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 an 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 ($\mu_{after} - \mu_{before}$) 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 ($\mu_{after} + \mu_{before}$). 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: \( \mu \) indicates the position on the screen that a subject perceived as lying in the straight-ahead direction and \( \sigma \) indicates how accurately a subject estimated this direction. Monte Carlo simulations were performed to estimate the errors in \( \mu \) and \( \sigma \). 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 (\( \mu_{\text{after}} - \mu_{\text{before}} \)) are mainly smaller than the estimated errors (error in \( \mu_{\text{after}} \) + error in \( \mu_{\text{before}} \)), 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 (\( \mu_{\text{after}} - \mu_{\text{before}} \)) are often larger than the estimated errors (error in \( \mu_{\text{after}} \) + error in \( \mu_{\text{before}} \)).

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.

| subject | Ratio | Experiment DIRECT | | | | | Experiment ADAPTATION | | | |
|---------|-------|-------------------|---|---|---|---|---|---|---|---|---|
|         |       | \( R^2 \) | Slope | Offset | \( R^2 \) | Slope | Offset |
|         |       | significant | significant | | significant | 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.