Stereo-slant adaptation is high level and does not involve disparity coding

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We have investigated the potential stages of visual processing at which adaptation may occur to a slanted surface produced by horizontal magnification. Predictions of three hypotheses were tested utilizing a property of depth from binocular disparity, namely that slant scales with distance. If adaptation occurs at the disparity level, then the after-effect expressed in units of horizontal magnification will be independent of the test distance. If adaptation occurs at either a perceived slant or mapping level, then the after-effect, expressed in units of slant, will be independent of the test distance. Adaptation at the disparity level will also transfer to a distance different from the adaptation distance. These results suggest that two types of adaptation occurred, namely adaptation on a mapping/perception level and adaptation contingent on distance.

Keywords: binocular vision, stereopsis, adaptation, after-effects, stereo-slant, disparity, HSR

Introduction

Recalibration of the visual system occurs continuously to compensate for alterations between environmental properties and visual signals. For example, when a horizontal surface is viewed through a horizontal cylindrical spectacle correction that magnifies the right eye’s image horizontally, a horizontal ground plane appears to slant down on the right and up on the left and a frontoparallel surface will appear nearer on the left than on the right side. These distortions fade away in a few days, and when the glasses are removed, a stereo-slant after-effect can be measured (i.e., surfaces appear slanted in the opposite direction) (Burian & Ogle, 1945). Stereo-slant or stereo-depth adaptation can also occur when only stereoscopic cues are present (Blakemore & Julesz, 1971). These after-effects could result from adaptation at several stages of visual processing. Stereoscopic after-effects have been attributed to fatigue among neural detectors tuned to specific binocular disparities (Blakemore & Julesz, 1971; Long & Over, 1973; Mitchell & Baker, 1973) (i.e., adaptation at a disparity level). They have also been attributed to recalibration of the mapping between retinal disparity and perceived depth (Epstein, 1972; Epstein & Morgan, 1970; Mack & Chitayat, 1970) or slant (Adams, Banks, & van Ee, 2001). Stereoscopic after-effects have further been attributed to down weighting or even suppression of the disparity cue due to conflicts between disparity and the monocular cues (Burian, 1943; Burian & Ogle, 1945; Miles, 1948). Finally, stereoscopic after-effects may result from perceived depth biases (Balch, Milewski, & Yonas, 1977; Duke & Wilcox, 2003). Thus, adaptation may occur at all stages of stereo-depth processing from the encoding of binocular disparity to the final depth percept.

It has been shown that stereo-depth adaptation does not result from a change in the weights of depth cues (Adams et al., 2001), nor can it be explained by adaptation of disparity alone (Domini, Adams, & Banks, 2001) or by adaptation of the percept alone (Berends & Erkelens, 2001). However, how much adaptation occurs at each stage of depth processing is unknown. The goal of this study is to investigate at which stages in visual processing stereo-slant adaptation occurs and also to quantify the amount of adaptation at various stages.

There is some evidence that stereo-depth and stereo-slant adaptation occur mainly at the perception level. Balch et al. (1977) found cross-cue after-effects that transferred from monocular to binocular slant cues. This indicates that the after-effect is at least partly caused by a general depth mechanism and not by the specific slant cues that generate the slant percept. This suggests that adaptation occurs at a perception level if there is no interaction between the depth cues at low level (a weak fusion model) (Landy, Maloney, Johnston, & Young, 1995). However,
other researchers (Poom & Borjesson, 1999) interpreted similar results as an interaction between cues at a low level. Other evidence was provided by Duke and Wilcox (2003). They found that adaptation to the same perceived slant generated by different combinations of horizontal and vertical magnification produced the same after-effects when tested with horizontal disparity. They considered it unlikely that horizontal and vertical disparities adapt exactly in the same way. Therefore, they postulated that adaptation resulted from perceived depth biases and that it did not occur at the disparity processing level. Although some evidence is found that adaptation occurs mainly at the perception level, neither of the above-mentioned studies excludes adaptation at the disparity level, and they did not quantify the amount of adaptation at various levels of depth processing. We used different viewing distances to the test stimuli to tease apart three different types of adaptation based on the idea of Domini et al. (2001).

