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Vertical disparity can alter perceived direction

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Abstract. It has been well established that vertical disparity is involved in perception of the three-dimensional layout of a visual scene. The goal of this paper was to examine whether vertical disparities can alter perceived direction. We dissociated the common relationship between vertical disparity and the stimulus direction by applying a vertical magnification to the image presented to one eye. We used a staircase paradigm to measure whether perceived straight-ahead depended on the amount of vertical magnification in the stimulus. Subjects judged whether a test dot was flashed to either the left or the right side of straight-ahead. We found that perceived straight-ahead did indeed depend on the amount of vertical magnification but only after subjects adapted (for 5 min) to vertical scale (and only in five out of nine subjects). We argue that vertical disparity is a factor in the calibration of the relationship between eye-position signals and perceived direction.

1 Introduction

Retinal signals and extra-retinal eye-position signals can be used for perception of the three-dimensional layout of a visual scene. Various methods for determining distance from retinal signals and extra-retinal eye-position signals have been proposed in the literature. Distance can be derived from a combination of horizontal and vertical disparity (Rogers and Bradshaw 1995). 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). That vertical disparity affects perceived distance does not necessarily imply that it is used for perceiving direction. Our goal here was to examine 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 (we define this scaling as positive), then the retinal vertical disparity corresponds to the disparity of an object that 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. We thus dissociated the directions specified by vertical disparity and by eye-position signals by means of 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 an interocular distance of 6.5 cm). If we assume that only eye-position signals are used to perceive direction, then the predicted change in perceived straight-ahead is zero.

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Other work is consistent with the prediction that scaling the stimulus vertically does not cause a change in perceived straight-ahead (Gillam and Lawergren 1983; Frisby 1984 for anecdotal evidence; and Banks et al 2002 for a thorough experiment), and thus that the actual vertical disparity is not used directly to determine perceived direction. This does not imply that vertical disparity and perceived direction are fully independent, because adaptation to vertical disparity might cause a change in perceived direction. Ebenholtz (1970) predicted that prolonged wearing of a magnifying lens in front of one eye would change the perceived direction. He reasoned that recalibration of the eye-position signals might occur because it can solve the conflict between direction specified by vertical disparity and direction specified by the eye-position signals. If adaptation occurs, then the maximum predicted change in perceived straight-ahead equals the difference between the conflicting directions specified by eye-position signals and vertical disparity. So far, Ebenholtz's hypothesis has not been tested experimentally.

Here, we investigate whether adaptation to a vertical scale causes a change in perceived direction, and attempt to replicate the finding that vertical scaling does not change the perceived direction immediately. 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 used to recalibrate the relationship between either disparity and perceived direction or eye-position signals and perceived direction. We argue that it is probably eye-position signals that are recalibrated.

2 Methods

2.1 *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 naïve (JB, MB, SH, RV, and LW).

2.2 *Apparatus*

An anaglyph setup was used for the generation of stereograms. The stimuli were generated by an HP750 graphics computer (refresh rate, 70 Hz) and back-projected on a frontoparallel translucent screen by a D-ILA projector (JVC DLA-G11E). The resolution (the minimum step in disparity) was 5.7 min of arc. The subject was seated 1 m from the screen. The red and green filters of the anaglyph setup were taped to the subject's head, so that the subject could not see the edges of the filters. 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 not restricted in making eye movements.

2.3 *Stimuli*

The stimuli were large stereograms (visual angles of 98 deg $\times$ 86 deg) consisting of sparse random-dot patterns, each containing 1250 dots. The dots were small (22.8 min of arc diameter), always circular, and not anti-aliased. Monocular flatness cues were minimised. A larger test dot (68.4 min of arc diameter) was used to measure perceived straight-ahead. The test dot was always placed at eye height, but its horizontal position was varied. The test dot was presented binocularly and it was transformed horizontally and vertically in the same way as the 'background' random-dot pattern.

2.4 *Task*

We used a purely visual task to measure changes in perceived direction. We asked subjects to judge whether a test dot was presented to their left or to their right (a forced-choice task).

We performed three experiments, one without adaptation (denoted 'direct') and two with (denoted 'adaptation' and 'control'). In the 'adaptation' experiment, we found that some subjects did not show an effect of adaptation. The strength of adaptation might be time-dependent. Therefore, it might be possible that a longer adaptation time results in an effect in subjects who did not show an effect and in a bigger effect in the other subjects. We examined this possibility in the 'control' experiment.

