Adaptation to the induced effect stimulus normalizes surface slant perception and recalibrates eye position signals for azimuth

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A frontoparallel plane viewed with unequal vertical magnification of the two ocular images appears rotated about a vertical axis (i.e., induced effect; Ogle, 1938). Several experiments were conducted to investigate changes in the visual system that occurred after adapting to the induced effect. Adaptation at 57 cm was tested using tall stimuli at various viewing distances to test for the adaptation of vertical size ratio (VSR) information and normalization of the slant percept. When aftereffects were expressed in units of slant, they were larger at 57 cm than other test distances and were not significantly different from each other at other distances. Short stimuli were used to test adaptation of eye position signals for azimuth. The aftereffects were in the opposite direction to those measured with tall stimuli. The combined results suggest that the visual system normalizes slant percepts based on the surface slant of the adaptation stimulus and when there is a conflict between VSR signals and eye position cues for azimuth that the primary eye position signal for azimuth is recalibrated toward the direction indicated by the binocular differential vertical magnification in the adaptation stimulus.

Keywords: aftereffects, binocular vision, disparity, eye position signals, induced effect, stereo-slant adaptation, stereopsis, VSR

Introduction

Adaptation

Adaptation of the visual system optimizes estimates of space to achieve veridical percepts. Adaptation is necessary because the relationship between measured signals and the physical world changes over time, for instance with ocular growth and optical devices. Two main types of adaptation are described in the literature, namely, normalization (Gibson, 1937; Howard & Rogers, 1995) and recalibration (Wallach, 1968). During adaptation, normalization occurs when a prolonged stimulus leads to a shift or bias in the percept of an expected value or prior such as the frontoparallel. Recalibration occurs when two cues or modalities provide conflicting information for estimating one scene property such as surface slant. During adaptation, individual cues are recalibrated to bring estimates into alignment.

Stereo-normalization

Stereo-depth adaptation was first reported by Blakemore & Julesz (1971). They found biases in depth perception after adaptation of depth produced by binocular disparity. Other studies investigated adaptation to surface slant or surface curvature generated from binocular disparities. Viewing a slanted surface produced by horizontal disparity for a few minutes caused a frontoparallel surface to be seen slanted in the opposite direction as the adaptation slant (Adams, Banks, & van Ee, 2001). A flat surface appeared to have a curvature opposite to the adapted surface after adaptation (Domini, Adams, & Banks, 2001; Graham & Rogers, 1982). In these experiments, cue conflicts between stereoscopic and monocular cues were minimized by using sparse random-dot stimuli. These are examples of normalization that is defined based on no-cue conflicts for surface depth, slant, or curvature of the adapting stimuli. There is evidence that adaptation to stereo-slant is a normalization process that occurs mainly at the perceptual level or mapping level (e.g., Berends, Liu, & Schor, 2005; Domini et al., 2001; Duke & Wilcox, 2003). If normalization of surface slant occurs at the perception or mapping level, it should not matter how stereoscopic slant is generated for the adaptation stimuli, that is, either by differential horizontal magnification or by differential vertical magnification. The slant percept can be identical with different combinations of horizontal and vertical magnifications (i.e., they are
metamers; Backus, 2002) and the aftereffects of adapting to the same slant percept might be expected to be the same.

Cue conflicts in stereo-perception: a stimulus for stereo-recalibration

Stereo-slant estimates are based on horizontal size ratios (HSR) and cues for distance and azimuth (Backus, Banks, van Ee, & Crowell, 1999). Two different cues for azimuth are vertical size ratio (VSR) and eye position signals. These cues normally agree with each other but they can be placed in conflict with unequal vertical magnification of the two ocular images. When a fronto-parallel surface is viewed with a vertical magnifier before one eye, the VSR influences the azimuth estimate and the frontoparallel surface is perceived as slanted around a vertical axis closer to the magnified eye (the induced effect) (Ogle, 1938). In the induced effect, there is a conflict between the azimuth specified by differential vertical magnification and eye position signals. The VSR provides an azimuth cue for gaze to the side of the magnified ocular image. In contrast, the eye position signal (extra-retinal information) specifies that the eyes are looking straight ahead when they are in primary position. Adaptation to the induced effect could involve both normalization of the slant percept and recalibration in response to the conflicts between individual cues for azimuth. The visual system may recalibrate either source of azimuth information or both of them to resolve the conflict. In the induced effect, either the azimuth indicated by eye position signals or the azimuth indicated by differential vertical magnification or both of them might be recalibrated.

Study design

Three types of adaptation to the induced effect are possible, that is, normalization of the perceived slant, recalibration of VSR signals, and recalibration of the eye position signals.

To distinguish between the potential normalization and recalibration components of adaptation to the induced effect, we used two properties of slant perception from binocular disparity. First, horizontal slant (i.e., slant around a vertical axis) stimulated by horizontal and vertical differential magnification scales with distance (see Property 1). Perceived slant is expected to increase with distance for a particular disparity pattern. This distance scaling property can be used to distinguish between recalibration of VSR signals and normalization of slant percepts, independent of viewing distance. We can also distinguish between recalibration of VSR and of eye position signals by varying test stimulus height (see Property 2). When an observer estimates a surface slant generated from stereoscopic cues, VSR signals are weighted more for tall surfaces and eye position signals are weighted more for short surfaces (Backus et al., 1999).

Property 1: Horizontal slant produced by a constant disparity pattern scales with distance

This property was used to distinguish the normalization of surface slant and recalibration of vertical disparities.

Surface slant relative to the straight-ahead direction (i.e., head-centric slant) can be estimated from combinations of viewing distance, azimuth, VSR, and HSR (Backus et al., 1999; Rogers & Bradshaw, 1993):

\[
\text{Slant} = -\tan^{-1}\left(\frac{1}{\mu}\frac{\text{HSR}}{\text{VSR}}\right) + \gamma,
\]

where \(\mu\) is the vergence angle, which is inversely proportional to the viewing distance, \(\gamma\) is the version angle, HSR is the horizontal disparity (i.e., horizontal size ratio, the ratio between the horizontal angles subtended by a surface patch in the left and the right eye), and VSR is the ratio between the vertical angles subtended by a surface patch in the left and right eye. This equation shows that head-centric slant from HSR and VSR depends on viewing distance. Slant produced by a particular disparity pattern (combination of HSR and VSR) increases with viewing distance.