An adaptation after-effect may transfer over distance or it may be contingent on the adaptation distance, as the motion after-effect is contingent on distance (Verstraten, Verlindt, Fredericksen, & van de Grind, 1994). According to a property of depth from binocular disparity, stereo slant scales with viewing distance (Ogle, 1950). In other words, stereo slant becomes larger when the viewing distance increases and the binocular disparity is kept constant. This property is utilized to make predictions for two hypotheses about the level at which adaptation that transfers over distance occurs. The mapping function between the horizontal size ratio (HSR) and perceived slant about the vertical axis (Backus, Banks, van Ee, & Crowell, 1999) shows that head-centric slant from HSR depends on viewing distance:

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

with \(\gamma\) the version signal (azimuth) and \(\mu\) the vergence signal, which is inversely proportional to the viewing distance.

The first hypothesis is that adaptation occurs among mechanisms that are sensitive to horizontal disparity. We will refer to this type of adaptation as adaptation at the disparity level. This type of adaptation is low level, because it occurs before disparity is mapped into slant by the mapping function. If the disparity signals (HSR) change during adaptation, then the change expressed in units of disparity will be constant when the after-effect is tested at various distances. Thus, if adaptation occurs at a low (disparity) level, we predict that the after-effect, expressed in units of disparity, will be independent of distance, and when expressed in units of slant, it will increase with viewing distance (see Figure 1).

The second hypothesis is that adaptation occurs at the level of three-dimensional (3D) shape-sensitive mechanisms or the mapping between disparity information and slant perception. We will refer to this type of adaptation as adaptation at the perception/mapping level or high-level adaptation. If the percept or the mapping function is adapted, then the change in slant percept will be constant when tested at various distances after adapting at one particular distance. Thus, if adaptation occurs at a high (perceived slant) level or at the mapping function from disparity to depth, then we predict that the after-effect expressed in units of slant will be constant and the after-effect expressed

![Figure 1](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933507/)

Figure 1. The predictions for the three different hypotheses. The first panel shows a plane view of the after-effect when the adaptation distance and the test distance are the same. After adaptation, a surface normally seen as frontoparallel is perceived as slanted (blue plane) in the direction opposite to the adaptation stimulus (green plane). When the test distance is farther away than the adaptation distance, the three hypotheses give different predictions. If adaptation occurs at the disparity level (second panel), the perceived after-effect is larger than in the first panel because a particular disparity (HSR) induces a larger slant at a greater distance. If adaptation occurs at the perceptual or mapping level and transfers over distance (third panel), the perceived after-effect is the same as in the first panel, because the change in percept is the same. If adaptation is fully contingent on distance (fourth panel), the perceived after-effect is zero, because the test distance is different from the adaptation distance.
in units of disparity will increase with decreasing test distance, because a particular slant requires a larger disparity as the distance gets smaller (see Figure 1). Equation 1 can be used to quantify the predictions for adaptation at the perception level.

This approach distinguishes between two types of adaptation that are not contingent on the viewing distance of the adaptation stimuli, namely the adaptation at low (disparity) level and those at higher levels. It cannot distinguish between mapping and perceptual bias, but it can distinguish between adaptation at the disparity level and at higher levels.

Testing at different distances after adaptation makes it possible to identify after-effects that do not transfer over distance. The third hypothesis is that adaptation is fully contingent on distance. In that case, the after-effect exists only when the adaptation and test distance are the same, and it is predicted to be zero when adaptation and test distance are different from each other (see Figure 1).

Both high-level and low-level after-effects might be (partly) contingent on distance. According to hypothesis 3, there is a very sharp fall off in the after-effect with vergence change from adapted vergence (and thus distance change). However, it is possible that the after-effects fall off slowly as the test condition becomes less similar to the adapting condition. In other words, as the test distance becomes farther away from the adaptation distance, the after-effects may gradually become smaller.

### Methods

In this study, we measured the effect of test distance on the stereo-slant after-effect. In each session, which lasted about 20 min, we measured adaptation in response to one particular amount of horizontal magnification at one particular test distance. The adaptation stimulus was always presented at the same distance (57 cm) \((Z_{\text{screen}})\), whereas the simulated test distance \((Z_{\text{simulated}})\) varied between measurement sessions (28, 57, 85, or 114 cm). The simulated test distance was specified by vertical disparity and vergence cues, both of which were altered by translating both eyes' images horizontally in the opposite direction. The total amount of translation \((\Delta)\) is defined by

\[
\Delta = I \cdot \left(1 - \frac{Z_{\text{screen}}}{Z_{\text{simulated}}}\right) \tag{2}
\]

with \(I\) symbolizing the interocular distance.

