Pergamon

PII: S0042-6989(97)00179-X

Vision Res., Vol. 38, No. 2, pp. 187–194, 1998

Printed in Great Britain
0042-6989/98 $19.00 + 0.00

Rapid Communication

Extra-retinal and Perspective Cues Cause the Small Range of the Induced Effect

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Received 21 January 1997; in revised form 18 April 1997; in final form 9 June 1997

With a horizontal magnifier before one eye, a frontoparallel surface appears rotated about a vertical axis (geometric effect). With a vertical magnifier, apparent rotation is opposite in direction (induced effect); to restore appearance of frontoparallelism, the surface must be rotated away from the magnified eye. The induced effect is interesting because it was thought until recently that vertical disparities do not play an important role in surface perception. As with the geometric effect, the required rotation for the induced effect increases linearly to ≈4% magnification; unlike the geometric effect, it plateaus at ~8%. Current theory explains the linear portion: vertical size ratios (*VSRs*) are used to compensate for changes in horizontal size ratios (*HSRs*) that accompany eccentric gaze, so changes in *VSR* cause changes in perceived slant. The theory does not explain the plateau. We demonstrate that it results from differing slant estimates obtained by use of various retinal and extra-retinal signals. When perspective cues to slant are minimized or sensed eye position is consistent with *VSR*, the induced and geometric effects have similar magnitudes even at large magnifications. © 1998 Elsevier Science Ltd

Binocular Stereopsis Eye movements Induced effect Slant perception

INTRODUCTION

When viewing a smooth surface at a finite distance, the two eyes receive slightly different images. The horizontal differences can be represented by *HSR*, the ratio of horizontal angles subtended in the two eyes (left/right) by a small surface patch (Bradshaw, Glennerster, & Rogers, 1996; Rogers & Bradshaw, 1993, 1995). We use *HSR* (and *VSR*) because they allow simple mathematical expressions of the disparity information in the retinal images; other quantities could be used (Frisby, 1984; Gårding, Porrill, Mayhew, & Frisby, 1995; Koenderink & van Doorn, 1976; Longuet-Higgins, 1982; Mayhew & Longuet-Higgins, 1982) without loss of generality in the conceptualization presented here. Changes in *HSR* are perceived as changes in slant about a vertical axis, but the slant of a surface patch cannot be estimated from *HSR* alone because *HSR* is a function of the patch's azimuth and distance as well as its slant (Frisby, 1984; Gårding *et al.*, 1995; Gillam & Lawergren, 1983; Mayhew & Longuet-Higgins, 1982; Rogers & Bradshaw, 1993, 1995). There are a variety of signals available to the visual system in static viewing situations that can, in principle, allow veridical slant estimation, given the observed *HSR*. All of the signals are probably used in various combinations, but it is simpler to describe their usage in terms of three computations.

Slant estimation from HSR and eye position

The sensed positions of the eyes can be used to interpret *HSR*. To a good approximation:

$$S = \tan^{-1}\left[-\frac{1}{\mu}\ln\left(\frac{HSR}{1+\mu\tan\gamma}\right)\right] \quad (1)$$

where S is the surface slant (the angle between the surface normal and the cyclopean visual line), γ is the azimuth of the surface patch (and is the eyes' version if the patch contains the fixation point), and μ is the vergence of visual lines to the surface patch (and is the eyes' vergence if the patch contains the fixation point).‡ Thus, slant at fixation can be estimated from *HSR* if γ and μ are determined via extra-retinal signals (Cumming, Johnston, & Parker, 1991; Collett, Schwarz, & Sobel, 1991; Foley, 1980; Gårding *et al.*, 1995). Slant for non-fixated patches

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‡Equation (1) and equation (2) estimate slant correctly to within 1.5 and 0.25 deg, respectively, for the following range of viewing conditions: 40 cm viewing distance, 6.0 cm interocular distance, slants from −50 to 50 deg, and azimuths from −30 to 30 deg.

