chapter. One of the three correction terms turns out to be slightly different from the one that was derived from simulations by Erkelens and Van Ee. The second part of the chapter describes simulations that show that the headcentric model can explain many of the results used as evidence for regionally processed vertical disparity. According to the headcentric model, vertical disparity is a global phenomenon. Thus, it is not clear whether vertical disparity is processed regionally or globally.

In conclusion, we found that the strengths of depth effects induced by three different types of vertical disparity fields depend on the subject and the type of vertical disparity. Therefore, we may conclude that the three types of vertical disparity are processed independently.

We carried out various experiments in order to answer important questions about adaptation to disparity. We found that adaptation not necessarily occurs at the level of slant perception. It can occur within the binocular system itself at the level of eye position signals and horizontal and vertical disparity. Moreover, we found that adaptation to disparity is not caused by a signal that is constant for a long period (fatigue), but it is probably caused by conflicts between vertical disparity and eye position signals. Furthermore, we found that adaptation to vertical disparity can change the perceived direction. The change in perceived direction may indicate recalibration of the eye position signals.

Chapter 8

Nederlandse samenvatting:
Het waarnemen van diepte en adaptatie aan dispariteiten

8.1 Inleiding

Mensen hebben twee ogen dicht bij elkaar in de voorkant van het hoofd, daarom overlappen de beelden op de netvliezen elkaar, maar is er een klein verschil in gezichtspunt van beide ogen. De verschillen tussen de beelden op beide netvliezen stellen de mens in staat om zijn omgeving drie-dimensionaal waar te nemen, terwijl de beelden op het netvlies twee-dimensionaal zijn. Dit vermogen wordt stereo-zien of stereopsis genoemd.

Stereopsis helpt ons te navigeren in onze omgeving. Het stelt ons in staat precisietaken uit te voeren, zoals een glas water inschenken en een draad in een naald steken. Stereopsis heeft vele wetenschappers geïntrigeerd. Wetenschappers wilden en willen weten hoe de twee beelden op de netvliezen met de oogstandsignalen gecombineerd worden. Ze ontwikkelden verschillende uitdrukkingen voor dispariteit en talloze modellen voor stereoscopisch diepte-waarnemen. Vele modellen werden ook weer verworpen, omdat experimenteel bewijs was gevonden dat het visueel systeem anders werkt dan werd aangenomen.

Er wordt al vele jaren onderzoek gedaan naar stereo-zien. Eén type experimenten, die gedaan zijn, zijn adaptatie experimenten. Adaptatie experimenten zijn een goede manier om stereo-zien te onderzoeken, want dit soort experimenten vertelt ons iets over de flexibiliteit van het visueel systeem. Ze laten zien welke signalen er kunnen veranderen en onder welke omstandigheden ze veranderen.

In de literatuur, zijn vele studies beschreven, die aantonen dat de waargenomen diepte niet alleen afhangt van de dispariteit in de stimulus, maar ook van de voorafgaande dispariteitstimulatie. De studies van Blakemore and Julesz (1971) en van Long and Over (1973) zijn daar goede voorbeelden van. In de experimenten van deze onderzoekers, keken proefpersonen naar een stereogram waarvan het middelste vierkantje in het ene half-beeld verschoven was ten opzichte van het andere half-beeld. De proefpersonen zagen het vierkantje daardoor voor de achtergrond zweven. Nadat de proefpersonen een tijdje geadapteerd hadden aan deze stimulus, zagen zij een ongetransformeerd stereogram (een stereogram, dat zij normaal gesproken plat waarnamen) als zijnde een vierkantje achter een groot vlak. Proefpersonen zagen dus een na-effect.

Hoewel er al veel onderzoek naar adaptatie aan dispariteit is gedaan, blijven er nog veel vragen onbeantwoord. Een belangrijke vraag is op welk niveau in de hersenen adaptatie optreedt. Een andere belangrijke vraag is wat de oorzaak is van adaptatie aan dispariteit. Verder is het interessant om te weten of de waargenomen richting verandert door adaptatie aan dispariteit. Dat zou het geval kunnen zijn als adaptatie aan dispariteit recalibratie van de oogstandsignalen veroorzaakt, zoals Ebenholtz (1970) voorspelde. In dit proefschrift proberen we een antwoord te vinden op deze vragen.