### Display and stimuli

The stimuli were displayed on a 20-in monochrome monitor (Monoray Model M20ECD5RE; Clinton Electronics, IL, USA) at 120-Hz noninterlaced frame rate with 1024 by 768 pixel resolution. This monitor had a fast DP 104 phosphor that decays to 0.1% peak in 0.6 ms with a burn-resistant property. The fast phosphor decay is critical for minimizing the cross talk between images presented to left and right eyes because we were using the same screen area with shutter glasses to generate the stereograms. Video images were controlled using a 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 test 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 discernable flicker.

The observer's head position was restricted by means of a bite board and headrest to position the observer at the calibrated 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.

Two types of stimuli were used. Subjects adapted to a horizontally magnified stereo-slant stimulus and the after-effect was measured with a horizontally magnified stereo-slant test stimulus, which varied between trials. The adaptation stimuli were large elliptic random-dot patches (30 deg horizontal by 24 deg vertical). The test stimuli were large circular random-dot patches (24 deg horizontal by 24 deg vertical). The difference in the outline between the adaptation and the test stimuli (i.e., oval vs. round) made it easy for subjects to distinguish between the two 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 the Gaussian luminance profile \((\sigma = 2/3 \text{ pixel})\) and its peak luminance of 4.2 cd/m² when viewed through the Ferro-shutters. Each slant stimulus presentation was a different random-dot display to avoid changes in perceived image compression as a cue. The stimuli were presented at the center of the screen (straight-ahead).

### Procedure and analysis

Each measurement session included three phases. In the pre-adaptation test phase, the amount of horizontal magnification needed to perceive the test stimulus as frontoparallel was quantified. Then in the adaptation phase, subjects looked at the adaptation stimulus for 5 min. In the post-adaptation phase after adaptation, the amount of horizontal magnification needed to perceive the test stimulus as being frontoparallel was quantified again (post-adaptation testing).

The adaptation stimulus was horizontally magnified to produce a perceived slant about the vertical axis. Four magnitudes of horizontal magnification were applied: −4%, −2%, 2%, and 4%. We defined a 2% magnification by 1% magnification in the left eye and 1% minification in the right eye. This range of magnification corresponds to slant angles ranging from approximately ±9.9 to ±19.0 deg.
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 after-effect. Each cycle started with a fixation mark near the adaptation stimulus that was presented for 2 s at 57 cm. Then a fixation cross was presented at the test distance of 28, 57, 85, or 114 cm for 1.5 s. Subjects needed this time to make vergence eye movement to obtain binocular alignment with the test stimulus placed at different simulated distances. 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 after-effect (Mitchell & Baker, 1973). Then the forced-choice task for the observer was to indicate 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 the correct response. The post-adaptation testing phase consisted of 50 cycles of the alternations between adaptation stimuli and the test stimuli. The amount of horizontal magnification in the test stimulus was varied during a session. 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).

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.

Three subjects were tested (CS, JC, and JD). JC and JD were naïve to the purpose of the experiments. Subjects were free to make eye movements when the adaptation stimulus was presented. Eye movements were minimized during presentation of the test stimulus because of the brief presentation time.

A point of subjective equality (PSE) and a threshold (just notable difference [JND]) were obtained in the pre-adaptation and post-adaptation tests by means of the MUEST method. The PSE is the value of 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 after-effect is defined as the difference in PSE between before and after adaptation ($\text{PSE}_{\text{pre}} - \text{PSE}_{\text{post}}$), and the estimated error is defined as the sum of SEs of both PSEs ($\text{se PSE}_{\text{pre}} + \text{se PSE}_{\text{post}}$).