2.5 *Procedure for the 'direct' experiment*

The 'direct' experiment was subdivided into four sessions. In each session, we measured the difference in perceived straight-ahead when a certain amount of scaling was used and when an untransformed stimulus was presented. Four magnitudes of vertical scaling were used: −6%, −3%, 3%, and 6%. These magnitudes covered the range that could be fused by all subjects. Carefully determined magnitudes of horizontal scaling were added to the vertical scaling so that subjects perceived each stimulus as being frontoparallel (for detailed procedure see Berends and Erkelens 2001a). These magnitudes of horizontal magnification are subject-dependent (van Ee and Erkelens 1998). It is important in our study that we present a frontoparallel surface, because in this way perceived direction is not influenced by the perceived slant. Furthermore, presenting a frontoparallel surface means that there are 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 50 trials of untransformed stimuli and 50 trials of scaled stimuli. The trials were presented in random order. The series of untransformed trials was used to measure what a subject perceived as straight-ahead under normal circumstances, ie when there were 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 setup.

During each trial, either the untransformed stimulus or the scaled stimulus was presented. After 1 s, the test dot was flashed for 100 ms. 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. Then the next trial 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 staircase method (MUEST: Snoeren and Puts 1997).

2.6 *Procedure for the 'adaptation' experiment*

The 'adaptation' experiment was subdivided into five sessions. In each session, we measured the change in perceived straight-ahead after 5-min adaptation to a combination of horizontal and vertical scaling. Five magnitudes of vertical scaling were presented: −6%, −3%, 0%, 3%, and 6%. The magnitudes of horizontal scaling were again carefully chosen such that subjects perceived the stimulus as being frontoparallel. In previous work (Berends and Erkelens 2001a), we showed that the percept of a frontoparallel surface did not change, not even after 5-min adaptation. Thus, as in the 'direct' experiment, the perceived slant of the stimulus could not influence perceived direction.

At the beginning of each session we determined what subjects perceived as being straight-ahead before adaptation by presenting untransformed stimuli in a series of 50 trials. The untransformed stimuli were identical to those used in the 'direct' experiment. Subsequently, subjects adapted for 5 min to a specific combination of horizontal and vertical scaling (which they perceived as being frontoparallel). Then, we determined what subjects perceived as being straight-ahead after adaptation by presenting scaled stimuli in another series of 50 trials. The amount of horizontal and vertical scaling was the same as that of the adaptation stimulus.

After the adaptation period, untransformed stimuli could not be presented, because adaptation may disappear if a vertical disparity field different from the one in the adaptation stimulus is presented.

2.7 *Procedure for the 'control' experiment*

The procedure for the 'control' experiment was the same as for the 'adaptation' experiment with the difference that the adaptation time was 10 min for the 'control' experiment instead of 5 min for the 'adaptation' experiment. Four subjects participated: two who showed an effect in the 'adaptation' experiment (RV and EB) and two who did not (RE and LD).

3 Results

In a previous experiment, we determined which combination of horizontal and vertical scaling subjects perceived as a frontoparallel surface. We found a specific ratio of horizontal to vertical scaling for each individual subject (Berends and Erkelens 2001b). The same experiment was carried out to determine the ratios of horizontal scaling to vertical scaling used in the adaptation stimuli. The resulting ratios are shown in table 1.

Table 1. Results of the 'direct' and 'adaptation' experiments.

Subject	Ratio	'Direct' experiment fit			'Adaptation' experiment fit		
		R^2	slope significant	offset significant	R^2	slope significant	offset significant
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	+**	−

** Slope negative.

3.1 *The 'direct' experiment*

Psychometric curves (cumulative normal function) were fitted to the data provided by the staircase method. 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 1. The differences in perceived straight-ahead ($\mu_{\text{after}} - \mu_{\text{before}}$) 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 scaling in the adaptation stimuli for each subject (table 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. Almost all of the offsets (except the ones reported by LW and SH) do not differ significantly from zero ($p > 0.05$).