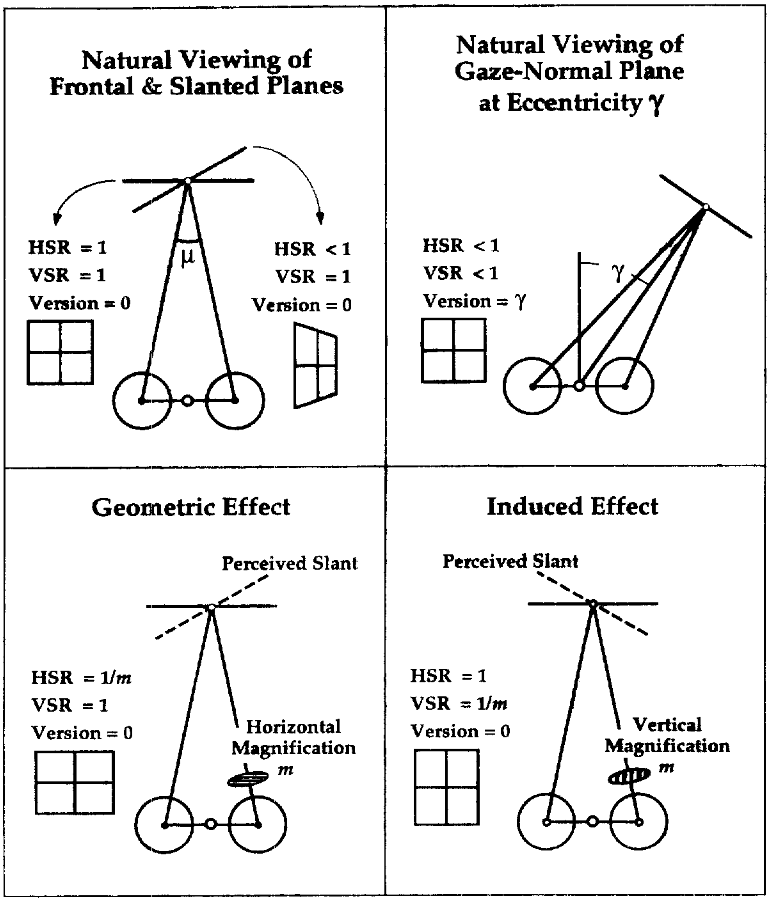

FIGURE 1. The viewing geometry and signals involved in slant estimation. The four panels represent different viewing situations. Three methods of estimating slant are described in the text; these methods use the *HSR*, *VSR*, version, and perspective signals that are represented in each panel. With natural viewing (upper panels), the three methods of estimating slant agree with one another. In the geometric effect (lower left), the two stereoscopic slant estimates (based on *HSR* and *VSR* and on *HSR* and eye position, respectively) agree with each other, but no longer agree with perspective. In the induced effect (lower right), slant from *HSR* and *VSR* disagrees with the other two estimates, which agree with each other.

can be determined via similar means by using the retinal coordinates of the surface patch (Gårding *et al.*, 1995).

Figure 1 schematizes the viewing geometry and signals involved in slant estimation. The panels represent four viewing situations in which an objectively gaze-normal patch is fixated. When the eyes are converged on a surface patch lying straight ahead (upper left), extra-retinal signals indicate version ≈ 0 and vergence >0; $HSR = 1$, so from equation (1), the slant estimate is 0. When the eyes are asymmetrically converged on a patch at an azimuth <0 (upper right panel), the signals indicate version <0. For gaze-normal planes, $HSR \approx 1 + \mu \tan\gamma$, so a slant estimate of 0 is again obtained.

Slant estimation from HSR and VSR

VSR, the ratio of vertical angles in the two eyes, can be used to interpret *HSR*. To close approximation:

$$S = \tan^{-1}\left[-\frac{1}{\tilde{\mu}}\ln\left(\frac{HSR}{VSR}\right)\right] \qquad (2)$$

where

$$\tilde{\mu} = 1/2\{\partial VSR/\partial\gamma + \surd[(\partial VSR/\partial\gamma)^2 + 4\ln(VSR)\ln(HSR/VSR)]\}$$

and $\partial VSR/\partial\gamma$ is the derivative of *VSR* with respect to azimuth. This method does not require extra-retinal eye-position signals. Recent experiments have shown that *VSR* variations do indeed affect perceived slant, curvature, and depth (Bradshaw *et al.*, 1996; Kaneko & Howard, 1996; Rogers & Bradshaw, 1993, 1995), so this (or a closely related) means of estimation must exist.