8.2 Opstelling en meetmethode

We maken gebruik van een anaglyf opstelling om afzonderlijke beelden voor het linker- en rechteroog te genereren, zodat deze beelden onafhankelijk van elkaar gemanipuleerd (getransformeerd) kunnen worden. In een anaglyf opstelling wordt het beeld voor het linkeroog in rood licht geprojecteerd en het beeld voor het rechteroog in groen licht. Proefpersonen dragen een bril met een rood en een groen transmissiefilter, zodat de beelden voor het linker- en rechteroog afzonderlijk aangeboden worden. De stimuli die met deze opstelling getoond worden heten stereogrammen. We gebruiken random-dot stereogrammen (stippen-patronen), omdat deze zo min mogelijk andere dieptecues bevatten, zoals perspectief.

De stimuli worden gegenereerd met een HP750 grafische computer. Ze worden met behulp van een projectie-TV op een groot scherm (190 cm x 250 cm) geprojecteerd. Proefpersonen zitten op 1 of 1.5 meter afstand. De resolutie (minimumstap in dispariteit) van deze opstelling is 3.8 of 5.7 boogminuten afhankelijk van de kijkafstand. Een kinsteun zorgt ervoor dat de proefpersoon gedurende het experiment op constante afstand blijft. Als bewegingen van de proefpersoon het experiment minder nauwkeurig zouden maken (richtingszien experimenten), wordt tevens een bijthoutje gebruikt.

We gebruiken psychofysische methoden om het visuele systeem te onderzoeken. Daarbij vragen we proefpersonen naar de kromming of de stand van de stimulus die zij waarnemen. Op basis van de stimulus-responsrelatie proberen we uitspraken te doen over mechanismen in het visuele systeem.

8.3 Sterktes van diepte-effecten veroorzaakt door drie verschillende soorten vertikale dispariteit (hoofdstuk 2)

Hoofdstuk 2 kan dienen als een introductie voor de volgende hoofdstukken, maar het kan ook als een aparte studie gelezen worden. Het doel van dit hoofdstuk is om de sterktes van diepte-effecten veroorzaakt door drie verschillende soorten vertikale dispariteit te vergelijken. De drie soorten vertikale dispariteitsvelden, die we onderzocht hebben, zijn de dispariteitsvelden opgewekt door de volgende transformaties: vertikale scale (= vertikaal uitrekken van één van de halfbeelden), vertikale shear (= afschuiving in de vertikale richting in één van de halfbeelden) en vertikale kwadratische mix (= een hogere orde vertikale transformatie). We hebben de sterkte van deze velden gemeten met behulp van een nulling taak. De diepte-effecten veroorzaakt door vertikale dispariteit werden opgeheven door het toevoegen van horizontale dispariteit. Een vertikaal gescalede stimulus wordt bijvoorbeeld waargenomen als een vlak dat gedraaid is om de vertikale as (slant). Horizontale scale kan dit diepte-effect opheffen, omdat het ook slant om de vertikale as veroorzaakt. We hebben gemeten hoeveel horizontale scale nodig was om een vertikale scale te nullen. Voor ieder soort vertikale dispariteit hebben we bepaald welke verhouding van tussen horizontale en vertikale dispariteit nodig was om een fronto-parallelle stimulus waar te nemen. We vonden dat de ratio's afhangen van het type vertikale dispariteit en van de proefpersoon. Dit feit hebben we gebruikt in de volgende hoofdstukken.

8.4 Adaptatie aan dispariteit en niet aan waargenomen diepte (hoofdstuk 3)

Het doel van het derde hoofdstuk is om te onderzoeken op welk niveau in de hersenen adaptatie plaatsvindt. Adaptatie zou kunnen plaatsvinden op het niveau van slantperceptie. Dan zou het aangedreven worden door conflicten tussen binoculaire en monoculaire signalen die aangeven wat de slant is. Een andere mogelijkheid is dat adaptatie plaatsvindt binnen het binoculaire systeem. In het waarnemen van random-dot stereogrammen spelen drie soorten binoculaire signalen een rol, namelijk oogstandsignalen en horizontale en vertikale dispariteit. Uit deze signalen volgt het percept. Wij onderzoeken of adaptatie kan plaatsvinden op het niveau van deze signalen. Daarvoor is een adaptatiestimulus nodig waarin geen conflict zit tussen de binoculaire en monoculaire diepte-cues. De monoculaire cues in onze set-up geven altijd aan dat de stimulus in het scherm ligt. Dus moeten de binoculaire cues ook aangeven dat de stimulus in het scherm ligt. Daarvoor komen de nulling ratio’s uit hoofdstuk 2 goed van pas. Proefpersonen moesten 5 minuten adapteren aan een combinatie van horizontale en vertikale dispariteit, die zij fronto-parallel waarnamen. Tijdens de adaptatieperiode bleven zij de adaptatiestimulus fronto-parallel waarnemen. Na de adaptatieperiode zagen zij een ongetransformeerde smalle teststrip (waar geen vertikale dispariteit informatie in zat) gedraaid of gekromd afhankelijk van het type vertikale dispariteit in de adaptatiestimulus. Zij zagen dus een na-effect. Dit experiment laat dus zien dat je niet aan het percept hoeft te adapteren maar dat je ook aan de dispariteit kunt adapteren. Het percept is namelijk altijd fronto-parallel, terwijl het na-effect afhangt van de dispariteit.

