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Adaptation to disparity but not to perceived depth

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Abstract

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. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Stereopsis; Binocular vision; Adaptation; Vertical disparity; Horizontal disparity; Depth perception

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 & Emery, 1947; Blakemore & Julesz, 1971; Long & Over, 1973; Mitchell & Baker, 1973; Ryan & Gillam, 1993). In other experiments, meridional lenses have been used to show adaptation to horizontal scale (Burian, 1943; Miles, 1948; Epstein & La Verne Morgan, 1970; Epstein, 1971, 1972; Epstein & Morgan-Paap, 1974). Adaptation to vertical scale has also been shown by using meridional lenses. Miles (1948), 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 1–4 h. They showed that the decrease of slant started within 0.5 h.

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In a pilot experiment, we too studied adaptation to a vertically transformed half-images. Subjects looked at vertically scaled random-dot stereograms for long periods ranging from 5 to 30 min. They reported that after a few minutes the slant started to decrease and that after about 10 min the surface looked fronto-parallel.

The above mentioned adaptation does 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 & Bradshaw, 1995; Bradshaw, Glennerster, & Rogers, 1996; Erkelens & Van Ee, 1998; Backus, Banks, Van Ee, & Crowell, 1999). The percept follows from these three signals. The goal of the study was to find out whether adaptation could occur at the level of these signals.

To reach our goal we pursued the following approach. Experiments were carried out in which three types of vertical disparity fields were presented. Horizontal disparities were added such that all stimuli were perceived as a fronto-parallel plane. These three types of stimuli were perceived as 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. Both phenomena were explored.

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 the 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 & Banks, 1999; Backus et al., 1999; Berends and Erkelens, 2001).

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, 2001). 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, 1939; Amigo, 1972; Stenton, Frisby, & Mayhew, 1984; Backus & Banks, 1999; Backus et al., 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 & 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, Frisby, Buckley, Gårding, Hippisley-Cox, & Porrill, 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 min. We checked the validity of their opinion in a forced-choice experiment (expt. 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 (expt. SCALE, SHEAR and MIX).

2.1. Subjects

Four subjects (aged 20–48 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).

2.2. Apparatus

An anaglyph set-up was used to generate the stereograms (see also Van Ee & Erkelens, 1995). The stimuli were generated by an HP750 graphics computer (frequency = 70 Hz) and back-projected on a fronto-parallel translucent screen by a CTR projector (Barco Data 800). The resolution (the smallest change in disparity possible) was 3.8 min of arc. 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. Besides the stimulus nothing else was visible. 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.

2.3. 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 (53 × 53°). It was a random dot pattern of 2500 dots. In the FLAT expt., the test stimulus had the same size as the adapting stimulus, whereas the test stimuli were thin strips (0.64 × 45°) 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 1° 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. It was 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 (0.25° diameter) so their perceived shape have little effect on the percept. The dots were not anti-aliased.

2.4. Procedure for experiment FLAT

In experiment FLAT we investigated how the adapting stimuli were perceived after a presentation period of 5 min.

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 & Erkelens, 2001), we determined which combinations of horizontal and vertical transformation subjects perceived as fronto-parallel surfaces. A specific ratio of horizontal to vertical transformation was found 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 & 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 & Erkelens, 2001) were carried out for the new subjects. The experiments were shortened by using a shorter presentation time (10 s) 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, adaptation to one type of vertical transformation was measured. One magnitude of each type of vertical transformation was measured, namely 0.03 (3%) for scale, 0.03 (1.7°) for shear and 0.08 for quadratic mix. At the beginning of each session the large adapting stimulus was presented for 5 min, whereupon the large test stimulus was presented for 10 s. 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 20 s presentation of the adapting stimulus, 10 s testing and a judgement. The change in percept of the adapting stimulus after a presentation period of 5 min 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. The MUEST method (Snoeren & Puts, 1997) was used, 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 the stop criterion.

2.5. 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 Fig. 1) the adapting stimulus was presented for 5 min, whereupon the thin horizontal test stimulus was presented for 10 s. 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 20 s adaptation, 10 s testing and a judgement (see Fig. 1). The presentation time of the adapting stimulus was limited to 20 s, because the test stimulus hardly contained any information about vertical disparity. Therefore, it was assumed that adaptation was maintained during inspection of the test stimulus.