Three hypotheses were tested using similar techniques to those used in previous research on adaptation to surface slant produced with HSR (Berends et al., 2005). The first hypothesis states that recalibration of VSR signals occurs (i.e., there is low-level adaptation). This predicts that aftereffects, expressed in units of differential horizontal magnification, will be constant when tested at different distances. The second hypothesis states that adaptation occurs at the perception or mapping level (i.e., slant normalization). This predicts that the aftereffects, expressed in units of slant, will be constant when tested at different viewing distances. In other words, surface slant percept could be normalized without recalibrating VSR signals for azimuth that contribute to the slant estimate. The results of the present experiments are predicted to show high-level adaptation (i.e., the perception or mapping level) since adaptation was previously found to be high-level for stereoscopic slanted surfaces (Berends et al., 2005). The third hypothesis is that the aftereffect is distance dependent such that adaptation is only, or principally, manifested at the same distance as the adaptation stimulus.

Using the relationship between the disparity pattern, viewing distance, and the perceived slant, the amount of aftereffects based on the three hypotheses can be predicted from the magnitude of the aftereffect tested at...
the same distance as the adaptation stimulus. By comparing the results with the predictions, we can determine which of the three different types of aftereffects occur. In the General discussion section, we discuss a method to quantify the amounts of each type of aftereffect.

Note that tall test stimuli were used so that adaptation of the eye position signals was down-weighted compared to VSR signals for azimuth (see Property 2) and this method does not test recalibration of the eye position signals for azimuth.

**Property 2: VSR and eye position signals are weighted differently with stimulus height according to their reliability**

This property was used to distinguish between recalibration of VSR and of eye position signals for azimuth.

Stereoscopic surface slant estimates can utilize azimuth signals from eye position version signals without using VSR information. Equation 1 shows how head-centric slant can be obtained from HSR, VSR, and azimuth information from the eye position signals. Head-centric slant can also be estimated from HSR and eye position signals without VSR information (see Equation 2).

\[
\text{Slant} \approx -\tan^{-1}\left(\frac{1}{\mu} \ln (\text{HSR}) - \tan \gamma\right) + \gamma.
\]  

Equation 2

On the other hand, if azimuth is estimated by the combination of VSR and the vergence signal (see Equation 3 below), a surface slant can be estimated without eye position version signals (see Equation 4 below).

\[
\gamma \approx \tan^{-1}\left(\frac{\ln \text{VSR}}{\mu}\right),
\]  

Equation 3

\[
\text{Slant} \approx -\tan^{-1}\left[\frac{1}{\mu} \ln(\text{HSR}) - \left(\frac{\ln \text{VSR}}{\mu}\right)\right] + \tan^{-1}\left(\frac{\ln \text{VSR}}{\mu}\right).
\]  

Equation 4

As shown in Equations 2 and 4, the visual system can use either eye position version signals or VSR for azimuth estimation and then surface slant can be estimated without using the other source of azimuth information. Previous research showed that the visual system assigns different weights to the two sources of azimuth for slant estimates depending on the height of a surface (Backkus et al., 1999). VSR signals are weighted more for tall stimuli, and eye position signals are weighted more for short stimuli. When VSR and eye position signals were in conflict with one another, for one subject, about 85% of the slant estimation of a 30° height stimulus was based on the combination of HSR and VSR. Meanwhile, about 70% of the slant estimation for a stimulus with 1.3° height was based on the combination of HSR and eye position signals.

In the current experiments, the adaptation stimuli were tall surfaces and the aftereffects were quantified with either short or tall test stimuli. The amplitude of the aftereffects is related to the height of test stimuli and the corresponding weights assigned to VSR and eye position signals. When the test stimulus was short, mainly adaptation of the slant percept and the recalibration of eye position signals for azimuth should be revealed. When the test stimulus was tall, mainly the adaptation of the percept and the recalibration of VSR signals should be revealed.

The signs of aftereffects due to different adaptation processes

Recalibration of VSR and eye position signals will produce aftereffects in opposite directions. We will first consider an example to clarify the conflicts between the azimuth indicated by VSR signals and by eye position signals and then we will illustrate how the aftereffects differ depending on what source of azimuth information is recalibrated. Assume that the left eye’s retinal image is vertically magnified in the adaptation stimulus. A slanted surface will be perceived with left side closer and right side farther away. This VSR specifies that the target azimuth is to the left, whereas eye position signals specify that azimuth is straight ahead. During adaptation, the azimuth indicated by VSR information may be recalibrated (biased) and the leftward azimuth indicated by vertical magnification in the adaptation stimuli shifts towards the cue for primary straight-ahead direction. Following adaptation of a stimulus with the left eye’s image vertically magnified, when a tall frontoparallel test stimulus is presented straight ahead without any differential vertical magnification, the azimuth estimate will be to the right and the surface will appear to be slanted to the left (i.e., slanted away to the left) in the opposite direction as the adaptation stimulus (negative aftereffect).

The sensed straight ahead from eye position signals may also be adapted to the cue conflict between VSR and eye position signals. During adaptation to the same stimulus, azimuth sensed from eye position in primary gaze could be shifted from straight ahead to the left in the direction of the azimuth indicated by differential vertical magnification. Following adaptation of azimuth estimates from eye position signals, when a short frontoparallel test stimulus is presented straight ahead, the surface will appear to be slanted to the right (i.e., slanted away to the right) in the same direction as the adaptation stimulus.
(positive aftereffect). Thus, adaptation of the azimuth cues from differential vertical magnification or eye position signals leads to opposite signs of the aftereffects and the results can be analyzed because of this property.

If there is normalization of the surface slant percept, the aftereffect is negative and has the same sign as the aftereffect from recalibration of VSR signals described above. Following the example in the previous paragraph, a vertical magnification of the left eye’s retinal image will generate a perception of a surface slanted to the right with right side farther away. After adaptation, the perception of the adapting stimulus may shift toward frontoparallel and a frontoparallel surface without the vertical magnifier will be seen as slanted in the opposite direction as the adaptation stimuli (i.e., slanted away to the left). The normalization aftereffect is negative, which is the same as the direction of the aftereffect due to recalibration of VSR signals. Therefore, it is impossible to distinguish normalization of slant percept and recalibration of VSR information simply from the sign of the aftereffects. However, these aftereffects can be distinguished by varying test distance as described above under Property 1. Recalibration of the eye position signals, on the other hand, can be distinguished from the other two types of adaptation (i.e., normalization of surface slant and recalibration of VSR signals) by the sign of the aftereffect.