8.5 Het bekijken van een niet-geslante stimulus kan zelfs een slant na-effect veroorzaken als de dispariteiten continu veranderen (hoofdstuk 4)

In het vierde hoofdstuk bestuderen we de oorzaak van adaptatie. In de literatuur worden twee verschillende oorzaken voor adaptatie gegeven. De eerste oorzaak die genoemd wordt is vermoeidheid. Als neuronen langere tijd gestimuleerd worden, neemt hun activiteit af (Blakemore and Julesz, 1971; Long and Over, 1973; Ryan and Gillam, 1993). De tweede oorzaak is recalibratie veroorzaakt door conflicten tussen verschillende signalen (Epstein and Morgan, 1970; Lee and Ciuffreda, 1983; Burian and Ogle, 1945; Miles, 1948). Wij hebben onderzocht of de eerste oorzaak die genoemd wordt (vermoeidheid) waar kan zijn. Neuronen kunnen vermoeid worden als een bepaald signaal lange tijd constant is. Wij hebben gekeken of adaptatie ook optreedt als zowel de retinale als de hoofdcentrische dispariteit niet constant zijn. Dat hebben we gedaan door de experimenten uit hoofdstuk 3 opnieuw uit te voeren met één verschil in de adaptatiestimulus, namelijk door verschillende modulaties van dispariteit toe te voegen aan de combinatie van horizontale en vertikale scale die fronto-parallel waargenomen werd. Ondanks dat de dispariteit constant varieerde tijdens de adaptatiefase, vonden we toch een na-effect. Dus hier is adaptatie niet veroorzaakt door het lange tijd constant blijven van een signaal (vermoeidheid), maar is het waarschijnlijk veroorzaakt door conflicten tussen verticale dispariteit en oogstandsignalen.

8.6 Verschillende rollen voor vertikale dispariteit in het waarnemen van richting en diepte (hoofdstuk 5)

In het vijfde hoofdstuk kijken we naar de relatie tussen richting-zien en diepte-zien. Voor richting-zien en diepte-zien kunnen dezelfde signalen gebruikt worden, namelijk retinale signalen en oogstandsignalen. Het is aangetoond dat zowel vertikale dispariteit als oogstandsignalen van invloed zijn op de waargenomen diepte (Rogers and Bradshaw, 1995; Backus, Banks, van Ee and Crowell, 1999). Wij onderzochten of vertikale dispariteit de waargenomen richting beïnvloedt. Daarvoor ontkoppelden we de gewone relatie tussen vertikale dispariteit en stimulus-richting door één van de half-beelden vertikaal te scalen. We hebben gemeten of waargenomen rechtvooruit afhangt van de hoeveelheid vertikale scale in de stimulus. We vonden dat waargenomen rechtvooruit wel afhangt van de hoeveelheid vertikale scale, maar alleen na adaptatie (5 minuten) en maar bij 5 van de 9 proefpersonen. Voor richting-zien wordt vertikale dispariteit dus niet onmiddellijk gebruikt zoals in diepte-zien. Een verklaring voor het feit dat het richting-zien wel verandert na adaptatie aan vertikale dispariteit is dat er recalibratie van de oogstandsignalen optreedt.