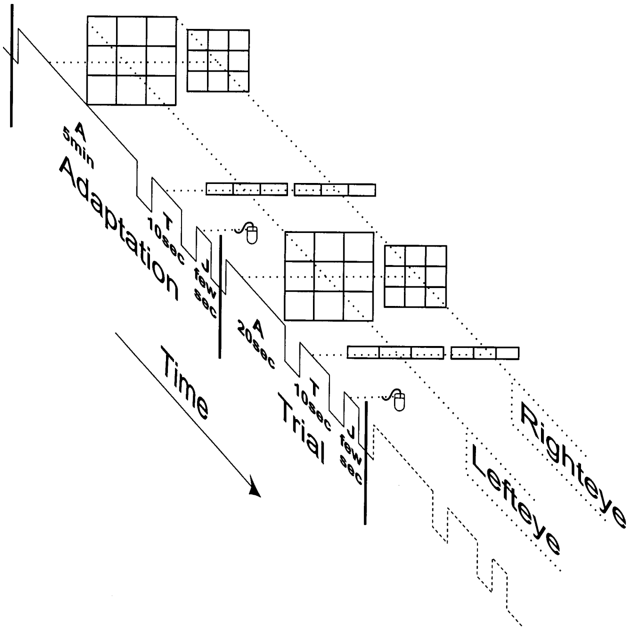

Fig. 1. Measurement scheme for experiment SCALE. The stimuli are shown schematically as grids. A measurement session started with five minutes presentation of the adapting stimulus (A), whereupon a test stimulus was presented (T) for 10 s. After the test stimulus the subject had to judge (J) whether the test stimulus was slanted towards the left or towards the right. Each following trial consisted of a period of 20 s adaptation (A), 10 s testing (T) and a judgement (J). The amount of horizontal scale in the test stimulus was adjusted every trial.

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 & Puts, 1997). A fixed number of trials, namely 50, were used as the stop criterion.

2.6. 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. The magnitude of the horizontal shear in the test stimulus that was perceived as a fronto-parallel strip was measured. The procedure was the same as in exp. SCALE. Adaptation to five magnitudes of vertical shear was measured: -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: -3.4, -1.7, 0, 1.7 and 3.4°). The thin test stimulus was oriented vertically so that subjects could discern slant about the horizontal axis.

2.7. Procedure for experiment MIX

In experiment MIX, we investigated adaptation to a combination of vertical quadratic mix and horizontal quadratic scale. The magnitude of the horizontal quadratic scale in the test stimulus that was needed to perceive the test strip as being fronto-parallel was measured. 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, adaptation to one magnitude of vertical quadratic mix was measured. 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.

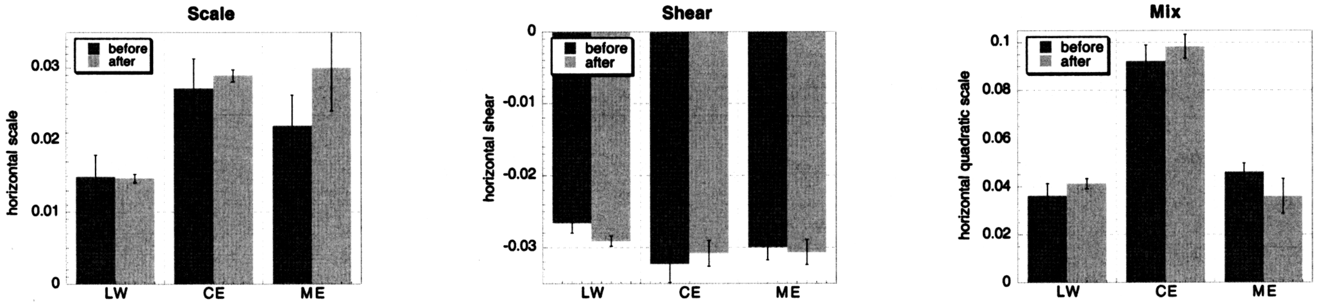

Fig. 2. The results of experiment FLAT. The amounts of horizontal transformation needed to perceive the adapting stimuli fronto-parallel before adaptation (dark grey bars) and after adaptation (light grey bars).

3. Results

3.1. Experiment FLAT

In experiment FLAT, we investigated whether the adapting stimuli were still perceived fronto-parallel after a presentation period of 5 min.

First, the combination of horizontal and vertical transformation that subjects perceived as being fronto-parallel before adaptation was determined. For subjects CE and LW, the ratios are known from previous experiments (Berends & Erkelens, 2001). For subject ME, those measurements were also carried out. 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 Fig. 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 Fig. 2).

Fig. 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.

3.2. 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. The results are shown in Fig. 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 1). The slopes of 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.

3.3. Experiment SHEAR

The results of exp. SHEAR are shown in Fig. 4. A linear relation (least squares) was fitted between the amount of shear in test strip and in the adapting stimulus of each subject (Table 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 ($P < 0.05$).