### Results

#### Results for identical adaptation and test distance

Figure 2 shows the results for three subjects when the adaptation and the test stimulus were both presented at 57 cm. A linear regression (least squares) was fit between the amount of horizontal magnification in the adaptation stimuli and the differences in PSE for the test stimuli between pre- and after adaptation (i.e., the after-effect) for each subject. The slopes are very similar (CS: $0.31$, JC: $0.31$, and JD: $0.43$). The slope is the ratio between the after-effects expressed in magnification and the amount of magnification of the adaptation stimuli, which can be used as a measure of the strength of the after-effect. The magnitudes of the after-effects are large, namely 30–40% of the adaptation stimulus. The offsets of CS and JD do not differ significantly from zero ($p > .05$), whereas the offset of JC does, which indicates a preferred adaptation direction. For all subjects we found an offset significantly different from zero for one or two of the test distances ($p < .05$). For further data analysis, we subtracted the offsets from the data.

![Figure 2](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933507/ on 11/03/2018)
When adaptation occurs only at the disparity level, the disparity gradient (HSR) changes during adaptation. The change in the disparity is then constant for various test distances. Therefore, the after-effects at different test distances in units of magnification are predicted to be the same (see Figure 3, first column):

\[ A_{\text{disp 27}} = A_{\text{57}} \]
\[ A_{\text{disp 85}} = A_{\text{57}} \]
\[ A_{\text{disp 114}} = A_{\text{57}} \]

To make the predictions for adaptation at the perception level, we used the geometrical relationship between magnification \( M \) (1% magnification corresponds to \( M = 0.01 \)) and the veridical slant angle \( S \), which is defined by

\[ S = \tan^{-1} \left( \frac{M}{M + 2} \cdot \frac{2 \cdot d}{I} \right) \]

with \( d \) representing the distance and \( I \) representing the interocular distance (Van Ee & Erkelens, 1998).

When adaptation occurs only at the perception or mapping level, the after-effects expressed in slant angle at different test distances are the same and the after-effects expressed in disparity (horizontal magnification) increase with decreasing distance (see Figure 3, second column):

\[ S_{\text{perc 28}} = S_{\text{57}} \Rightarrow A_{\text{perc 28}} = \frac{114 \cdot A_{\text{57}}}{56 - 29 \cdot A_{\text{57}}} \]
\[ S_{\text{perc 85}} = S_{\text{57}} \Rightarrow A_{\text{perc 85}} = \frac{114 \cdot A_{\text{57}}}{170 + 28 \cdot A_{\text{57}}} \]
\[ S_{\text{perc 114}} = S_{\text{57}} \Rightarrow A_{\text{perc 114}} = \frac{114 \cdot A_{\text{57}}}{228 + 57 \cdot A_{\text{57}}} \]

When there is only adaptation contingent on distance, the after-effects are zero when the test distance is not the same as the adaptation distance (see Figure 3, third column):

\[ A_{\text{cont 27}} = 0 \]
\[ A_{\text{cont 85}} = 0 \]
\[ A_{\text{cont 114}} = 0 \]

### Results for all test distances

We found that the after-effect expressed in units of horizontal magnification was not constant for different test distances but increased with decreasing distance (see Figure 4, top row). Therefore, the after-effect is not (only) a change of the disparity signals (hypothesis 1). However, when the after-effects are plotted as slant angles (Figure 4, bottom row), the curves for different distances are not superimposed. Therefore, the after-effect is not only a change at the mapping or perception level (hypothesis 2). For CS and JD, the after-effect at 57 cm is significantly larger (\( p < .05 \)) than both the after-effects at shorter and greater test distance. This indicates that part of the after-effect is contingent on distance. This context-specific adaptation is only manifest when the test is presented at the same distance as the adaptation stimulus. The slopes at 28, 85, and 114 cm do not differ significantly from each other (\( p > .05 \)). This pattern of results indicates that the after-effect is a combination of adaptation at the perception/mapping level that transfers over distance and adaptation that is contingent on distance, which may be either high-level or low-level adaptation.

For JC, the pattern of results is not as clear as for the other two subjects. For JC, the slope at 57 cm is significantly larger (\( p < .05 \)) than the slopes at 28 and 114 cm, but the slope at 85 cm does not differ significantly (\( p > .05 \)) from the slope at 57 cm. From this we might conclude that for JC, there is some adaptation at the disparity level. However, the errors in slant nulling (see the error bars of the original data points in Figure 4) are larger for this subject than for the other two subjects. When the inaccuracy in slant discrimination is taken into account, the four curves representing the four test distances are superimposed for JC. Therefore, we only found adaptation at the perception/mapping level for subject JC.