When setting a surface patch to appear gaze normal, it suffices to find the slant yielding $HSR/VSR = 1$ (Bradshaw *et al.*, 1996; Kaneko & Howard, 1996; Ogle, 1950; Rogers & Bradshaw, 1995). In a recent computational model (Gårding *et al.*, 1995), "relief" tasks (e.g., adjusting a plane to appear gaze normal) are distinguished from "metric" tasks (estimating slant magnitude). The difference, as formalized in equation (2), is that $\tilde{\mu}$ is not needed to do relief tasks such as the apparent gaze-normal task used here and by Ogle (Ogle, 1938, 1950).

Slant estimation by perspective cues. Useful indications of surface slant are provided by perspective cues such as the texture gradient created by projection onto the retinae of surfaces with statistically regular textures (Buckley & Frisby, 1993; Cumming *et al.*, 1993; Cutting & Millard, 1984; Gillam & Ryan, 1992). In the upper panels of Fig. 1, this method provides estimates of ~0 for the central and eccentric surfaces.

In our conceptualization, a final slant estimate is derived from the combination of weighted inputs from the various signals.* One can conceive of this as combination of weighted inputs from the three methods of slant estimation, but the signals may be combined in other ways.† The weights depend on the informativeness of the signals. For example, *VSR* cannot be calculated when the stimulus consists of vertical rods (Amigo, 1967; Herzau & Ogle, 1937), so slant estimation from *HSR* and *VSR* has a weight of zero for that stimulus.

Under normal viewing, the slants estimated by these three methods agree. Interpreting *HSR* via *VSR* and eye position has the important consequence of compensating for the changes in binocular viewing geometry that occur with eccentric gaze (Kaneko & Howard, 1996; Ogle, 1950). Placing a meridional magnifier before one eye alters the natural relationships among *HSR*, eye position, *VSR*, and perspective cues. In the geometric effect, horizontal magnification of the right eye's image yields a decrease in *HSR*, but other signals are virtually unaltered. In estimating slant from *HSR* and eye position, equation (1) becomes:

$$S = \tan^{-1}\left[-\frac{1}{\mu}\ln(HSR)\right] \quad (3)$$

where *HSR* is the size ratio after magnification and is equal to $\hat{HSR}/m$, where $\hat{HSR}$ is the ratio before magnification and m is the magnification factor to the right eye. To make it appear gaze normal, a plane must be rotated clockwise until $\hat{HSR} = m$, which yields $HSR = 1$.

When an observer estimates slant from *HSR* and *VSR* [instantiated by equation (2)], the amount of rotation required to restore the appearance of gaze normal ought to be the same in magnitude, but opposite in sign, for the induced and geometric effects. Despite this clear prediction from current stereoscopic theory (Frisby, 1984; Gårding *et al.*, 1995; Gillam *et al.*, 1988; Gillam & Lawergren, 1983; Kaneko & Howard, 1996; Koenderink & van Doorn, 1976; Mayhew, 1982; Rogers & Bradshaw, 1995), the induced effect is typically smaller than the geometric effect at magnifications greater than 3–4%. Within the framework of current theory, there have been several explanations for this difference.

Conflicting estimates of azimuth. With increasing magnification, the azimuth of the fixated surface, indicated by *VSR* and $\partial VSR/\partial\gamma$, becomes increasingly different from extra-retinal estimates of eye position and this conflict causes an attenuation of perceived slant (Gillam *et al.*, 1988). Changes in *VSR* and $\partial VSR/\partial\gamma$ do not alter perceived azimuth (Ogle, 1950), so it is not clear how the proposed conflict would arise in the first place.

Implausible stimulus location. *VSR*s created by vertical magnification imply azimuths and distances at which observers do not normally inspect a surface (Frisby, 1984; Gillam *et al.*, 1988; Mayhew, 1982; Ogle, 1950). This hypothesis predicts a decreasing magnification for the plateau with increasing distance and this is not observed (Gillam *et al.*, 1988; Ogle, 1938, 1950).

Fusion failure. The smaller induced effect could result from an inability to fuse large vertical disparities (Ogle, 1950). This hypothesis can be rejected because magnifications at plateau are the same in symmetric and asymmetric convergence (Ogle, 1940), even though vertical disparities are much larger in the latter.

Perspective conflict

Ogle attempted to eliminate perspective slant cues from some of his experiments by using a plane sprinkled with randomly positioned spots (Gillam *et al.*, 1988; Ogle, 1938), but such a stimulus provides a texture gradient cue, so perspective and *HSR*–*VSR* cues still specify conflicting slants. The perspective conflict hypothesis, however, does not explain why the same conflict causes no attenuation of the geometric effect.