3.4. Experiment MIX

The results of exp. MIX are depicted in Fig. 5. A linear relation (least squares) was fitted between the amount of scale in test strip and in the adapting stimulus of each subject (Table 1). All the slopes of these fits differ significantly from zero ($P < 0.05$). Thus, a significant after-effect was found in exp. MIX. Only one offset (of subject ME) differed significantly from zero ($P < 0.05$).

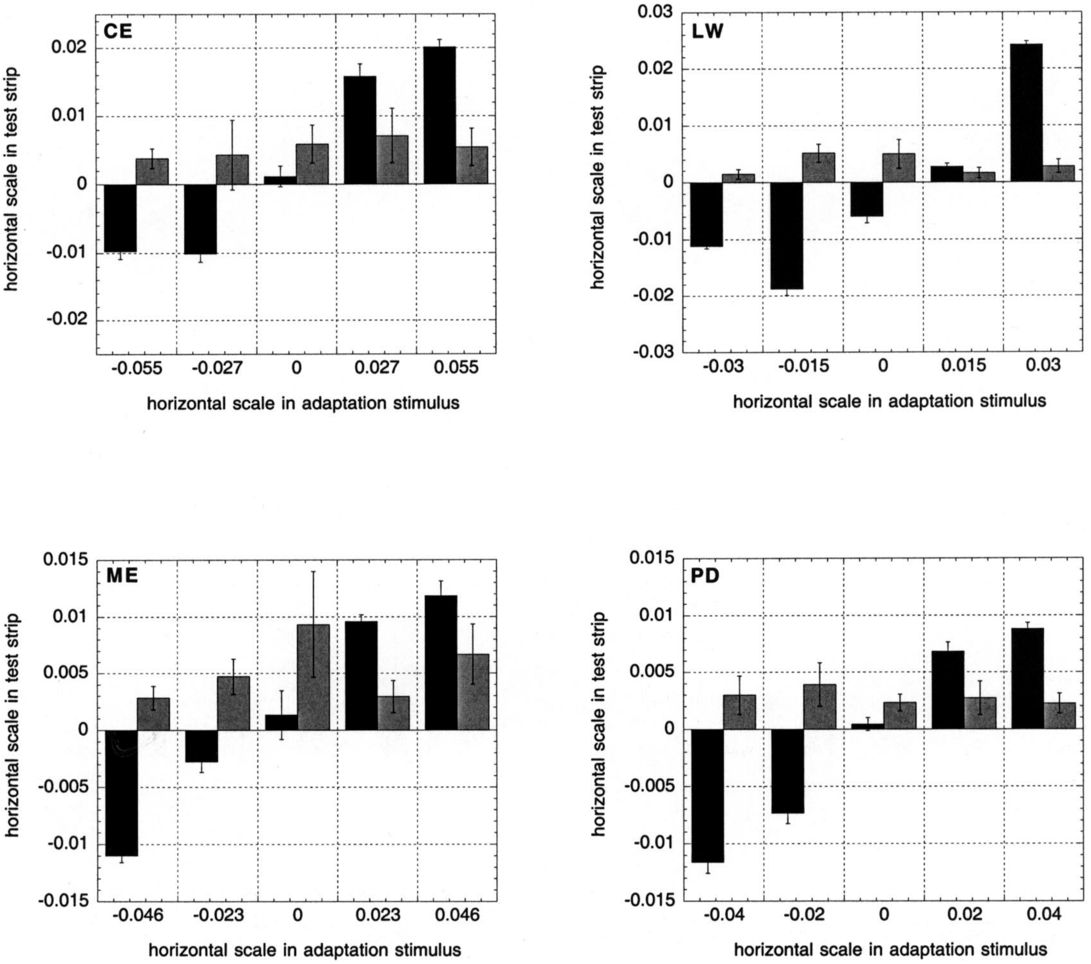

Fig. 3. The results of exp. SCALE. Adjacent pairs of black and grey bars represent a measurement session in which the parameters of a psychometric function were determined. The black bar is the μ value, which is the amount of horizontal scale needed to null the after-effect. The grey bar is the σ value, 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.