Can VSR and/or eye position signals for azimuth be adapted?

Berends & Erkelens (2001) demonstrated that recalibration occurred when there was a cue conflict between VSR and eye position signals for azimuth. When observers adapted to a tall frontoparallel surface generated by a combination of horizontal and vertical magnification of one ocular image, there was a cue conflict between eye position signals and the VSR signals for azimuth. When aftereffects were tested with a tall test strip, no aftereffects were found, suggesting that there was no adaptation of VSR signals or horizontal disparity or that aftereffects were in opposite directions and they cancelled one another. When the resulting aftereffects to the tall stimulus were tested using a short test strip that emphasized the weight of eye position signals in slant estimation, they found that a significant amount of horizontal disparity was required to null the aftereffect. The results suggested that eye position signals might be recalibrated after adaptation. Because the adapting stimulus was a frontoparallel plane, it was not possible to test for the normalization of surface slant. Duke & Wilcox (2003) also provided evidence that adaptation to VSR did not occur. In their experiments, adaptation of the same slant percept generated from different combinations of HSR and VSR led to the same aftereffects tested by using only horizontal disparity. This result suggests that there is no adaptation to VSR signals per se, but there is adaptation to the high-level slant perception (i.e., normalization of the slant percept). This study did not use short and tall stimuli to test for recalibration of eye position signals for azimuth. The present paper investigated the possibility of recalibration of azimuth signals and normalization of slant percepts following adaptation to the induced effect.

Summary

A surface is perceived as slanted around a vertical axis when one half-image is vertically magnified relative to the other (i.e., the induced effect). The induced effect introduces a cue conflict between VSR and eye position signals for azimuth. In the present study, we investigated three possible adaptation processes in the visual system after adaptation to the induced effect: stereo-depth adaptation that occurs at the perception or mapping level (i.e., normalization of surface slant), recalibration of eye position signals, and recalibration of VSR signals for azimuth.

General methods

Experiments 1–4 had similar display technology, stimuli, subjects, and procedures. The experiments differ in terms of how the aftereffect was measured and the differences are listed under each experiment.

Display and stimuli

Stimuli were presented on a 20-in. monochrome monitor (Monoray Model M20ECD5RE; Clinton Electronics, IL, USA) at 120 Hz noninterlaced frame rate with 1024 × 768-pixel resolution. This monitor had a fast DP 104 phosphor that decayed to 0.1% peak in 0.6 ms. Because the same screen area was used to generate the stereograms with shutter glasses, the fast phosphor decay was used to minimize the cross talk between images presented to left and right eyes. Video images were controlled by using Visual Stimulus Generators (VSG) 2/5 graphics card (Cambridge Research Systems, Kent, England) in a host Pentium II computer. The images were corrected for any screen distortions at the 57-cm viewing distance using a grid-loom calibration method (Backus et al., 1999). At that viewing distance, each pixel subtended 2.1 arcmin. Subpixel resolution was obtained by anti-aliasing each dot. Stimuli were viewed through 120-Hz Ferro-shutter optics (model FE-1 ferro-electric shutter goggle; Cambridge Research Systems, Kent,
England). Each eye viewed stimuli at 60 Hz with no discernible flicker.

Two types of stimuli were used. Adaptation stimuli were large elliptic patches (30° horizontal × 24° vertical) composed of random dots with vertically magnified half-images. The test stimuli were large round random-dot patches (24° horizontal × 24° vertical) with horizontally magnified half-images. The difference in the outline between adaptation and test stimuli (i.e., oval vs. round) made it easy for subjects to distinguish between the two kinds of stimuli. The random dots were sparse (5% dot density) and irregularly spaced to minimize perspective and texture cues for surface orientation. The size of a dot is defined by the width of a Gaussian luminance profile (σ = 2/3 pixel) and its peak luminance of 4.2 cd/m² when viewed through the Ferro-shutters. Surface patches had different distributions of random dots, which was to avoid changes in perceived image compression to be used as a cue for surface slant.

The half-images were differently vertically magnified in the adaptation stimulus to produce a perceived slant about the vertical axis. Four magnitudes of vertical magnification were applied: −4%, −2%, 2%, and 4%. A positive magnification corresponds to a vertical magnification of the left eye’s image and a vertical magnification of the right eye’s image. A 2% vertical magnification is accomplished by 1% vertical magnification in the left eye’s image and 1% vertical magnification in the right eye’s image.

Test stimuli were generated with horizontal magnification of the half-images to produce a perceived slant about the vertical axis. A 2% horizontal magnification is accomplished by 1% horizontal magnification in the left eye’s image and 1% horizontal magnification in the right eye’s image. In the present set of experiments, test stimuli were generated by varying horizontal magnification continuously while keeping differential vertical magnification at one. Since a certain amount of surface slant can be generated from different combinations of vertical and horizontal magnifications (i.e., they are metamers; Backus, 2002), the amount of horizontal magnification in the test stimuli that is required to null the aftereffects is an indication of the amount of aftereffect expressed in vertical magnification. Here we assume that the horizontal disparity in the adaptation stimuli is not adapted as suggested by previous study (Berends et al., 2005). With this technique, the three hypotheses about the adaptation level can be tested (see the Introduction section) by using a geometric relationship between horizontal disparity, viewing distance and perceived slant (van Ee & Erkelens, 1996; see Equation 5 below). Prediction about perceived slant at different distances can be made based on the amount of horizontal disparity needed to null the after-effect at the adaptation distance and the viewing distance of the test stimuli (see details in the General discussion section). This method also makes the results comparable to the study on the adaptation to surface slant generated by horizontal disparity (Berends et al., 2005).

\[
\text{Slant} = \arctan \left( \frac{M - 1}{M + 1} \frac{2Z_0}{I} \right),
\]

Equation 5 shows the relationship between mathematical prediction of surface slant, horizontal magnification, and viewing distance. \( M \) is the horizontal magnification, \( Z_0 \) is the viewing distance, and \( I \) is the inter-ocular distance. As indicated by the equation, when the distance increases, the same amount of horizontal magnification leads to larger surface slant.