We propose that the smaller range of the induced effect relative to the geometric effect can only be understood from considering *all* the signals in static slant estimation. As the analysis in Fig. 1 shows, the two stereoscopic estimates in the induced effect are in conflict and slant estimation from perspective cues agrees with one of them; in the geometric effect, the stereoscopic estimates are in agreement and conflict with perspective cues. As a consequence, the final slant estimate is affected differently by vertical and horizontal magnification. We tested this idea by varying the informativeness of perspective cues and by making slant estimation by *HSR* and eye position consistent and inconsistent with estimation by *HSR* and *VSR*.

EXPERIMENT 1

In the first experiment, we measured the induced and geometric effects in the presence of strong and weak perspective cues. Figure 2 displays the results for the four observers. Icons representing the strong- and weak-cue

*These equations allow estimates for all slants, but in our experiments, we only used a slant-nulling task. We assume that the mechanisms involved in slant nulling are the same as those involved in estimating non-zero slants, but we have no definitive proof. Partial justification for our assumption comes from the fact that slant-nulling and slant-estimation tasks both reveal larger geometric than induced effects at magnifications greater than ≈4% (Gillam, Chambers, & Lawergren, 1988; Kaneko & Howard, 1996; Ogle, 1950).

†Gillam (1993) reported that horizontal magnification can lead to perceived slant in the direction opposite that predicted geometrically when perspective information is strong. As she noted, weighting the outputs of independent modules cannot account for this phenomenon, so our conceptualization will not explain this phenomenon.