4. Discussion

4.1. Adaptation to disparity, not to perceived depth

We investigated whether adaptation to disparity can occur in the absence of a perceptual drive. It was found that the percept of the adapting stimulus did not change during prolonged viewing of combinations of vertical and horizontal transformations. The adapting stimulus was always perceived as a fronto-parallel plane. Stimulus-specific after-effects were found 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 an after-effect was found. The other explanation is that the visual system

Table 1
The ratios of horizontal transformation to vertical transformation in the adapting stimulus and the linear fit parameters for exp. SCALE, SHEAR and MIX

		CE	LW	ME	PD
SCALE	Ratio	0.91	0.50	0.76	0.67
	Slope	0.31[a]	0.61[a]	0.25[a]	0.27[a]
	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[a]	0.41[a]	0.24[a]	0.41[a]
	Offset	0.0089[a]	0.0111[a]	0.0122[a]	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[a]	0.41[a]	0.16[a]	0.25[a]
	Offset	−0.0115	0.0099	0.0095[a]	−0.0004
	R^2	0.89	0.87	0.88	0.79

[a] The offsets and the slopes differ significantly from zero ($P < 0.05$).

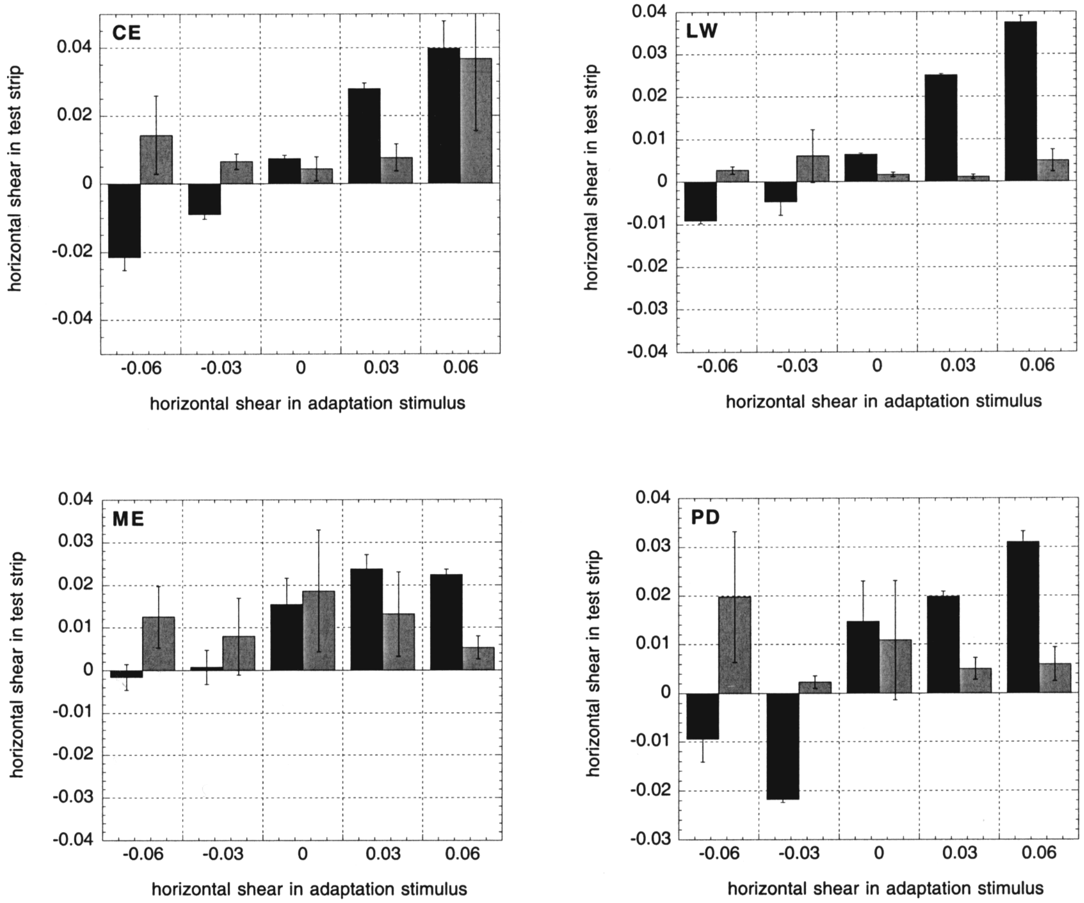

Fig. 4. The results of exp. SHEAR. Adjacent pairs of black and grey bars represent a measurement session in which the parameters of a psychometric function were determined. The black bar is the μ value, which is the amount of horizontal shear needed to null the after-effect. The grey bar is the σ value, 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.

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 otherwise the adapting stimulus could not remain fronto-parallel during adaptation. The present experiments do not 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.

4.2. 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 5°, opposite rotation of the visual fields in the two eyes. They measured the after-effect after 5 and after 20 min. 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 min 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 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 & Ellerbrock, 1946; Howard & 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 the 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.