The adaptation stimulus was always presented at 57 cm from the observer whereas the simulated test distance for test stimuli ranged across measurement sessions (28, 57, 85, or 114 cm). The simulated distances were specified by the horizontal gradient of vertical disparity (Rogers & Bradshaw, 1993) and vergence cues, both of which were altered by translating both eyes’ images horizontally in the opposite direction. The stimulus to accommodation remained fixed at the distance of the monitor, located 57 cm from the observer. The total amount of translation is defined by

\[
\Delta = I \left( 1 - \frac{z_{\text{screen}}}{z_{\text{simulated}}} \right),
\]

with \( I \) symbolizing the inter-ocular distance. The \( z_{\text{screen}} \) is the distance of the monitor to the eyes and \( z_{\text{simulated}} \) is the simulated distance of the stimuli to the eyes.

**Procedure**

The experiments were conducted in separate sessions that lasted about 20 min each. There were three phases in each measurement session. In the pre-adaptation phase, the amount of horizontal magnification needed to perceive the test stimulus as frontoparallel was measured. The pre-adaptation phase was followed by the adaptation phase during which subjects viewed the adaptation stimulus for 5 min. In the post-adaptation phase, the horizontal magnification needed to perceive the test stimulus as frontoparallel was quantified. Perceived slant was varied with horizontal magnification during the pre- and post-adaptation test phases.

The stimuli were presented at the center of the screen (straight ahead). The observer’s head position was restricted by a bite bar and a headrest. The eye position was kept at the viewpoint. The stimuli were presented in complete darkness to eliminate visibility of the room, edges of the monitor, and facial features as a frame of reference.
In the post-adaptation testing phase, a “topping-up” procedure (Graham & Rogers, 1982) was used in which adaptation and test stimuli were presented alternately to prevent decay or dissipation of the aftereffect. Each alternation started with a fixation mark that was placed in the center of the display at 57 cm and the mark was surrounded above and below by two vertical Nonius lines (1° long). Observers initiated a trial by pressing a mouse button. During the post-adaptation phase, the Nonius lines were followed by the adaptation stimulus that was presented for 2 s at 57 cm. Subjects were free to make eye movements when the adaptation stimulus was presented. Then, a fixation cross was presented at the test distance of 28, 57, 85, or 114 cm for 1.5 s. This period was used to provide sufficient time for subjects to make vergence eye movement to obtain binocular alignment of the test stimulus placed at a different simulated distance than the adaptation distance. Subsequently, the test stimulus was presented for 300 ms at the same simulated distance as the fixation cross. During one measurement session, the simulated test distance was constant. The exposure time of the test stimulus was brief (300 ms) to prevent dissipation of the aftereffect (Mitchell & Baker, 1973). Eye movements were minimized during presentation of the test stimulus because of the brief presentation time. Then, the observer was asked to indicate (by pressing left or right mouse button) whether the left or right side of the test stimulus was slanted farther away from the observer relative to frontoparallel. No feedback was provided regarding to the correct response. The post-adaptation testing phase consisted of 50 alternations of the presentations of adaptation and test stimuli. The amount of horizontal magnification in the test stimulus was varied during a session.

The pre-adaptation testing phase was the same as the post-adaptation testing phase, except that a frontoparallel stimulus (i.e., no magnifications in the half-images) was presented instead of the adaptation stimulus. The frontoparallel stimulus had the same size and dot density as the adaptation stimulus. In the pre- and post-adaptation phases, the amount of horizontal magnification needed to perceive the test stimulus as frontoparallel (nulling method) was determined by an adaptive method, MUEST (Snoeren & Puts, 1997). A point of subjective equality (PSE) and a threshold (just notable difference; JND) were obtained. The PSE is the value of the horizontal magnification for which 50% of the test stimuli were perceived as slanted to the left. The JND is half of the difference between the values of the horizontal magnification corresponding to 16% and 84% of correct performance (d’ = 1). We estimated the SEs of PSE and JND by performing 500 Monte Carlo simulations (termed bootstrap replications) on the data sets. The aftereffect is defined as the difference in PSEs before and after adaptation (PSE\textsubscript{post} − PSE\textsubscript{pre}), and the estimated error is defined as the sum of SEs in both PSEs (SE PSE\textsubscript{pre} + SE PSE\textsubscript{post}).

Experiment 1

Does adaptation to the induced effect occur at the slant percept level or at the disparity level?

The first experiment investigated whether adaptation to surface slant generated by differential vertical magnification occurs at the perception/mapping level or at the disparity level (low level). Subjects adapted to vertically magnified half-images and tested the aftereffect at different distances. Tall stimuli were used as test stimuli to evaluate adaptation of the slant percept and of VSR. If the aftereffect, expressed in units of equivalent surface slant, is constant across distances, the results provide evidence supporting adaptation at the perceptual or mapping level. If the aftereffect expressed in horizontal magnification (which is used to measure the amount of aftereffect in VSR, see the General methods section for a more detailed explanation) is constant across distances, the results provide evidence supporting adaptation at the disparity level. There may also be some distance-specific adaptation that occurs only at the adaptation distance. The HSR for the adaptation stimuli was kept at 1 (the same for the two eyes’ retinal images) to minimize adaptation to horizontal disparity.

Subjects

Three subjects were tested (CS, BL, and JC). Two subjects were authors and the third subject, JC, was naive to the purpose of the experiments.

Results

Figure 1 plots the aftereffects of three observers at four test distances. Aftereffects, calculated as the PSE difference between pre- and post-adaptation, are plotted either in units of equivalent surface slant or horizontal magnification as a function of vertical magnification in the adaptation stimuli. Linear regressions were performed on the aftereffects for each test distance. The slopes of these regression curves indicated the strength of the aftereffects with larger slopes indicating stronger aftereffects. The slopes were significantly different from zero under most of the conditions (p < .05) except for observer CS at distance of 114 cm (this slope was not included for further analysis except for the analysis of the linear additive model in the General discussion section). The intercepts of the regression fits were significantly different from 0 for 11 out of 12 linear fittings for all observers (p < .05), which indicated that observers had a small bias in their slant estimates. The sign of the intercepts for each
observer was the same across various test distances, which showed that the bias was consistent. The intercepts were subtracted in Figure 1 and also in future analyses.