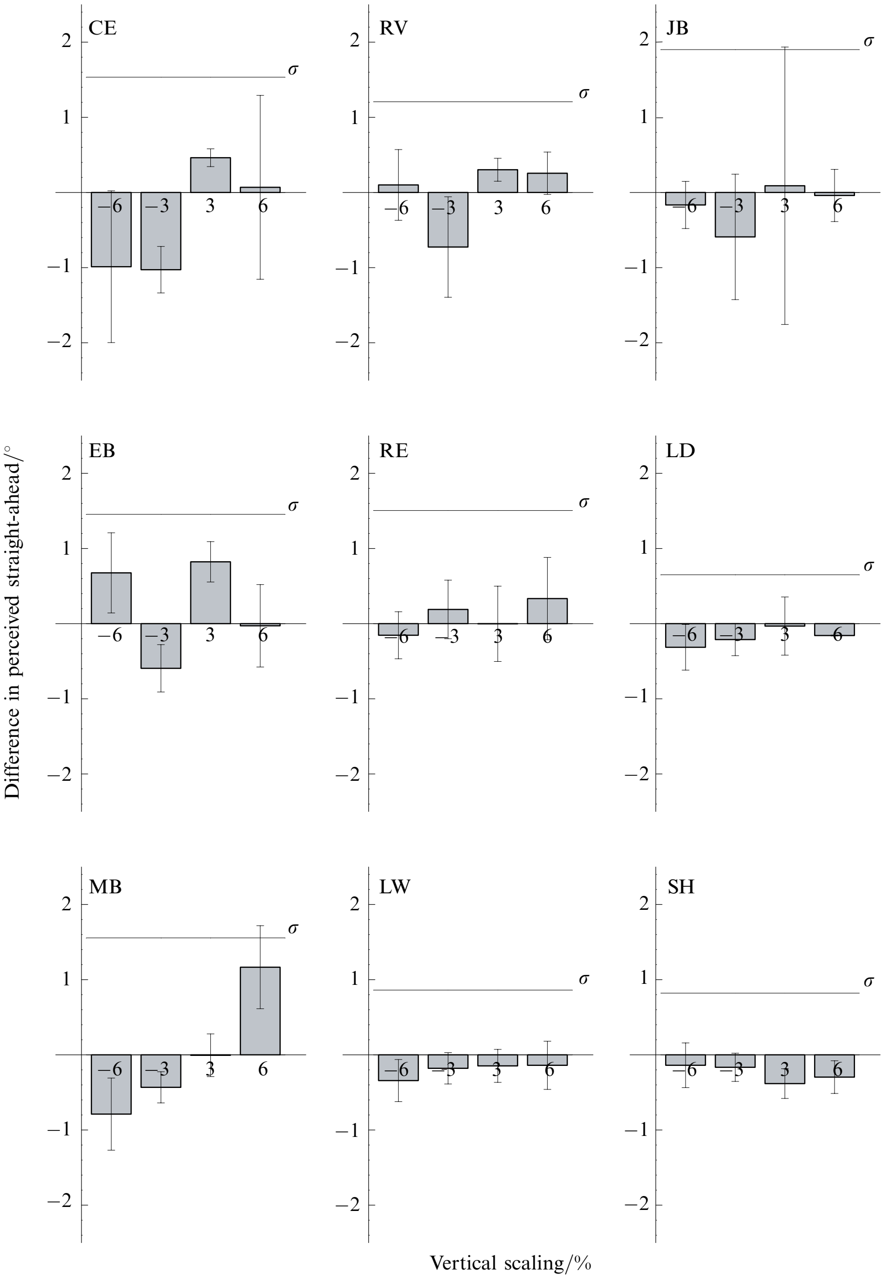

Figure 1. Results of the 'direct' experiment. Each panel shows the results for one subject. In each panel, the values on the x-axis represent the amount of vertical scaling in the stimulus. Positive scaling means a magnification of the image presented to the left eye. The heights of the shaded bars represent the change in perceived straight-ahead ($\mu_{\text{after}} - \mu_{\text{before}}$). A positive change is a change to the right. 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 ($\sigma_{\text{after}} + \sigma_{\text{before}}$). It indicates the sensitivity of the subject.

3.2 *The 'adaptation' experiment*

The staircase method was also applied to find the straight-ahead direction before and after adaptation. The processing of the data of the 'adaptation' experiment was the same as in the 'direct' experiment. The results are shown in figure 2. The changes in perceived straight-ahead ($\mu_{\text{after}} - \mu_{\text{before}}$) are often larger than the estimated errors (error in μ_{after} + error in μ_{before}).