To check for desensitizing, which is associated with low-level adaptation (Stevenson, Cormack, Schor, & Tyler, 1992), we compared the JNDs before and after adaptation. Stevenson et al. (1992) found that desensitizing is contingent on horizontal disparity. Therefore, we compared both the JNDs at all distances and the JNDs at 57 cm. Table 1 shows the averages and SDs of JND before and after adaptation for each subject. There is no significant difference between the JNDs before and after adaptation (\( p > .05 \)) when the JNDs are averaged over all test distances and all magnifications or when the JNDs are averaged over all magnifications at 57 cm. This indicates that there is no desensitizing, which agrees with our finding that there is no low-level disparity adaptation after-effect.

<table>
<thead>
<tr>
<th>Average JND ± Standard Deviation JND</th>
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<tbody>
<tr>
<td><strong>Averaged over all distances</strong></td>
</tr>
<tr>
<td>Before adaptation</td>
</tr>
<tr>
<td>CS 0.24 ± 0.07</td>
</tr>
<tr>
<td>JC 0.68 ± 0.30</td>
</tr>
<tr>
<td>JD 0.36 ± 0.17</td>
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</table>

Table 1. Comparison of JNDs before and after adaptation. On the left side, the JNDs are averaged over all magnifications and all test distances. On the right side, the JNDs are averaged over all magnifications at 57 cm.
Hypothesis 1:
Adaptation at disparity level

Hypothesis 2:
Adaptation at perceptual level that transfers over distance

Hypothesis 3:
Adaptation at perceptual level that is contingent on distance

Figure 3. Predictions for subject CS for the three hypotheses (plotted in the three columns). Data from adaptation and testing at the same distance (57 cm) were used to make predictions for the other test distances (represented by the different colors). The predictions are plotted in two ways: in units of horizontal magnification (top row) and in units of slant (bottom row).

Figure 4. The results for the three subjects are plotted in three columns. The results are plotted in two ways: i.e., in units of horizontal magnification (top row) and in units of slant (bottom row). The colors represent the different distances and agree with the colors used in Figure 3.
Discussion

Conclusion
The results on the strengths of the after-effects at various test distances are consistent with the prediction from the mapping/perception level hypothesis. The prediction of the disparity level hypothesis is not supported by the data. If the disparity level hypothesis holds, there would have been greater after-effects (in units of slant) for the 114- and 85-cm test stimuli than for the 28-cm ones, but this was not the case. The slopes at 28, 85, and 114 cm do not differ significantly from each other ($p > .05$) when the data are expressed as slant angles. Furthermore, we found that when the after-effects are expressed as slant angles, the after-effect at 57 cm is significantly larger than the after-effects at other test distances ($p < .05$) for two out of three subjects, indicating that the after-effect is partly contingent on distance. From the general pattern of results, we conclude that adaptation at the slant/mapping level occurs and adaptation is also partly contingent on distance.

The present approach cannot distinguish between adaptation at the mapping and at the perception level. The mapping function can change in many different ways, because adaptation can change any term in Equation 1 by either adding a bias or a multiplier. Adaptation contingent on distance can occur at either a high level or a low level. Several factors are involved in the adaptation contingent on binocular depth, namely estimated target distance and possibly vergence angle in combination with either horizontal disparity or slant.

Present results and existing research
Our conclusions support the evidence that stereo-depth and stereo-slant adaptation occur mainly at the perception level (Balch et al., 1977; Duke & Wilcox, 2003). Our results seem to be in contradiction with the results of Berends and Erkelens (2001), who concluded that adaptation to disparity signals can occur with perceptual metamerists. In their study, subjects adapted to a combination of horizontal and vertical magnification, which was perceived as being frontoparallel. Thus, adaptation to the percept was not possible. The vertical magnification, which is absent in the present study, caused a cue conflict between vertical disparity and eye position signals for version. Therefore, adaptation of vertical disparity or eye position signals might be possible in Berends and Erkelens’ study but not in the present study. We could only expect adaptation of horizontal disparity in the present set of experiments. The after-effect they found is probably caused by adaptation of vertical disparity or adaptation of version eye position signals or both, because we know from the present study that it is not caused by adaptation of horizontal disparity.

