Adaptation to three-dimensional distortions in human vision

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When people get new glasses, they often experience distortions in the apparent three-dimensional layout of the environment; the distortions fade away in a week or so. Here we asked observers to wear a horizontal magnifier in front of one eye for several days, causing them to initially perceive large three-dimensional distortions. We found that adaptation to the magnifier was not caused by changes in the weights given to disparity and texture, or by monocular adaptation, but rather by a change in the mapping between retinal disparity and perceived slant.

A scene's three-dimensional structure can be recovered from many cues, including texture and disparity. When estimating the slant of a surface, combination of these cues is well modeled by a linear weighting scheme.

$$\hat{S} = w_t(g_t S_t + b_t) + w_d(g_d S_d + b_d) \tag{1}$$

Here, S_t and S_d are the texture- and disparity-specified slants of the surface at the retinas, g_t, g_d, b_t and b_d are the gains and biases for the texture and disparity estimators, and w_t and w_d are the weights assigned to the estimates[1,2].

Wearing glasses or contact lenses with different powers (and hence different magnifications) in the two eyes alters the relationship between slant and disparity. A lens with horizontal magnification M in front of one eye should make a fronto-parallel plane have the following apparent slant.

$$S_d = \tan^{-1}\left[\frac{M-1}{M+1}\right]\frac{2d}{I} \tag{2}$$

Here, d is distance and I is interocular separation[3,4]. Horizontal magnification occurs when a person's optical correction (glasses or contact lenses) changes the astigmatic correction. Overall magnification (vertical equals horizontal) occurs when the correction changes overall lens power, producing a similar but weaker perceptual effect. To restore veridical perception, slant from disparity must either be recalibrated or down-weighted in favor of other cues.

Several investigators have examined the perceptual effects of wearing a horizontal magnifier before one eye. Surfaces initially appear rotated away from the magnified eye (as implied by Eq. 2). However, in the next several days, perceptual adaptation occurs; that is, the distortion diminishes[3–11]. Many people experience this adaptation phenomenon (following spectacle or contact lens modification) and, unlike most demonstrations of adaptation[12], the change in behavior is purely visual rather than a re-mapping between visual stimuli and motor responses. Previous investigators concluded that the adaptation mechanism was a down-weighting rather than a recalibration of disparity[3–8]. However, because they either did not test for it[3–8] or because their procedures were contaminated by monocular slant cues[9–11], they could not determine how much of the adaptation was due to changes in the disparity and texture weights as opposed to changes in slant from disparity.

Our procedure allowed separate evaluations of weight change and recalibration of disparity. Six observers wore a 3.8% horizontal magnifier over the right eye continuously for six days while engaging in everyday activities. They were tested before, during and after wearing the lens. Three types of stimuli were used.

First, with the 'strong-perspective' stimuli (Fig. 1a), we measured perceived slant from texture (first term in Eq. 1). The monocular stimuli were presented to the right (magnified) eye. After each one-second stimulus presentation, observers adjusted the angle between two lines to indicate perceived slant. The reported slants were close to the physically specified slants before, during and after introduction of the lens. Thus, slant from texture did not change.

Second, with the 'cue-conflict' stimuli (Fig. 1a), we measured the relative weights assigned to disparity and texture. In each stimulus, the difference between disparity- and texture-specified slants was –10 or +10°. Observers indicated perceived slant as above. By using the values obtained for b_t and g_t from the strong-perspective task, for each observer and session, a least-squares analysis was used to recover b_d and the product $w_d\, g_d$ from the cue-conflict data (Eq. 1). The average weight-gain product for

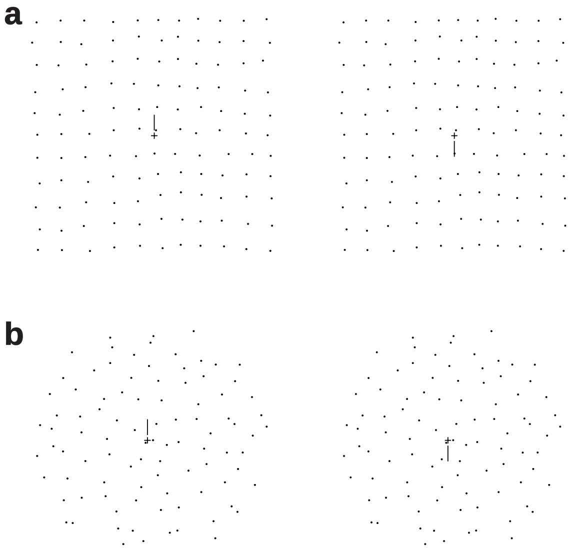

Fig. 1. Stimuli. (**a**) 'Strong-perspective' and 'cue-conflict' stimuli. When viewed monocularly, the strong-perspective stimuli measured slant from texture. When viewed binocularly, the cue-conflict stimuli measured relative weights for stereo (here, ≠0°) and texture (here, 0°). The stimuli consisted of roughly regular grids of 121 dots. Texture specified a slant of 0, ±10, ±20, ±30 or ±40°. Disparity-specified slant was 0, ±10, ±20 or ±30° (differing either –10 or +10° from texture). (**b**) 'Pure-stereo' stimuli tested slant from disparity (here, ≠0°). The random texture and roughly circular outline made slant from texture ill-defined, but always consistent with 0°. All stimuli were 16° in diameter. View by cross-fusing.