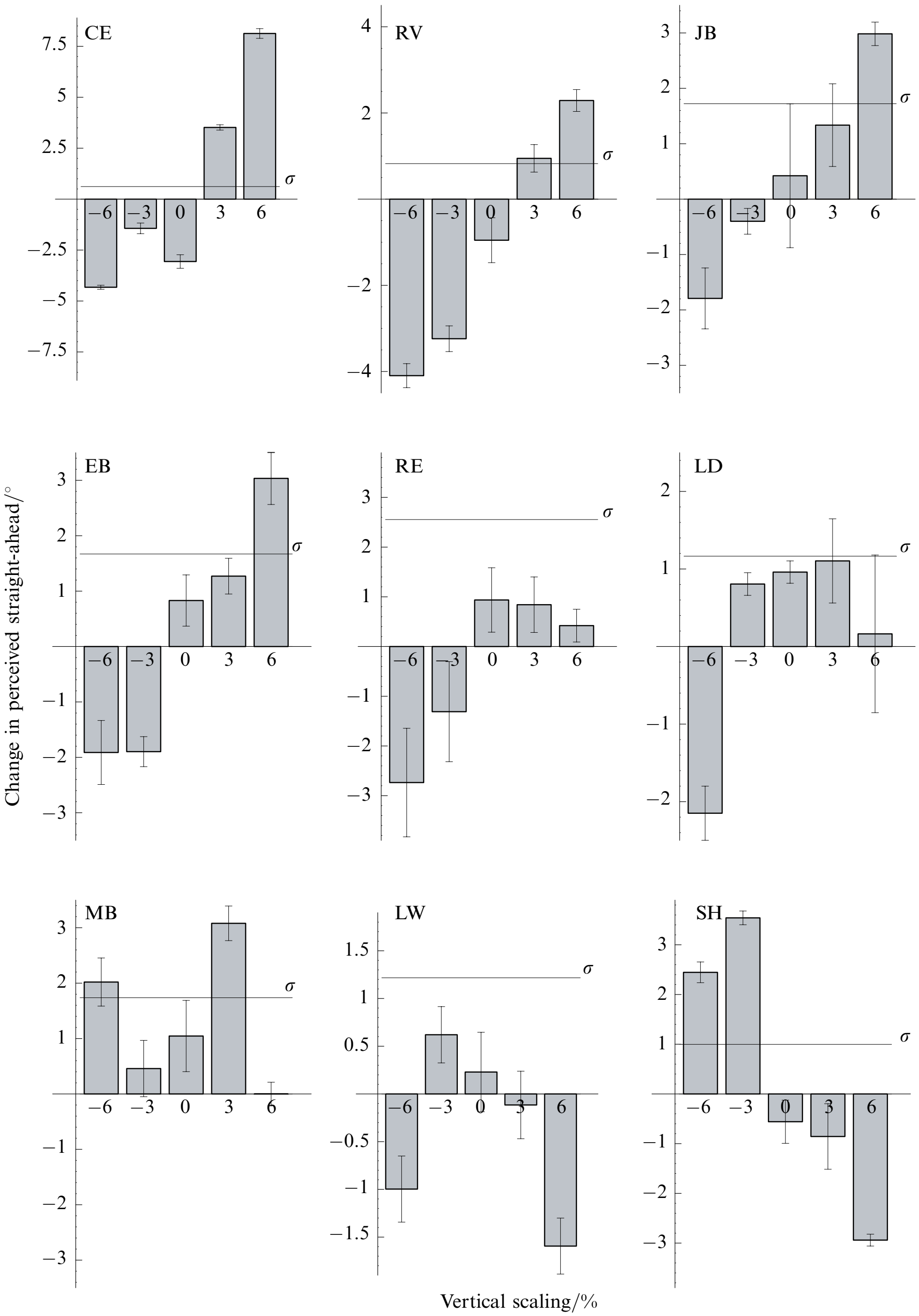

Figure 2. As figure 1, but for the 'adaptation' experiment (5-min adaptation time). Note that the scales on the vertical axes differ across subjects.