The original aftereffects from all observers at different test distances were used for another linear regression analysis. The slopes of the regressions at different distances are shown in Figure 2. The two plots show the slopes of the aftereffects based on the results expressed in units of disparity and in units of slant, respectively. If adaptation occurs at the disparity level (i.e., recalibration of VSR signals occurs), the slopes based on disparity results should remain constant across test distances and be similar to each other in the left plot. If adaptation occurs at the perception or mapping level, the slopes based on the results in slant angle should be constant in the right plot. If there is any aftereffect specific to the adaptation distance, the slope at 57 cm should be larger than other distances. In the left plot, when the slopes are calculated based on the aftereffects in units of disparity, all pairs of the slopes were significantly different ($p < .05$) except

![Figure 1](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932834/)

**Figure 1.** Plot of the aftereffects tested at various distances and expressed in units of horizontal magnification or in units of equivalent surface slant for three observers. The different curves are the linear regression fits for different test distances.

![Figure 2](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932834/)

**Figure 2.** The slopes of the aftereffects of all observers at different test distances are plotted. The left plot shows the results in units of disparity (i.e., horizontal magnification) and the right plot shows the results in units of slant.
those between 28 and 57 cm and between 85 and 114 cm. The basic pattern shows that the aftereffects in units of disparity increase as the viewing distance increases, which suggests that the recalibration of VSR signals that is distance independent did not occur. As shown in the right plot of Figure 2, the slopes of the aftereffects expressed in units of slant were not significantly different from each other for test distances of 28, 85, and 114 cm ($p > .05$) and the slope at 57 cm was significantly larger than other distances ($p < .05$). The strength of the induced aftereffect at the 57-cm adaptation distance was around 17.5% of the adapting vertical magnification, which was less than the strength of aftereffect from adapting to horizontal magnification (Graham & Rogers, 1982). The results indicate that there is adaptation at the perception or mapping level and also that there is some distance- or context-specific adaptation at the adaptation distance.

The thresholds (JNDs) before and after adaptation were also analyzed. There was no significant difference between the thresholds measured before and after adaptation ($p > .05$). Therefore, there was no desensitization and the measured aftereffects were not due to desensitization.

The analyses of the aftereffects at different test distances indicate that the aftereffects of adapting to vertically magnified images occurred mainly at a perceptual or mapping level, which was similar to the adaptation to surface slant generated by horizontal magnification (Berends et al., 2005). The recalibration of VSR signals did not seem to occur because the aftereffects expressed in units of disparity did not remain constant as the distance of the test stimuli varied. Because of the existence of the cue conflict between the azimuth from VSR and from eye position signals, the eye position signals may also have been recalibrated during adaptation. Experiment 2 tested this possibility.

### Experiment 2

**Is there recalibration of eye position signals?**

The goal of the second experiment was to test the adaptation of eye position signals for azimuth. The scaling of surface slant by azimuth information (i.e., VSR and eye position signals) will be influenced by the weights given to different sources of azimuth information which are, in turn, affected by the stimulus height (see Property 2). VSR signals are weighted more for tall stimuli while eye position signals are weighted more for short stimuli. Note that the aftereffects due to normalization of slant percept and recalibration of VSR information are of the same sign and they have opposite signs to the aftereffect from recalibration of eye position signals. In Experiment 2, the aftereffects of adapting to the induced effect were tested by using test stimuli with various heights. The weight that is put on the eye position signals for slant estimate increases as the height of the test stimuli decreases. The results demonstrated that aftereffects for short and tall stimuli had opposite signs, which suggested that there was recalibration of the eye position signals for azimuth.

### Methods

The display, stimuli, and procedures were similar to those used in Experiment 1 with the exception of several differences listed below. One more subject (JD) participated in the experiment besides the three subjects in Experiment 1. She was naïve about the experimental setting and purpose. The height of the test stimuli was varied to be 0.5°, 4°, and 24° and the test stimuli were always presented at the same distance as the adaptation stimuli (i.e., 57 cm). For test stimuli with different heights, the number of dots shown on a surface was varied to make the dot density appear roughly the same across different conditions. The number of dots on the test surface patch was 12, 20, and 100 for stimulus heights of 0.5°, 4°, and 24°, respectively. For test stimuli with 0.5° height, the experiments were repeated once and the results were averaged across two sessions for each condition to get a more reliable estimate of the performance.

### Results

For short test stimuli (0.5° and 4°), the aftereffects for all subjects were in the opposite direction comparing to tall height test stimuli (24°, see Figure 3). This result indicated that the eye position signals for azimuth were recalibrated in response to azimuth signals from VSR in the adaptation stimuli. Seven out of eight comparisons between the slopes for tall (24°) and short (4° and 0.5° height) stimuli were significant ($p < .05$). The other comparison (subject JD, between 24° and 4°) was very close to significant ($p = .054$). As the height of the test stimuli was reduced from 4° to 0.5°, the slopes of the aftereffect increased slightly for three out of four subjects, but the differences between the slopes of the aftereffects under the two conditions were not significant for all subjects ($p > .05$).

According to the results of Experiment 1, we assume that there is no adaptation of VSR signals. Then, the measured aftereffect caused by recalibration of the eye position signals can be estimated as approximately the difference between the aftereffects tested with the tall (24°) and the short height (0.5°) test stimuli. The results suggest that the aftereffect caused by recalibration of the eye position signals is large. It is about twice as large as the measured aftereffect caused by normalization of the percept (24° test stimuli). The aftereffects caused by adaptation of the eye position signals would be even
larger if there had been any recalibration of eye position signals affecting aftereffects measured with the tall test stimuli. Furthermore, we might have not estimated the full adaptation of the eye position signals with the narrow test stimuli if the weight given to the eye position signals was not 1.0 for surfaces with 0.5° height.