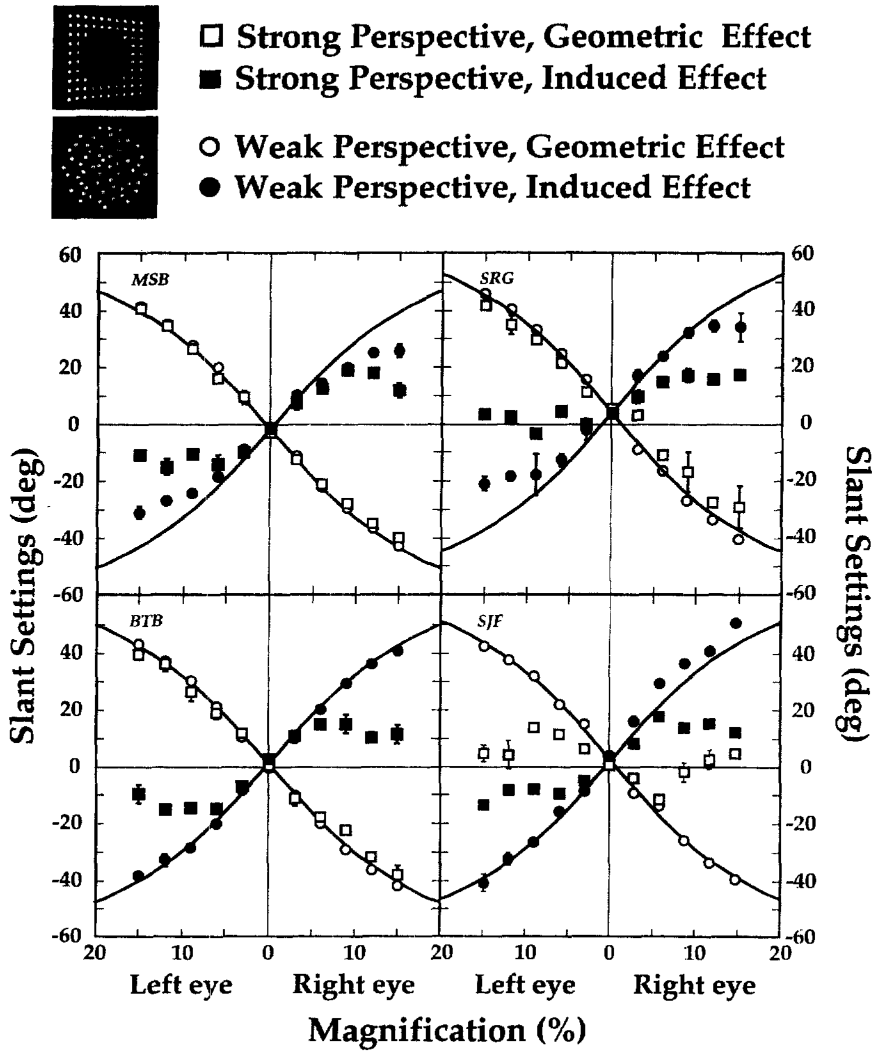

FIGURE 2. Slant settings as a function of magnification and perspective information (Experiment 1). A haploscope was used, so the left and right eyes viewed different CRTs via mirrors. The stimuli were 300 dots, composed of 2 × 2 pixel clusters with anti-aliasing, on a black background. CRT distortions were eliminated by mapping true visual directions, as seen by the left and right eyes, to corresponding screen locations. The room was dark, so environmental features such as the CRT frames were invisible. The head was fixed with a bite bar. Observers maintained fixation on a small marker in the center of the display. The eyes were symmetrically converged at 40 cm (version = 0 deg, vergence ≈9 deg). To create the stereoscopic displays, points in a virtual plane were projected to the two eyes separately. The center of the plane was always 40 cm in front of the midpoint of the interocular axis. Induced and geometric effects were measured in the presence of strong and weak perspective cues; observers adjusted the slant of the stimulus (rotation about a vertical axis) until it appeared gaze normal. In the strong-perspective condition (upper icon), the points in the virtual plane created a 17-cm square lattice with regular 0.35-cm spacing. When the plane was unmagnified and normal to one eye's line of sight, the lattice subtended 25 × 25 deg at that eye; to insure that clear plateaux were observed for the induced effect, we followed a suggestion of Ogle (1950) and removed dots within the central 14 cm (20 deg when gaze normal). The points were affixed to the plane before rotation so, after rotation, the square lattices projected to the two eyes in geometrically correct fashion (dot size and brightness were constant). In the weak-perspective condition (lower icon), 300 points were chosen at random from a frontoparallel disk 25 deg in diameter and were back-projected onto the virtual plane, *after* rotation of the plane, from the perspective of a point midway between the eyes. With this projection technique, there is no useful slant information in the monocular images. For both strong- and weak-perspective stimuli, one eye's image was then magnified horizontally or vertically in software. The data are displayed in separate panels for the four observers. The abscissae are the percent magnification applied to the left or right eye. Ordinates are the slant of the virtual plane when it appeared gaze normal. Data points represent averages of six settings; error bars are ±1 standard deviation. Open symbols represent settings with horizontal magnification (geometric effect) and filled symbols settings with vertical magnification (induced effect). Circles represent settings with weak perspective cues and squares settings with strong perspective cues. Predictions of the three means of slant estimation are the following. With vertical magnification, slant estimation by *HSR* and *VSR* [equation (2)] predicts the curves running from lower left to upper right; slant estimation by *HSR* and eye position [equation (1)] and slant estimation by perspective predict the horizontal lines. With horizontal magnification, slant estimation by *HSR* and *VSR* and estimation by *HSR* and eye position predict the curves from upper left to lower right; slant estimation by perspective predicts the horizontal lines. The diagonal curves have been shifted vertically as a unit such that they go through the individual observers' settings when magnification is 0%.