4.3. 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 the explanation that adaptation is caused by a constant disparity signal will be discussed. 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, absolute retinal disparity was constant during adaptation. It is comprehensible that they attributed the after-effect to the adaptation of disparity-specific neurones. In the experiments of Ryan and Gillam (1993) and in the present experiments the subjects were free to look around. Thus, retinal disparity varied during the adaptation phases. Nevertheless, adaptation was found. 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

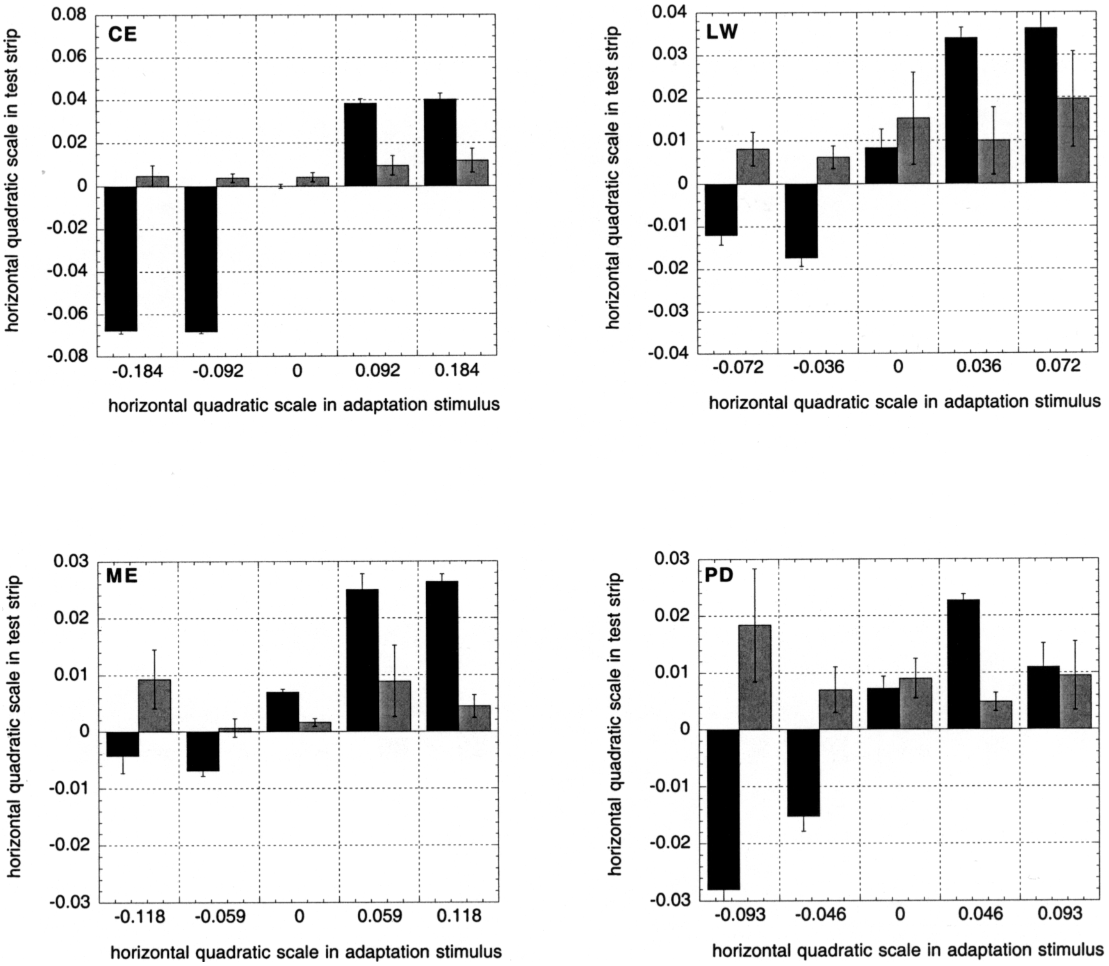

Fig. 5. The results of exp. MIX. Adjacent pairs of black and grey bars represent a measurement session in which the parameters of a psychometric function were determined. The black bar is the μ value, which is the amount of horizontal quadratic scale needed to null the after-effect. The grey bar is the 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.

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-Paap (1974) explained the adaptation in terms of recalibration of the relationship between retinal disparity and perceived depth. Burian (1943), Epstein (1971, 1972), Epstein and Morgan-Paap (1974), Lee and Ciuffreda (1983), Morrison (1972) 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 (Erkelens & 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 depth did not change during presentation of the adapting stimuli.

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