The conflict between the azimuth from VSR and eye position signals is a special property of the induced effect. For surface slant generated by horizontal disparity, the two cues for azimuth are not in conflict with each other. To confirm that the results of Experiment 2 are due to the conflict between VSR and eye position signals, adaptation of surface slant generated from horizontal disparity was tested by stimuli with various heights in Experiment 3.

Experiment 3

Control: test whether the aftereffects of adapting to surface slant produced by horizontal disparity are different when the height of the test stimuli varies

Previous research (Berends et al., 2005) and the first experiment in the current study showed that the adaptation occurs at the perception or mapping level when adapting to a stereo-defined slanted surface. For surface slant perception generated by horizontal magnification, there is no conflict in the different sources of azimuth information. Thus, no recalibration of azimuth signals from VSR or eye position signals is expected in response to slant produced by horizontal disparity. Therefore, the aftereffect after adapting to surface slant generated from horizontal disparity should not vary with the height of the test stimulus since only normalization of the surface percept occurs. When the adaptation of surface slant generated by horizontal disparity is tested with test stimuli of various heights, no difference in the aftereffect is expected. Experiment 3 tested this prediction and did not find any difference between the aftereffects measured with tall and short test stimuli.

Methods

The experiments were similar to Experiment 2 with the following differences. The adaptation stimuli were horizontally magnified with a magnification of –4%, –2%, 2%, and 4%. This range of magnification corresponds to slant angles ranging from approximately ±9.9° to ±19.0°. The height of the test stimulus was varied to be 4° and 24°.

Results

The aftereffects represented by PSE difference between pre- and post-adaptation in units of horizontal magnification

Figure 3. The aftereffect expressed in units of slant is plotted for four subjects as a function of vertical magnification in the adaptation stimuli. The different curves are the linear regression fittings of the aftereffects tested by three different heights of the test stimuli. The light blue data marked with label “percept” are predictions of the amount of aftereffect of the induced effect that is due to normalization of the slant percept (see the Results section of Experiment 4).
are plotted for 24° and 4° height test stimuli as a function of the amount of horizontal magnification in the adaptation stimuli (see Figure 4). The slopes of linear regressions under the two conditions (i.e., different heights of test stimuli) were of the same sign and did not differ significantly \((p > .05)\). For observer CS, the results of the two linear regressions completely overlapped. The results had a different pattern than those from Experiment 2. In Experiment 2, the aftereffects from adapting to surface slants due to vertical magnification were significantly different when tested using tall and short test stimuli and they were of opposite signs (see Figure 3). The aftereffects measured with test stimuli of different heights did not differ significantly in Experiment 3. The results suggest that the opposite aftereffects found with various height test stimuli in Experiment 2 were the results of the conflict between azimuth estimates from VSR and eye position signals.

Experiment 3 quantified the aftereffects that were only due to normalization of surface slant by using horizontal disparity in the adaptation stimuli. If normalization of surface slant percept occurs for surfaces generated either from differential horizontal or vertical magnification, the amount of aftereffects should be similar in the two cases. However, the results from previous experiments cannot be compared directly because the perceived slant is not the same for surfaces generated by the same amount of horizontal and vertical magnification. Experiment 4 tested the amount of perceived slant due to vertical or horizontal magnification. The results can be used to predict the amount of aftereffects due to normalization of the percept after adapting to the induced effect.

**Experiment 4**

**Control: compare the amount of perceived slant in the geometric and induced effects**

Experiment 4 compared the perceived slant angle produced either by horizontal magnification (i.e., the geometric effect) or vertical magnification (i.e., the induced effect) of the half-images. From the results of Experiments 3 and 4, we can predict the magnitude of the aftereffect caused by normalization of slant percept after adapting to the induced effect.

**Methods**

The magnitudes of perceived slant due to the geometric and induced effects were measured by estimating surface slant for a range of horizontal and vertical magnifications. Subjects were the same as in Experiments 2 and 3 and apparatus was the same as in the previous experiments.

**Stimuli**

Large elliptical random-dot surfaces (30° horizontal \(\times\) 24° vertical) that appeared frontoparallel (with no horizontal or vertical magnification) were used as reference stimuli. Large round random-dot surfaces (24° horizontal \(\times\) 24° vertical) were used as test stimuli. Test stimuli could be
vertically or horizontally magnified. The magnifications of retinal images ranged from −7% to 7% with 1% increment for a total of 15 steps. A 1% magnification is defined as 0.5% magnification in the left eye’s retinal image and 0.5% minification in the right eye’s retinal image. All the stimuli were presented at a distance of 57 cm from the viewing point.

Procedure

Before each session of the experiments, observers looked at a fixation point at the center of the screen and two vertical Nonius lines (1° long) around it. After observers accurately fused the fixation point (i.e., aligned the Nonius lines vertically), they could initiate a trial by pressing a mouse button. A frontoparallel reference surface with no vertical or horizontal magnification was presented for 2 s followed by a blank screen of 500 ms. After that, a vertically or horizontally magnified surface was presented for 2 s. Subsequently, two lines and a symbol of the head were shown as a probe figure representing the plan view of the two surface patches previously shown. In the probe figure, the two lines extended about 15° visual angle and were presented at the center of the screen. A horizontal line with fixed orientation represented the frontoparallel reference surface patch. An oblique line represented the slanted surface. Observers were asked to rotate the oblique line to make the angle between the oblique and horizontal line the same as the slant angle of the second surface patch relative to the first frontoparallel plane. The orientation of the oblique line could be varied continuously by moving the mouse up or down. After observers were satisfied with the setting, they pressed a mouse button to start the next trial.

Within one session of experiments, stimuli with either horizontal or vertical magnification were presented. Each stimulus with 1 of the 15 possible magnitudes was presented four times randomly within each session. Sixty trials were included in one session. The sessions with horizontal or vertical magnifications were run alternately. Each subject ran two sessions of experiments on surface slant from vertical magnification and two sessions on surface slant from horizontal magnification. Therefore, each condition had eight repeats for one subject.

Results

The results of the perceived slant due to the geometric and the induced effects were plotted in Figure 5. Linear regressions were fitted to the results. The perceived slants under these two conditions were of opposite signs to each other.