8.7 Het hoofdcentrische model voor het stereoscopisch diepte waarnemen opnieuw bekeken (hoofdstuk 6)

In het laatste hoofdstuk keren we terug naar de theorie. We bekijken het hoofdcentrische model voor het stereoscopisch diepte waarnemen (Erkelens and Van Ee, 1998) opnieuw. Het hoofdcentrisch model maakt gebruik van correctietermen die de relatie tussen dispariteit en diepte (afstand) corrigeren als er fouten in de oogstandsignalen optreden. Erkelens en Van Ee hebben de correctietermen niet analytisch afgeleid, daarom hebben wij dat gedaan in het eerste deel van dit hoofdstuk. Het bleek dat één van de correctietermen een beetje verschilde met de correctieterm die Erkelens en Van Ee uit simulaties bepaald hadden. Met simulaties hebben we aangetoond dat het effect van deze afwijking erg klein is. In het tweede deel van dit hoofdstuk worden simulaties beschreven die aantonen dat het hoofdcentrisch model veel resultaten verklaart die worden gebruikt als bewijs dat vertikale dispariteit regionaal werkt. Volgens het hoofdcentrische model werkt vertikale dispariteit niet regionaal maar globaal, daarom is het nog steeds niet duidelijk of vertikale dispariteit regionaal of globaal werkt.

8.8 Conclusie

We hebben gevonden dat de sterkte van de diepte-effecten veroorzaakt door verschillende soorten vertikale dispariteit afhangt van de proefpersoon en de soort vertikale dispariteit. Daaruit zou geconcludeerd kunnen worden dat verschillende soorten dispariteit onafhankelijk van elkaar verwerkt worden.

We hebben verscheidene experimenten gedaan om belangrijke vragen over adaptatie aan dispariteit te beantwoorden. We hebben gevonden dat adaptatie niet op het niveau van slantperceptie hoeft plaats te vinden. Het kan ook plaatsvinden binnen het binoculaire systeem op het niveau van de oogstandsignalen en horizontale en vertikale dispariteit. Verder hebben we gevonden dat adaptatie aan dispariteit niet veroorzaakt wordt door het lange tijd constant blijven van een signaal (vermoeidheid), maar dat het waarschijnlijk veroorzaakt wordt door conflicten tussen verticale dispariteit en oogstandsignalen. We hebben bovendien ontdekt dat adaptatie aan vertikale dispariteit de waargenomen richting kan veranderen. De verandering in waargenomen richting na adaptatie zou kunnen duiden op recalibratie van de oogstandsignalen.

References

A

Adams, W. J., Frisby, J. P., Buckley, D., Garding, J., Hippisley-Cox, S. D. & Porrill, J. (1996). Pooling of vertical disparities by the human visual system. *Perception*, 25, 165-176.

Adams, W. J., Banks, M. S. & Van Ee, R. (1999). Disparity adaptation following prolonged use of aniseikonic lenses. *Investigative Ophthalmology and Visual Science*, 40, 2193.

Allison, R. S., Howard, I. P., Rogers, B. J. & Bridge, H. (1998). Temporal aspects of slant and inclination perception. *Perception*, 27, 1287-1304.

Amigo, G. (1972). The stereoscopic frame of reference in asymmetric convergence of the eyes: Response to 'point' stimulation of the retina. *Optica Acta*, 19, 993-1006.

B

Backus, B. T. & Banks, M. S. (1999). Estimator reliability and distance scaling in stereoscopic slant perception. *Perception*, 27, 217-242.

Backus, B. T., Banks, M. S., van Ee, R. & Crowell, J. A. (1999). Horizontal and vertical disparity, eye position, and stereoscopic slant perception. *Vision Research*, 39, 1143-1170.

Berends, E. M. & Erkelens, C. J. (2001a). Adaptation to disparity but not to perceived depth. *Vision Research*, 41, 883 - 892.

Berends, E. M. & Erkelens, C. J. (2001b). Strength of depth effects induced by three types of vertical disparity. *Vision Research*, 41, 37-45.

Berends, E. M., Van Ee, R. & Erkelens, C. J. (2001). Differing roles of vertical disparity in perceiving direction and perceiving depth. *Perception*, submitted.

Beverly, K. I. & Regan, D. (1974). Temporal integration of disparity information in stereoscopic perception. *Experimental Brain Research*, 19, 228 – 232.

Blakemore, C. & Julesz, B. (1971). Stereoscopic depth aftereffect produced without monocular cues. *Science*, 171, 286 – 288.

Blakemore, C. & Hague, B. (1972). Evidence for disparity detecting neurones in the human visual system. *Journal of Psychology*, 255, 437 – 455.

Bradshaw, M. F., Glennerster, A. & Rogers, B. J. (1996). The effect of display size on disparity scaling from differential perspective and vergence cues. *Vision Research*, 36, 1255-1264.

Burian, H. M. (1943). Influence of prolonged wearing of meridional size lenses on spatial localization. *Archives of Ophthalmology*, 30, 645 – 666.

Burian, H. M. & Ogle, K. N. (1945). Aniseikonia and spatial orientation. *American Journal of Ophthalmology*, 28, 735 -743.