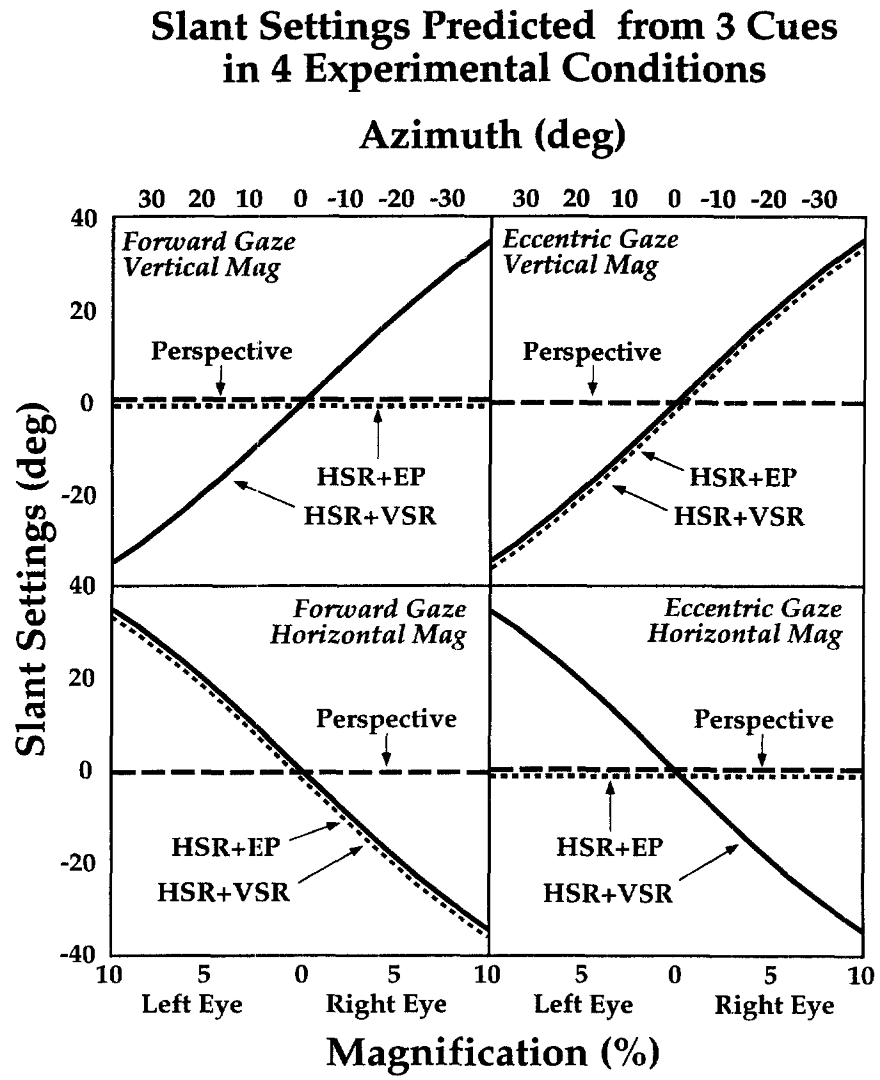

FIGURE 3. Predicted slant settings based on the three methods of slant estimation as a function of magnification and fixation azimuth (Experiment 2). Methods are described in the Fig. 4 caption.

stimuli are shown at the top of the figure, and experimental methods are described in the caption. The predictions of the three means of slant estimation are shown by the solid lines, also described in the figure caption.

For three of the four observers, the settings in the geometric-effect condition (open symbols) were very consistent with prediction whether perspective cues were strong (squares) or weak (circles). Observer SJF showed a smaller geometric effect with strong perspective. The settings in the induced-effect condition (filled symbols) exhibited the typical plateau at ~8% when perspective cues to slant were informative (squares). With a reduction in the salience of perspective cues, however, the induced effect was nearly identical to the geometric effect, even at magnifications greater than 8% (circles). Indeed, two observers (BTB and SJF) exhibited induced effects close to theoretical prediction [equation (2)] up to 30% magnification. These data are consistent with an earlier observation that perceived slant increases monotonically up through large vertical magnifications (Rogers & Koenderink, 1986), but they add to it by showing that *VSR* alterations created by vertical magnification affect the perception of gaze normal in just the way predicted by slant estimation from *HSR* and *VSR* when perspective cues are not informative.* The observation of unattenuated induced effects at large magnifications is not consistent with the hypothesis that the plateau in the induced effect is a consequence of creating implausible combinations of *VSR* and $\partial VSR/\partial\gamma$ (Frisby, 1984; Gillam *et al.*, 1988; Mayhew, 1982; Ogle, 1938).

*We believe that Gillam *et al.* (1988) and Kaneko and Howard (1996) found larger geometric than induced effects in part because the perspective cues were stronger in their stimuli than in our weak perspective condition. In particular, the dots in their displays were larger and large dots provide two visible perspective cues: projected shape and projected size. The absence of shape and size changes provides information that the display is frontoparallel. We used small dots (<6 min diameter) with fuzzy edges which minimizes these cues to frontoparallelism.