The present findings for slant after-effects agree with the findings of Domini et al. (2001) for curvature after-effects. They found that the curvature after-effect expressed in curvature was constant over test distance and adaptation distance. Therefore, they concluded that the 3D after-effects appear to be caused by adaptation among mechanisms specifying surface shape rather than among mechanisms signaling the disparity pattern. Domini et al. (2001) did not consider any adaptation contingent on distance, and at first glance their results did not show that type of adaptation. We reevaluated their data and found that two out of four subjects showed some adaptation contingent on distance. It seems that adaptation contingent on distance contributes more to slant after-effects than to curvature after-effects. However, this difference may also be caused by variabilities between subjects.

Desensitizing
We found no significant adaptation at the disparity level. The absence of low-level adaptation is also supported by the fact that desensitizing does not occur (i.e., we found no increase in threshold [JND] due to adaptation). Desensitizing was found in stereo-processing (Stevenson et al., 1992) when interocular correlation thresholds were measured. The after-effect found by Stevenson et al. is probably a different type of after-effect than the one we studied. Ryan and Gillam (1993) classified spatial after-effects into after-effects that are contingent on precise fixation, that have been attributed to adaptation of neural detectors tuned to disparity (e.g., Blakemore & Julesz, 1971) and after-effects that are not contingent on retinal locus (e.g., slant after-effects, Bergman & Gibson, 1959). The after-effect reported by Stevenson et al. is an after-effect that is contingent on precise fixation, whereas the stereo-slant after-effect that we studied is not. The present results support the classification of Ryan and Gillam (1993).

Imperfect distance scaling
In a depth and size setting task, approximately 35% of the scaling required for complete depth constancy was obtained (Bradshaw, Glennerster, & Rogers, 1996). This compression of visual space might be a problem in the present experiments. However, we performed a nulling task, which is not affected by biases in distance scaling. Incorrect distance scaling has an effect on the magnitude of the perceived slant, but not on the direction of the perceived slant. Thus, zero slant is perceived correctly. A curvature nulling task has shown perfect distance scaling (Rogers & Bradshaw, 1995).

Linear additive model
We developed a model to quantitatively analyze various types of adaptation. The first approximation is a linear-additive model that excludes interactions between the different types of adaptation. The linear additive model was used to quantify the amount of adaptation at the disparity level, adaptation at the mapping/perception level, and adaptation that is contingent on distance.
Various test distances were used to tease apart three different types of adaptation, namely adaptation at the disparity level, the mapping/perception level, and the adaptation contingent on distance. Assuming that adaptation occurs at three stages of visual depth processing, then a linear, additive model can describe the total after-effect. Then the after-effect is the sum of these three components. The amount of each type of adaptation can be expressed as its proportion of the total amount of adaptation. Using the predictions for each type of adaptation, the total after-effect can be expressed as

\[ A = w_{\text{disp}} \cdot A_{\text{disp}} + w_{\text{perc}} \cdot A_{\text{perc}} + w_{\text{cont}} \cdot A_{\text{cont}}. \]  

\( A \) is the magnitude of all the measured adaptation (slope in Figure 2). \( A_{\text{disp}} \), \( A_{\text{perc}} \), and \( A_{\text{cont}} \) are the predictions for the three hypotheses: adaptation only at the disparity level, adaptation only at the mapping/perception level, and adaptation that is only contingent on distance, respectively (slopes in Figure 3). \( w_{\text{disp}} \), \( w_{\text{perc}} \), and \( w_{\text{cont}} \) are the proportions of total adaptation that occur at each of the three levels (\( \Sigma w = 1 \)). Using Equation 7, the proportions of adaptation at the various levels of stereo-depth processing can be quantified by means of a least squares fit.