C

Cagenello, R. B. & Rogers, B. J. (1990). Orientation disparity, cyclotorsion and the perception of surface slant. *Investigative ophthalmology and visual science*, 31, 97.

Collett, T., Schwarz, U. & Sobel, E. (1991). The interaction of oculomotor cues and stimulus size in stereoscopic depth constancy. *Perception*, 20, 733-754.

Collewijn, H. & Erkelens, C. J. (1990). Binocular Eye Movements and the Perception of Depth. In Kowler, E., (Eds), Eye movements and their role in visual and cognitive processes, pp. 213-261. London: Elsevier Publishers.

Craske, B. (1967). Adaptation to prisms: change in internally registered eye-position. *British Journal of Psychology*, 58, 329 - 335.

Cumming, B. G., Johnston, E. B. & Parker, A. J. (1991). Vertical disparities and perception of three-dimensional shape. *Nature*, 349, 411-3.

E

Ebenholtz, S. M. (1970). On the relation between interocular transfer of adaptation and Hering's law of equal innervation. *Psychological Review*, 77, 343 - 347.

Epstein, W. & Morgan, C. L. (1970). Adaptation to uniocular magnification: modification of the disparity-depth relationship. *American Journal of Psychology*, 83, 322 – 329.

Epstein, W. (1971). Adaptation to uniocular image magnification after varying preadaptation activities. *American Journal of Psychology*, 84, 66 – 74.

Epstein, W. (1972a). Retention of adaptation to uniocular image magnification: effect of interpolated activity. *Journal of Experimental Psychology*, 92, 319 – 324.

Epstein, W. (1972b). Adaptation to uniocular image magnification: Is the underlying shift proprioceptive? *Perception and Psychophysics*, 11, 89 - 91.

Epstein, W. & Daviess, N. (1972). Modification of depth judgement following exposures to magnification of uniocular image: Are changes in perceived absolute distance and registered direction of gaze involved? *Perception and Psychophysics*, 12, 315 -317.

Epstein, W. & Morgan-Paap, C. L. (1974). The effect of level of depth processing and degree of informational discrepancy on adaptation to uniocular image magnification. *Journal of Experimental Psychology*, 102, 585 – 594.

Erkelens, C. J. & Van Ee, R. (1998). A computational model of depth perception based on headcentric disparity. *Vision Research*, 38, 2999-3018.

F

Foley, J. M. (1980). Binocular distance perception. *Psychological Review*, 87, 411-34.

G

Gårding, J., Porrill, J., Mayhew, J. E. & Frisby, J. P. (1995). Stereopsis, vertical disparity and relief transformations. *Vision Research*, 35, 703-722.

Gillam, B. J. & Lawergren, B. (1983). The induced effect, vertical disparity, and stereoscopic theory. *Perception & Psychophysics*, 34, 121-30.

Gillam, B. J., Chambers, D. & Lawergren, B. (1988). The role of vertical disparity in the scaling of stereoscopic depth perception: an empirical and theoretical study. *Perception & Psychophysics*, 44, 473-83.

Gillam, B. J. & Rogers, B. J. (1991). Orientation disparity, deformation, and stereoscopic slant perception. *Perception*, 20, 441-8.

H

Harris, C. S. (1965). Perceptual adaptation to inverted, reversed, and displaced vision. *Psychological Review*, 72, 419 - 444.

Hay, J. C. & Pick, H. L. (1966). Visual and proprioceptive adaptation to optical displacement of the visual stimulus. *Journal of Experimental Psychology*, 71, 150 - 158.

Held, R. & Freedman, S. J. (1963). Plasticity in human sensorimotor control. *Science*, 142, 455 - 462.

Helmholtz von, H. (1911). *Helmholtz's treatise on physiological optics*. New York: The Optical Society of America.

Hill, A. L. (1972). Direction constancy. *Perception and Psychophysics*, 11, 175 - 178.

Howard, I. P. & Kaneko, H. (1994). Relative shear disparities and the perception of surface inclination. *Vision Research*, 34, 2505-2517.

Howard, I. P. & Pierce, B. J. (1998). Types of shear disparity and the perception of surface inclination. *Perception*, 27, 129 - 145.

J

Jacobs, R. A. & Fine, I. (1999). Experience-dependent integration of texture and motion cues to depth. *Vision Research*, 39, 4062 – 4075.

Johnston, E. B., Cumming, B. G. & Landy, M. S. (1991). Systematic distortions of stereopsis and motion shape cues. *Vision Research*, 34, 2259 - 2275.