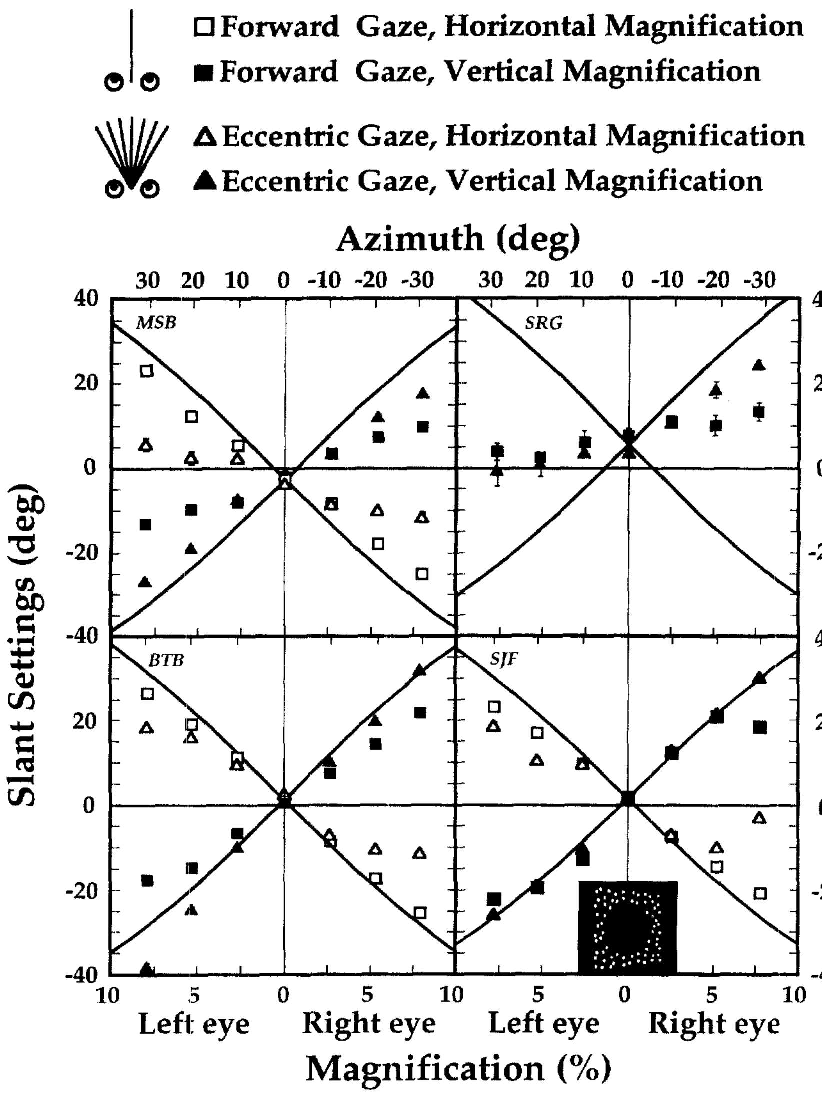

FIGURE 4. Slant settings as a function of magnification with forward and eccentric gaze. Each panel shows data from a different observer. Data points represent averages of four apparent gaze-normal settings. The haploscope arms were rotated about points below the centers of rotations of the eyes, so the head-centric azimuth of the stimulus could be varied without altering the retinal images. The strong-perspective configuration used in Experiment 1 was used again, except the lattice subtended 20 × 20 deg when gaze normal to allow for larger target azimuths. (In Experiment 1, SJF exhibited small induced and geometric effects due to a large effect of perspective, so we altered the stimulus for her by placing randomly rather than regularly positioned dots in a square patch on the virtual plane; see icon in lower right panel.) There were four conditions: vertical and horizontal magnification in forward gaze (conventional induced and geometric effects) and vertical and horizontal magnification in eccentric gaze. In the forward-gaze conditions, the images were presented straight ahead, so the eyes' version was 0 deg and vergence was ~9 deg. In the eccentric-gaze conditions, the images were presented at various headcentric azimuths, so the eyes' version varied. For vertical magnification, *VSR* and $\partial VSR/\partial\gamma$ in the retinal images were appropriate for a plane surrounding the eccentric fixation point; stated another way, the head-centric azimuth was the one that would, in natural viewing, give rise to the *VSR* and $\partial VSR/\partial\gamma$ in the stimulus. For horizontal magnification, *VSR* and $\partial VSR/\partial\gamma$ remained appropriate for straight ahead: the head-centric azimuth was the azimuth at which a truly gaze-normal plane gives rise to an *HSR* value equal to the horizontal magnification in the stimulus. For gaze-normal planes, *HSR* = *VSR* at fixation, so the same azimuth was used at a given magnification for horizontal and vertical magnifications.