We carried out a multiple least squares linear regression. For each magnitude of the measured adaptation (slope in Figure 2), we computed three predicted values (Equations 3, 5, and 6) according to the three hypotheses. The measured data (\( A \) in Equation 7) are the dependent variable of the multiple regression. The three independent variables are the three predictions. The regression coefficient \( w_{\text{disp}} \) is not significantly different from zero (\( p >> .05 \)) for all subjects, which indicates that in this experiment adaptation at the disparity level that transfers over distance does not occur. This agrees with the results that the slopes at 28, 85, and 114 cm are superimposed when the data are expressed in slant angles. Therefore, the variable \( A_{\text{disp}} \) was eliminated and the regression was carried out on the remaining two variables (see Table 2). The regression coefficients \( w_{\text{perc}} \) and \( w_{\text{cont}} \) are significant (\( p < .05 \)) for CS and JD. \( R^2 \) is close to 1 for both of them, which implies that the model fits their data very well. The model fits the data of JC not as good as for the other two subjects (\( R^2_{\text{adj}} = 0.92 \)). The contribution of adaptation contingent on distance (\( w_{\text{cont}} \)) is not significant (\( p > .05 \)).

Two types of adaptation appear to occur, namely adaptation at the perception level that transfers over distance (between 51% and 74% depending on the subject) and adaptation that is contingent on distance (between 26% and 49%). The adaptation contingent on distance is not significant in one subject. Therefore, one could argue that the contribution of distance contingent adaptation is 0% for this subject.

### Table 2. The results of the multiple linear regression.

<table>
<thead>
<tr>
<th></th>
<th>( w_{\text{perc}} )</th>
<th>SE ( w_{\text{perc}} )</th>
<th>( w_{\text{cont}} )</th>
<th>SE ( w_{\text{cont}} )</th>
<th>( R^2_{\text{adj}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0.64</td>
<td>0.02</td>
<td>0.36</td>
<td>0.04</td>
<td>0.99</td>
</tr>
<tr>
<td>JC</td>
<td>0.74</td>
<td>0.04</td>
<td>0.26*</td>
<td>0.11</td>
<td>0.92</td>
</tr>
<tr>
<td>JD</td>
<td>0.51</td>
<td>0.01</td>
<td>0.49</td>
<td>0.03</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 2. The results of the multiple linear regression. \( w_{\text{perc}} \) and \( w_{\text{cont}} \) are the contributions to the two types of adaptation that occur, namely adaptation of slant perception that transfers over distance and adaptation that is contingent on distance. We did not find any low-level (disparity) adaptation (\( w_{\text{disp}} \) is not significant for all three subjects). \( \text{se} \ w_{\text{perc}} \) and \( \text{se} \ w_{\text{cont}} \) are the SEs in both contributions. The contribution \( w \) marked with an asterisk is not significant (\( p > .05 \)). \( R^2_{\text{adj}} \) is the adjusted \( R^2 \), which is a measure for the accuracy of the model with two independent variables.

### Adaptation that gradually falls off with distance

An alternative approach to model the data is to assume that there are two types of after-effects, namely adaptation at the disparity level and adaptation at the mapping/perception level. Both of them fall off with distance away from the adaptation distance. The distance dependency may be a gradual fall off with distance (or vergence) or a very steep fall off as stated by hypothesis 3.

To check for such a gradual fall off in either the after-effect caused by adaptation at the perception/mapping level or adaptation at the disparity level, the strength of the after-effect (slopes in Figure 4) is plotted as a function of vergence in Figure 5 in two different ways. Adaptation is ex-

![Figure 5](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933507/)
pressed in units of magnification (left panel) and in units of slant (right panel). If there were only an after-effect caused by adaptation at the disparity level that falls off gradually with vergence, then we would expect a peak at 6 deg (57 cm distance) in the left panel (Figure 5). However, there is no peak in the left panel. The curve increases monotonically with vergence for every subject. Therefore, the after-effect cannot be explained only by adaptation at the disparity level that falls off with distance.

If there is a gradual fall off of the after-effect caused by adaptation at the perception/mapping level, then we would expect a peak at 6 deg (57 cm distance) in the right panel (Figure 5). Interestingly, this peak is present for all subjects. The fall off is steep for subjects CS and JD, because for them the slopes at 28, 85, and 114 cm do not differ significantly from each other (p > .05). It might be possible that there is some fall off, which we cannot measure with the sparse sampling of test distances in the present experiments. For JC, the fall off is gradual, but this may be an artifact due to the low accuracy in slant discrimination of this subject.

The equal strengths of the after-effects expressed in slant at distances of 28, 85, and 114 cm provide evidence that adaptation occurs at the perception level, and adaptation at the disparity processing level is not significant and can be neglected.

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