Johnston, E. B. (1993). Integration of shape from stereopsis. *Vision Research*, 31, 1351 - 1360.

Julesz, B. (1960). Binocular depth perception of computer-generated patterns. *Bell Systems Technical Journal*, 39, 1125 –1162.

K

Kalil, R. E. & Freedman, S. J. (1966). Persistence of ocular rotation following compensation for displaced vision. *Perceptual and Motor Skills*, 22, 135 - 139.

Kaneko, H. & Howard, I. P. (1996). Relative size disparities and the perception of surface slant. *Vision Research*, 36, 1919-1930.

Kaneko, H. & Howard, I. P. (1997a). Spatial limitation of vertical-size disparity processing. *Vision Research*, 37, 2871 - 2878.

Kaneko, H. & Howard, I. P. (1997b). Spatial properties of shear disparity processing. *Vision Research*, 37, 315 - 323.

Kapoula, Z., Eggert, T. & Bucci, M. P. (1995). Immediate saccade amplitude disconjugacy induced by unequal images. *Vision Research*, 35, 3505 - 3518.

Koenderink, J. J. & van Doorn, A. J. (1976). Geometry of binocular vision and a model for stereopsis. *Biological Cybernetics*, 21, 29-35.

Köhler, W. & Emery, D. A. (1947). Figural after-effects in the third dimension of visual space. *American Journal of Psychology*, 60, 159 – 201.

L

Landy, M. S., Maloney, L. T., Johnston, E. B. & Young, M. (1995). Measurement and modeling of depth cue combination: in defense of weak fusion. *Vision Research*, 35, 389-412.

Lee, D. Y. & Ciuffreda, K. J. (1983). Short-term adaptation to the induced effect. *Ophthalmic & Physiological Optics*, 3, 129 – 135.

Liu, L., Stevenson, S. B. & Schor, C. M. (1994). A polar coordinate system for describing binocular disparity. *Vision Research*, 34, 1205-22.

Long, N. & Over, R. (1973). Stereoscopic depth aftereffects with random-dot patterns. *Vision Research*, 13, 1283 – 1287.

M

Mack, A. & Chitayat, D. (1970). Eye-dependent and disparity adaptation to opposite visual-field rotations. *American Journal of Psychology*, 83, 352 – 371.

Mayhew, J. E. (1982). The interpolation of stereo-disparity information: the computation of surface orientation and depth. *Perception*, 11, 387-403.

Mayhew, J. E. & Longuet-Higgins, H. C. (1982). A computational model of binocular depth perception. *Nature*, 297, 376-378.

McLaughlin, S. C. (1967). Changes in straight-ahead eye position during adaptation to wedge prisms. *Perception and Psychophysics*, 2, 37 - 44.

Miles, P. W. (1948). A comparison of aniseikonic test instruments and prolonged induction of artificial aniseikonia. *American Journal of Ophthalmology*, 31, 687 – 696.

Mitchell, D. E. & Baker, A. G. (1973). Stereoscopic aftereffects: evidence for disparity-specific neurones in the human visual system. *Vision Research*, 13, 2273 – 2288.

Morrison, L. C. (1972). Further studies on the adaptation to artificially-induced aniseikonia. *British Journal of Physiological Optics*, 27, 84 – 101.

O

Ogle, K. N. (1938). Induced size effect. I. A new phenomenon in binocular space perception associated with the relative sizes of the images of the two eyes. *Archives of Ophthalmology*, 20, 604-623.

Ogle, K. N. (1939). Induced size effect. II. An experimental study of the phenomenon with restricted fusion stimuli. *Archives of Ophthalmology*, 21, 604-625.

Ogle, K. N. & Ellerbrock, V. J. (1946). Cyclofusional movements. *Archives of Ophthalmology*, 36, 700 – 735.

Ogle, K. N. (1950). *Researches in binocular vision*. Philadelphia, London: W.B. Saunders Co.

Ono, H. & Angus, R. G. (1974). Adaptation to sensori-motor conflict produced by the visual direction of the hand specified from the cyclopean eye. *Journal of Experimental Psychology*, 103, 1-8.

P

Patterson, R., Cayko, R., Short, G. L., Flanagan, R., Moe, L., Taylor, E. & Day, P. (1995). Temporal integration differences between crossed and uncrossed stereoscopic mechanisms. *Perception and Psychophysics*, 57, 891 –897.