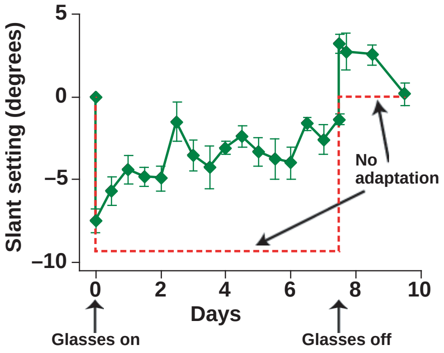

Fig. 2. Disparity adaptation. The disparity-specified slant that appeared fronto-parallel over the 10 days. Dashed red lines indicate slant settings consistent with no adaptation. Error bars represent ±1 s.e.m. between subjects.

disparity ($w_d\, g_d$) and for texture ($w_t\, g_t$) was nearly constant before, during and after lens wearing (mean ± s.d., 0.35 ± 0.05 and 0.46 ± 0.03, respectively). Thus, even as observers' percepts in natural environments were becoming veridical, the disparity and texture weights and gains did not change. This result directly contradicts previous accounts[3–8].

Third, with 'pure-stereo' stimuli (Fig. 1b), we measured perceived slant from disparity. The stimulus was a sparse, random-dot surface. The texture always specified a fronto-parallel plane. Observers adjusted the horizontal disparity gradient (consistent with rotation about a vertical axis) until the surface appeared fronto-parallel. This test, unlike previous ones[3–11], is not contaminated by monocular slant cues and is thus a pure test of slant from disparity[13,14] (Fig. 2). When the lens was first introduced, a disparity-specified slant of –7.5° appeared fronto-parallel. This is close to the predicted value of –9.4° at the 28.5-cm viewing distance (Eq. 2). Over the next six days, the apparently frontal slant decreased to –1.4°. When the lens was first removed, a clear aftereffect was observed; a slant of +3.2° appeared frontal. This aftereffect disappeared within a few days. These data show that the perceptual distortions caused by the lens were nearly completely eliminated by one adaptation mechanism, recalibration of slant from disparity.

How is the recalibration of slant from disparity implemented? Horizontal magnification of one eye's image causes a distance-dependent change in the perceived slant of a fronto-parallel surface[3,4,14] (Eq. 2). Thus, recalibrating the slant computed from disparity could be complicated. Two simpler solutions are possible. First, the visual system could adapt by biasing disparity directly, before slant is computed. Second, monocular adaptation could occur. The lens changes image width in one eye. If the system compensated for that monocular change before combination of the two eyes' images, the required distance-dependent change would result and distortions in perceived shapes of familiar objects, viewed with the magnified eye, would be corrected.

To test whether monocular adaptation accounted for recalibration of slant from disparity (Fig. 2), we again measured perceived slant with the pure-stereo stimulus and nulling task (Fig. 3, clear disparity recalibration, followed by an aftereffect). To measure monocular adaptation, we presented rectangles and found the aspect ratios that appeared square for the magnified and unmagnified eyes. The ratio of the aspect ratios (RE/LE) is plotted in Fig. 3 for each measurement; the left and right ordinates represent the equivalent slants (Eq. 2) and aspect ratios, respectively. When the lens was first introduced, the effects on slant and aspect-ratio settings were

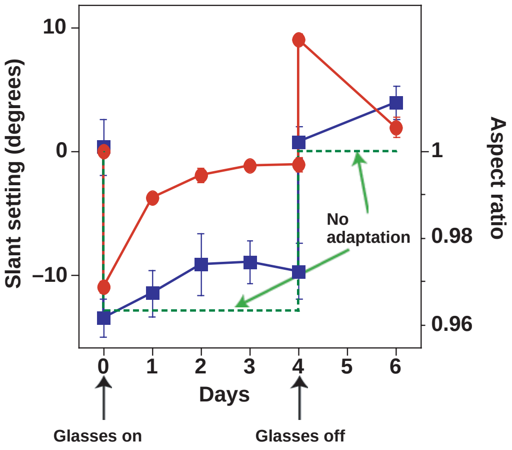

Fig. 3. Strong binocular and weak monocular adaptation. Disparity-specified slant that appeared fronto-parallel (red circles) and aspect ratios that appeared square (blue squares). In the aspect-ratio test of monocular adaptation, the observer judged whether a monocular rectangle looked wider than it was tall. Aspect ratio of the apparently square rectangle was determined for each eye using a staircase procedure. Within each session, the aspect-ratio responses for right (magnified) eye were divided by responses for left eye, to counter day-to-day changes in the observer's criterion. Data were averaged across rectangle sizes of 3, 5 and 7° (this variable had no effect). Error bars, ±1 s.e.m. Dashed green lines, predicted data (square and slant settings) for no adaptation.

consistent with the expected effects of image magnification (dashed lines). As the observer's perceived slant from disparity changed over the next four days, there was a small change in aspect-ratio settings. Thus, some monocular adaptation occurred, but not nearly enough to explain the change in slant from disparity.

Here we examined a common perceptual experience, the initial spatial distortion and subsequent adaptation that occurs when wearing glasses or contact lenses that alter the width of one eye's image. With improved procedures, we showed that adaptation is not due to down-weighting of disparity[3–8]; rather, it is the consequence of recalibration of the relationship between disparity and perceived slant.

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