Figure 5. The amount of perceived slant is plotted as a function of horizontal or vertical magnification of half-images. The blue diamond symbols are the results of geometric effect (horizontal magnification) and the pink square symbols are the results of induced effect (vertical magnification).
other. Horizontal magnification introduced larger perceived slants (the geometric effect) than the same amount of vertical magnification (the induced effect). The ratios between the slopes of the perceived slant generated by horizontal and vertical magnification were \(-1.04\), \(-1.38\), \(-1.50\), and \(-1.28\) for subjects BL, CS, JC, and JD, respectively. The differences in the absolute slopes were significant for observers CS and JD \((p < .05)\). To check whether the difference in the aftereffects of adapting to the geometric and the induced effects can be explained by the difference in slant percept under the two conditions, ratios between the aftereffects of adapting to the geometric and induced effect were computed. The ratios between the aftereffects in units of slant were \(-0.77\), \(-2.40\), \(-2.72\), and \(-2.54\) for subjects BL, CS, JC, and JD, respectively. Three subjects had aftereffect ratios larger than the percept ratios. This suggests that the differences in aftereffects can partly be explained by the difference in slant percept, but there is another difference between the adaptation responses to surfaces generated from vertical or horizontal disparity, namely, the adaptation of eye position signals which were manifest even with the 24° high test stimulus when vertical magnification was used.

The results of Experiments 3 and 4 were used to estimate the amount of the aftereffect of the induced effect measured in Experiment 2 that was due to normalization of slant percept. We assume that when the adaptation stimuli in Experiment 3 were generated from horizontal disparity, there was only adaptation of the slant percept (i.e., normalization). From the results of Experiment 4, we know the amount of slant that is perceived from a certain amount of horizontal or vertical magnification. They are not the same. Using the results of Experiment 4, the amount of horizontal magnification used for the adaptation stimulus in Experiment 3 to produce the geometric effect was transformed to the equivalent amount of vertical magnification of a 24° high stimulus that is required to produce the same perceived slant. The aftereffects expressed in equivalent slant from Experiment 3 were then plotted as a function of the equivalent amount of vertical magnification. The predicted aftereffects at the normalization level were compared in Figure 3 (labeled as “percept”) to measured aftereffects of the induced effect in Experiment 2.

As shown in Figure 3, the predicted amount of aftereffects attributed to the perceptual stage (shown as the light blue line as “percept”) is greater than what we measured using tall test stimuli (24°, the dark blue line) for three out of four subjects (i.e., the slopes of the predicted aftereffects due to surface percept normalization are larger than the slopes of the 24° stimuli). They were the same for one subject (BL). We postulated that some adaptation to eye position signals occurred when adaptation to the induced effect was tested using 24° height stimuli. However, the slopes based on the predictions from adaptation to the slant percept and the slopes of the aftereffects tested with tall test stimuli (24°) were not significantly different from each other \((p > .05)\). We conclude that the aftereffects that were found by using tall test stimuli were mainly due to adaptation to surface percept and the difference between the different conditions of stimulus height in Experiment 2 was due to recalibration of eye position signals.

### General discussion

#### Basic findings

The present study investigated the changes in the visual system after observers adapted to surface slants generated from vertically magnified half-images (i.e., the induced effect). Different cues for slant estimation may have changed after adapting to the induced effect: horizontal disparity, VSR, and oculomotor signals (i.e., eye position version signals). Furthermore, the perceived slant or the mapping function might have changed. Since there is no horizontal magnification in the adaptation stimuli and our previous study did not find adaptation of horizontal disparity (Berends et al., 2005), no adaptation to horizontal disparity is expected. The conflicts between VSR and eye position signals for azimuth may lead to recalibration of both sources of information or either of them.

In the first experiment, the aftereffects of adapting to the induced effect were tested with tall test stimuli at various distances, either the same as the adaptation distance or different from it. The aftereffects, expressed in units of slant, were greatest when tested at the adaptation distance of 57 cm and were smaller but equal at other test distances. When the aftereffects were expressed in units of disparity, they varied across distances. The results provided evidence for adaptation at the percept or mapping level and also for context-specific adaptation at the adaptation distance. Little if any recalibration of VSR signals occurred.

In Experiment 2, adaptation to the induced effect was tested by using short test stimuli in which eye position signals were mainly used for azimuth estimation rather than VSR signals. The aftereffects were in the opposite direction to those tested by tall test stimuli, presumably because of the recalibration of eye position signals.

The third experiment investigated adaptation to surface slants generated from horizontally magnified images using tall and short test stimuli and no difference in the aftereffects was found between the two conditions. The results confirmed that the findings of Experiment 2 were indeed due to the conflicts between VSR and eye position signals.
Experiment 4 quantified the amount of perceived surface slant due to the geometric and the induced effect. Observers perceived more slant in the geometric effect than the induced effect. The results from Experiments 3 and 4 were used to predict the amount of adaptation that was only due to the normalization of surface slant.

Normalization of the slant percept, but no adaptation of VSR signals

The findings from the first experiment provided evidence for adaptation of the stereoscopic surface slant percept, which has been found for the adaptation to curvature (Domini et al., 2001) and the adaptation to surface slant (Berends et al., 2005) both generated by horizontal disparity. These two studies varied the viewing distances when testing the aftereffects and found that the aftereffects expressed in surface slant or surface curvature did not change with test distance. The results support the idea that adaptation occurs at the percept or mapping level, and not at low levels (i.e., disparity information). Experiment 1 in the present study followed the same paradigm of experiment design and found that aftereffects expressed in slant angles did not vary with test distance. The results showed that the adaptation of perceived slant at one distance could be transferred to other distances, but the amount of adaptation expressed in units of disparity could not be transferred to other distances. The results indicate that the perceptual identity of a frontoparallel surface shifted towards the surface slant of the adaptation stimulus. The slant of the adaptation surface changed the neutral point of the slant percept (i.e., the perceived frontoparallel). Therefore, a tall frontoparallel surface is seen as slanted opposite to the slant direction of the adaptation stimulus. The results suggest that normalization occurs at the perception/mapping level. Other research also indicates that adaptation to surface slant occurs at a high level. Duke & Wilcox (2003) compared the aftereffects caused by adaptation to slanted surfaces that were generated by different combinations of horizontal and vertical magnifications (i.e., metamers). They found no difference in the aftereffects between slants generated by different combinations of vertical and horizontal magnification, suggesting that adaptation to vertical and horizontal disparity did not occur and adaptation was at a high level.