Pick, H. L., Hay, J. C. & Martin, R. (1969). Adaptation to split-field wedge prism spectacles. *Journal of Experimental Psychology*, 80, 125 -132.

Pierce, B. J. & Howard, I. P. (1997). Types of size disparity and the perception of surface slant. *Perception*, 27, 129 - 145.

R

Rogers, B. J. & Koenderink, J. (1986). Monocular aniseikonia: a motion parallax analogue of the disparity-induced effect. *Nature*, 322, 62-63.

Rogers, B. J. (1992). The perception and representation of depth and slant in stereoscopic surfaces. In Orban, G. & Nagel, H., (Eds), Artificial and Biological Vision Systems, pp. 241-266. Berlin: Springer.

Rogers, B. J. & Bradshaw, M. F. (1993). Vertical disparities, differential perspective and binocular stereopsis. *Nature*, 361, 253-5.

Rogers, B. J. & Bradshaw, M. F. (1995). Disparity scaling and the perception of frontoparallel surfaces. *Perception*, 24, 155-179.

Ryan, C. & Gillam, B. (1993). A proximity-contingent stereoscopic depth aftereffect: evidence for adaptation to disparity gradients. *Perception*, 22, 403-18.

S

Snoeren, P. R. & Puts, M. J. H. (1997). Multiple parameter estimation in an adaptive psychometric method: MUEST, an extension of the quest method. *Journal of Mathematical Psychology*, 41, 431 – 439.

Sobel, E. C. & Collett, T. S. (1991). Does vertical disparity scale the perception of stereoscopic depth? *Proceedings of the Royal Society London B: Biological Sciences*, 244, 87-90.

Stenton, S. P., Frisby, J. P. & Mayhew, J. E. (1984). Vertical disparity pooling and the induced effect. *Nature,* 309, 622-623.

T

Treutwein, B. (1995). Adaptive psychophysical procedures. *Vision Research*, 35, 2503 –2522.

Turner, J., Braunstein, M. L. & Andersen, G. J. (1997). Relationship between binocular disparity and motion parallax in surface detection. *Perception and Psychophysics*, 59, 370 – 380.

V

Van der Steen, J. & Bruno, P. (1995). Unequal amplitude saccades produced by aniseikonic patterns: effects of viewing distance. *Vision Research*, 35, 3459 - 3471.

Van Ee, R. & Erkelens, C. J. (1995). Binocular perception of slant about oblique axes relative to a visual frame of reference. *Perception,* 24, 299-314.

Van Ee, R. & Erkelens, C. J. (1996). Temporal aspects of binocular slant perception. *Vision Research*, 36, 43-51.

Van Ee, R. & Erkelens, C. J. (1998). Temporal aspects of stereoscopic slant estimation: an evaluation and extension of Howard and Kaneko’s theory. *Vision Research*, 38, 3871 –3882.

Van Ee, R., Banks, M. S. & Backus, B. T. (1999). An analysis of binocular slant contrast. *Perception*, 28, 1121-1145.

W

Wade, N. J. (1998). *A Natural History of Vision*. Massachutes: MIT Press.

Warren, D. H. (1975). Understanding prism adaptation: an individual differences approach. *Perception and Psychophysics*, 17, 337 - 345.

Watson, A. B. & Pelli, D. G. (1983). Quest: a Bayesian adaptive psychometric method. *Perception and Psychophysics*, 33, 113 – 120.

Weinshall, D. (1990). Qualitative depth from stereo, with applications. *Computer Vision, Graphics, and Image Processing*, 49, 222 - 241.

Welch, R. B. & Rhoades, R. W. (1969). The manipulation of informational feedback and its effects upon prism adaptation. *Canadian Journal of Psychology*, 23, 415 - 428.

Y

Young, M. J., Landy, M. S. & Malony, L. T. (1993). A perturbation analysis of depth perception from combinations of texture and motion cues. *Vision Research*, 33, 2685 – 2696.

Dankwoord

Men zegt wel eens dat het de twee delen van het proefschrift zijn die het meest worden gelezen: de inleiding en het dankwoord. En niet voor niets: de inleiding geeft je de mogelijkheid om een idee te krijgen van het onderzoek waar de schrijver zich de afgelopen jaren in heeft verdiept, zonder daarbij al te diep in te moeten gaan op wat de schrijver daadwerkelijk heeft verricht (daar is de samenvatting voor). En het dankwoord lees je voor jezelf: sta ik er wel in? En waar sta ik dan? Sta ik vooraan in het dankwoord of achteraan: Net als in het theater bevinden zich daar de meest vooraanstaande plaatsen. Of sta ik ergens in het midden…samen met een aantal anderen in één zin?