Linear relations (least squares) were fitted between the changes in perceived straight-ahead and the amounts of vertical scaling in the adaptation stimuli for each subject (table 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 scaling 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 the 'direct' experiment.

3.3 *Results versus predictions*

In the 'adaptation' experiment, we found a change in perceived straight-ahead directions. In this section, we compare the direction and the magnitude of these changes with those resulting from our prediction that the cue conflict between vertical disparity and eye-position signals causes recalibration of the eye-position signals.

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. The conflict between directions indicated by oculomotor signals and by vertical disparity reduces when the eye-position signals that are used for perception of direction, and thus perceived straight-ahead, shift to the right. In four subjects, we did indeed find that adaptation to positive scaling induced a change to the right in perceived straight-ahead direction. We have no explanation for the fact that one subject showed a change in the opposite direction.

The predicted maximum change in perceived straight-ahead after adaptation is equal to the difference between the direction specified by the eye position and the direction specified by vertical disparity, 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 we could not even measure changes in perceived straight-ahead. Several reasons can be given for this difference. The first reason may be that the maximum adaptation was not yet reached after the limited adaptation time (5 min). The second reason may be the presence of visual references which counteracted the scaling of the stimulus. There were references that could not be removed, for instance the nose and the eyebrows of the subject. Although the nose and the eyebrows themselves were not visible because the room was completely dark, these facial features cause different occlusions in images presented to the left and the right eye. We suggest that different sensitivities of individual subjects to these visual references may explain the differences between subjects. A reason for not finding an effect in all subjects might be due to a difference in strategy between subjects. Because subjects are looking at a frontoparallel stimulus, they might be determining straight-ahead by determining where the cyclopean line of sight is normal to the frontoparallel surface. If subjects use this strategy instead of determining direction directly, they will not show a change in perceived straight-ahead, because the percept of the stimulus does not change (Berends and Erkelens 2001a).

3.4 *The 'control' experiment*

In the 5-min adaptation experiment, we found that only five out of nine subjects showed an effect of adaptation. It might be the case that a 5-min adaptation period is not sufficient. In the 'control' experiment, we examined whether 10 min of adaptation would show results more consistent across subjects. The data were processed in the same way as for the 5-min adaptation experiment. Figure 3 shows the results. Linear relations (least squares) were fitted between the changes in perceived straight-ahead and the amounts of vertical scaling in the adaptation stimuli for each subject. For subjects LD and RE, who did not show an effect for the 5-min experiment, the slopes of these fits did not differ significantly from zero ($p > 0.05$). Thus, the longer adaptation period did not result in an effect for these subjects. For subjects RV and EB, the slopes of the fits in the 10-min adaptation experiment did not differ significantly from the ones with 5-min adaptation ($p > 0.05$). Thus, for these subjects the longer adaptation time did not result in a bigger effect. It seems that 5-min adaptation time is enough for reaching maximum adaptation.

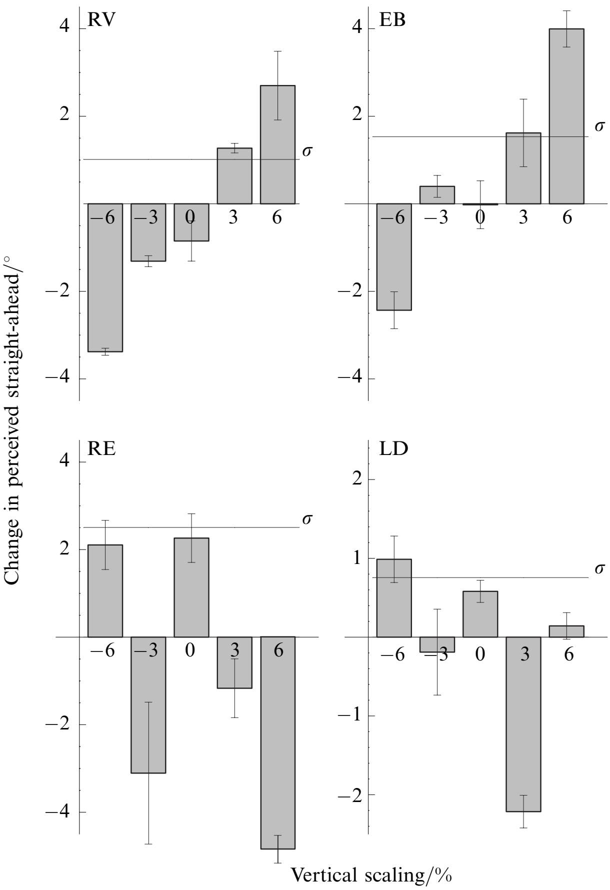

Figure 3. As figure 1, but for the 'control' experiment (10-min adaptation time). Note that the scales on the vertical axes differ across subjects.