Another related finding in Experiment 1 is that there was a distance-specific component to adaptation, which occurred when the aftereffects were tested at the same distance as the adaptation stimulus. The aftereffects were larger when tested at the adaptation distance than other distances. This result has been demonstrated before with adaptation to surface slant generated from horizontal magnification (Berends et al., 2005).

Recalibration of the eye position signals

The second experiment was carried out to investigate the possible recalibration of eye position signals by using the relationship between surface height and the weights given to VSR signals and eye position signals for azimuth. The property of the induced effect, which is different from the geometric effect, is that the azimuth signals indicated by VSR and version eye-position signals are different. The question is how does the visual system resolve the conflict between these two cues for azimuth and which source of information gets modified or recalibrated after adaptation? Since the height of a surface patch is closely related to whether VSR signals or eye position signals are used in slant estimation (Backus et al., 1999), various heights of the test stimuli were used to evaluate the VSR information and/or eye position components of adaptation besides adaptation to the surface slant percept.

The results of Experiment 2 showed very strong recalibration of eye position signals. When using tall test stimuli, the aftereffects due to adaptation to VSR and to surface slant perception were tested. The aftereffects were mainly due to adaptation to slant perception (Experiment 1). When short test stimuli were used, the aftereffects due to adaptation to eye position signal and to slant percept were tested. The difference between the two conditions (i.e., tall vs. short test stimuli) illustrated changes in the azimuth from recalibration of eye position signals. The opposite signs of the aftereffects for tall and short test stimuli demonstrated that the amount of aftereffect due to recalibration of eye position signals was greater than that only due to adaptation to slant percept.

The findings on recalibration to eye position signals were further confirmed by Experiment 3. In Experiment 3, the adaptation surface slant was generated by horizontal disparity and the aftereffects did not change significantly when tested with either tall or short stimuli. The different patterns of the results in Experiments 2 and 3 suggested that recalibration of eye position signals was indeed a special property of adapting to the induced effect, which presents a conflict between the azimuth indicated by VSR and eye position signals.

Version eye position signals are not only used for stereoscopic depth perception, but also for direction perception. Berends, van Ee, & Erkelens (2002) showed that perceived direction can change after a prolonged inspection of a stimulus that was both horizontally and vertically magnified. This agrees with our finding that low-level adaptation of the eye position signals occurs. However, the changes in perceived direction were only a few degrees (depending on the subject 0°–7°) in their study, whereas the changes in perceived slant due to adaptation of the eye position signals was more than 10° for some subjects. The differences in the magnitude of aftereffects may be due to the different tasks and different subjects in the two studies.
Differences between the induced and geometric stereo-slant aftereffect

There are some differences between the aftereffects due to geometric and induced effects. The first and most important one is the finding related to the recalibration of eye position signals. Another difference is associated with the amount of perceived surface slant in the induced and the geometric effect. Experiment 4 measured slant estimates from the geometric and the induced effect. The results showed that the amount of perceived slant was less in the induced than in the geometric effect. According to our previous study (Berends et al., 2005), we assume that the aftereffects from adaptation of the geometric effect are mainly due to slant percept adaptation. The results from Experiments 3 and 4 were then used to predict the amount of aftereffects that was only due to slant percept normalization after adaptation of the induced effect. The predicted amount of aftereffects based on slant percept was not significantly different from the aftereffects of adapting to the induced effect when tested by tall test stimuli (see Figure 3 in Experiment 2). The results supported the idea that adaptation to surface slant generated by differential vertical magnification shares similar properties as adaptation to horizontally magnified surfaces and the adaptation occurs at the percept level no matter how the surface slant was generated.

Linear additive model

We used a linear additive model (Berends et al., 2005) to quantitatively analyze various types of adaptation that occur for each subject in Experiment 1. This model predicted the aftereffects due to recalibration of VSR information and normalization of surface slant percept. In Experiment 1, tall test stimuli were used to quantify the amount of aftereffects and the eye position signal cue for azimuth was down-weighted in slant estimation. The aftereffects due to recalibration of eye position signals were minimized by the tall stimulus and were not considered in the model. A linear regression was carried out to analyze the aftereffects predicted from three components (three hypotheses) that may contribute to the total aftereffect:

- Perception or mapping level: If adaptation occurs at the perception level, the aftereffect in units of slant will be the same for all distances as at 57-cm adaptation distance.
- Disparity level: If adaptation occurs at disparity level, the aftereffects expressed in horizontal disparity will be the same for all distances as at 57 cm adaptation distance.
- Contingent on distance: The aftereffect only occurs at 57 cm, not other distances.

The slopes of the aftereffects at the four test distances were used as the dependent variable and the predicted slopes of the aftereffects based on the three hypotheses (using the aftereffect at 57 cm test distance) were treated as independent variables. Linear regressions were carried out using predictions from the three hypotheses. The weight (i.e., regression coefficient) on the prediction based on adaptation at disparity level was not significantly different from 0 (p > .05). A linear regression was then carried out using only the two independent variables based on the two predictions from the context-specific hypothesis (i.e., only adaptation at the adaptation distance) and the percept hypothesis. The regression coefficients (see Table 1) showed that the weight on adaptation at the perception level was significantly different from 0 (p < .05) for all three subjects, which indicated that stereo-slant adaptation generated by differential vertical magnification occurred at high level (i.e., mapping or perception level), similar to the adaptation to slant generated by horizontal disparity. The weights on adaptation contingent on distance was significant for observer BL and CS (p < .05), which showed that the aftereffects were related to the distance of the adaptation and test stimuli. The outcomes of the linear additive model agree with our conclusions drawn from Experiment 1.

Conclusions

The results from the present set of experiments demonstrated that normalization of surface slant percept occurred when adaptation surface slant was generated by vertical magnification. Adaptation that was specific to the adaptation distance was also found. The results also showed that recalibration of the eye position signals occurred when there was a conflict between the azimuth indicated by VSR and eye position signals. On the other hand, no recalibration of VSR signals was observed. During adaptation the sensed eye position was shifted toward the azimuth indicated by the differential vertical magnification in the adaptation stimulus.
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