Als schrijver heb je het er maar moeilijk mee, want verschillende mensen hebben je op verschillende manieren geholpen bij het tot stand komen van je onderzoek, door het geven van begeleiding, met goede ideeën, door het bekijken van stimuli, door het bijstaan in de moeilijke tijden, bij het vergezellen op de leuke ontspannende momenten, door het corrigeren van artikelen, bij het regelen van praktische zaken zoals het boeken van vluchten naar verre oorden voor belangrijke conferenties, enzovoorts, enzovoorts…Het één niet minder belangrijk dan het ander, maar op een andere manier belangrijk.

Vandaar dat ik op deze manier iedereen die mij op die éne of op die andere manier heeft geholpen wil bedanken.

Casper, Raymond, Mieke, Sylvia, Harold, Ansgar, Martin, Jasper, Eelco, Susan, Stefan, Jan, Ans, Astrid, Elena, Hans, Pieter, Evert-Jan, Ninke, Karel, Herman, Paul, Raymond, Jan Joris, Lu, Sheila, Irene, Jirka, Lukas, Bram, Jasper, Sander, Mohamed, Pieter, Iris, Maarten, Loes, Marc, Moef, Vader, Richard, Yvette, Audrey,

Curriculum Vitae

Ellen Berends werd op 11 september 1972 geboren in Arnhem. Het grootste deel van haar jeugd woonde zij in Brummen. Zij haalde in 1990 haar VWO-B diploma aan het Baudartius College te Zutphen.

Daarna ging zij Technische Natuurkunde studeren aan de Universiteit Twente. Ze volgde verschillende Lage Temperaturen en Biomedische keuzevakken. Ze heeft stage gelopen aan de Universiteit van Zaragoza (Spanje) bij de vakgroep Materiaalkunde bij Lage Temperaturen. Zij deed daar calorimetrie bij zeer lage temperaturen. In 1996 studeerde ze af bij de groep Biomagnetisme, een onderdeel van de vakgroep Lage Temperaturen. Voor haar afstudeerproject onderzocht ze welke informatiecriteria gebruikt kunnen worden om uit EEG- en MEG-data het aantal actieve gebieden in de hersenen te bepalen. Tijdens haar studie was zij actief bij diverse commissies van de studievereniging Arago en was ze secretaris bij de kanovereniging Euros.

Na haar afstuderen heeft zij vier maanden onderzoek gedaan voor het Joint Research Centre (Ispra, Italië) in het kader van het European Energy Labeling Project. Ze onderzocht de temperatuursafhankelijkheid van de daar toegepaste modellen.

In februari 1997 startte zij met haar promotie bij de vakgroep Fysica van de Mens (Helmholtz Instituut) aan de Universiteit Utrecht. Het resultaat van de afgelopen vier jaar werken bij het Helmholtz Instituut ligt nu voor u in de vorm van dit proefschrift. Naast het verrichten van onderzoek heeft zij de afgelopen jaren onderwijs gegeven aan biologie studenten en heeft zij in de Colloquium Commissie gezeten.

Publications

Articles

Berends, E. M. & Erkelens, C. J. (2001). Strength of depth effects induced by three types of vertical disparity. Vision Research, 41, 37-45.

Berends, E. M. & Erkelens, C. J. (2001). Adaptation to disparity but not to perceived depth. Vision Research, 41, 883 - 892.

Berends, E. M., Van Ee, R. & Erkelens, C. J.. Stereoscopic viewing of an unslanted stimulus can induce a slant aftereffect even if the disparities change continuously. Proceedings of the Royal Society of London B, submitted.

Berends, E. M., Van Ee, R. & Erkelens, C. J.. Differing roles of vertical disparity in perceiving direction and perceiving depth. Perception, submitted.

Refereed abstracts

Berends, E. M., Erkelens, C. J. (1998). Depth perception induced by three types of vertical disparity. Perception, 27 supplement, 99b.

Berends, E. M., Erkelens, C. J. (1999). Visual adaptation to disparity, not to perceived depth. Investigative Ophthalmology & Visual Science, 40, 2201.

Berends, E. M., Erkelens, C. J. (2000). Nulling ratios of horizontal to vertical disparity do not depend on distance. Investigative Ophthalmology & Visual Science, 41, 1225.

Berends, E. M. & Erkelens, C. J. & Van Ee, R. (2000). Adaptation to oscillating disparity. Perception, 29 supplement, 27b.