4 Discussion

Our main finding is that perceived straight-ahead did depend on the amount of vertical magnification in the stimulus, but only after subjects adapted for 5 min (and only in five out of nine subjects).

In the 'direct' experiment, 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 is consistent with the observations of Gillam and Lawergren (1983) and Frisby (1984) and the experimental results of Banks et al (2002). Banks et al performed experiments in which they varied the amount of vertical magnification between -11% and 11% for a viewing distance of 19 cm and between -4% and 4% for a viewing distance of 57 cm. The task of the subjects was to indicate perceived direction of a visual stimulus by manually moving an unseen pointer. Banks et al found that perceived direction did not depend on the amount of vertical disparity in the stimulus. They argued that perceived direction is estimated from eye-position signals rather than from vertical disparity.

In the 'adaptation' experiment, we found that the direction of perceived straight-ahead changed significantly in five out of nine subjects after adaptation to magnified stimuli. Thus, an adaptation period is required to change perceived straight-ahead. The change in perceived straight-ahead might be caused by a recalibration of the relationship between vertical disparity and perceived direction[1] and/or by a recalibration of the relationship between the eye-position signals and perceived direction[2]. We found in the 'direct' experiment that disparity does not influence perceived direction. Thus, disparity is not used for perceiving direction. Therefore, a change in perceived direction is probably not caused by a recalibration of disparity. Thus, we suggest that our results reflect a recalibration of the eye-position signals.

4.1 *Adaptation to vertical disparity*

In this section, we discuss whether the adaptation could have been caused either by a perceptual drive or by the horizontal and/or the vertical disparities in the stimulus. In a previous paper, we showed that the perceived slant of the stimulus remained zero during adaptation (Berends and Erkelens 2001b). Therefore, there is no perceptual drive that may cause the adaptation. Thus, adaptation must be caused by disparities.

The experiments of Epstein and Daviess (1972) indicate that adaptation is not caused by the horizontal disparities either. Epstein and Daviess investigated whether perceived straight-ahead changed after subjects had adapted to a meridional size lens with a vertical axis, which induced only a horizontal scale. They found no change in perceived direction. Their results suggest that in our experiments vertical scaling is responsible for the change in perceived direction. Another reason why adaptation is not likely to be caused by horizontal disparity is that horizontal disparity gives ambiguous information about the direction of a stimulus. Two surface patches placed at different eccentricities (azimuth) and different slants about the vertical axis can have the same horizontal disparities (von Helmholtz 1911/1925; Ogle 1950).

4.2 *Feedback from the oculomotor system*

It is known that perceived direction can change after a period of adaptation. Von Helmholtz (1911/1925) showed that visually perceived direction could change after prolonged wearing of wedge prisms. After Helmholtz, 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

(1) Similar to the recalibration of the relationship between horizontal disparity and perceived slant that occurs after prolonged wearing of a horizontally magnifying lens as showed by Adams et al (2001) and suggested by Epstein and Morgan (1970) and Epstein (1972).

(2) Similar to the recalibration of the relationship between eye-position signals and perceived slant as suggested by Berends and Erkelens (2001a).

experiments it is not clear what was adapted. Hay and Pick (1966), Kalil and Freedman (1966), Craske (1967), McLaughlin (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, feedback from the proprioceptive system of the hand was involved in the adaptation. In our experiments there was no feedback from the proprioceptive system of the hand. Therefore, we believe that in our experiment feedback must have been provided by the oculomotor system.

4.3 *Adaptation of the oculomotor system?*

There are two types of eye-position signals which could have been 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. 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. Kapoula et al (1995) and van der Steen and Bruno (1995) found that the amplitudes of horizontal and vertical saccades were adapted after presentation of a combination of horizontal and vertical scaling. Thus, the change in saccade amplitudes and the change in perceived direction might both be manifestations of the same effect.

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