EXPERIMENT 2

Why does the manipulation of perspective cues affect the induced effect so dramatically and not the geometric effect? We propose that this difference is a consequence of the fact that slant estimation from *HSR* and eye position agrees not with slant estimation from *HSR* and *VSR* (as in the geometric effect), but rather with slant estimation by perspective cues. To test this possibility, we conducted a second experiment using eccentric gaze to see if the attenuation of the induced effect could be abolished by making eye position consistent with *VSR*: this manipulation causes *HSR* and eye position no longer to agree with perspective, but rather with *HSR* and *VSR*. Similarly, we tested whether the geometric effect can be made to plateau at higher *HSR*s, when slant from *HSR* and eye position is made consistent with perspective rather than with slant from *HSR* and *VSR*.

Predictions when version = 0 deg (forward gaze) and version ≠ 0 deg (eccentric gaze) are described in Fig. 3. Because the retinal images were the same in the forward- and eccentric-gaze conditions, any differences in slant settings between the two conditions must reflect the contribution of eye position sensed via extra-retinal signals.

The upper panels of Fig. 3 show the predictions for vertical magnification for the three means of slant estimation. Slant estimation by *HSR* and *VSR* [equation (2)] predicts the diagonal curve for forward and eccentric gaze (because this means of estimation is unaffected by eye position *per se*). Slant estimation by *HSR* and eye position [equation (1)] makes different predictions depending on the gaze condition: it predicts the horizontal line for forward gaze and the diagonal curve in eccentric gaze. Slant estimation from perspective predicts the horizontal line for both gaze conditions. The details of the experimental method are described in the caption to Fig. 4.

The filled symbols in Fig. 4 represent the results for vertical magnification. With forward gaze, the slant required to make the plane apparently gaze normal was significantly less than predicted by equation (2). However, with eccentric gaze, slant settings were larger and closer to prediction; moreover, no clear plateaux were observed. Observers reported clear phenomenological differences between the two conditions after setting the stimulus to apparent gaze normal. When the eyes were turned to the appropriate azimuth for the vertical magnification, the stimulus looked like a trapezoidal grid painted on a gaze-normal plane. When the eyes were straight ahead, settings were less certain and the stimulus did not appear so clearly planar.

The lower panels of Fig. 3 show the predictions for horizontal magnification. Slant estimation by *HSR* and *VSR* [equation (2)] again predicts a diagonal curve, and perspective again predicts the horizontal line, for both gaze conditions. Now, however, slant estimation by *HSR* and eye position [equation (1)] predicts the diagonal curve for forward gaze and the horizontal line in eccentric gaze.

The horizontal-magnification results for the three observers who ran this condition are represented by the open symbols. With forward gaze, the slant required to make the plane appear gaze normal was close to the predictions of equation (2). However, with eccentric gaze, the apparently gaze-normal slant was significantly attenuated. Thus, like the induced effect, the geometric effect can exhibit a plateau when estimation by *HSR* and eye position agrees with perspective rather than with estimation by *HSR* and *VSR*.

Finally, we ran the conditions depicted in Fig. 4 with the weak-perspective configuration of Experiment 1. When observers viewed the stimuli in eccentric gaze (azimuth appropriate for the *VSR*), slant settings at vertical magnifications up to 8% (the highest value we could present) were very close to the predictions of slant estimation by *HSR* and *VSR*. This finding demonstrates that induced-effect plateaux can be eliminated altogether when eye position is made consistent with the observed disparities and when perspective cues are made uninformative.

CONCLUSION

Estimating the slant of a stereoscopically defined surface is a difficult problem because horizontal disparities are affected by the surface's distance and azimuth as well as its slant. The visual system uses a variety of retinal and extra-retinal signals to solve the problem. Magnification of one eye's image alters the natural relationships among those signals and, by tracing what happens to them, one can understand the smaller range of the induced effect compared with the geometric effect. The induced effect is attenuated in part by conflicting perspective cues and this fact is manifest in the observation in Experiment 1 that its attenuation is virtually eliminated by making perspective signals uninformative. The differing effects of conflicting perspective signals on the induced and geometric effects is a consequence of the influence of slant estimates corrected by sensed eye position; this is manifest by the observation in Experiment 2 that unattenuated induced effects are obtained in the presence of strongly conflicting perspective cues when eye position is consistent with the observed vertical magnification. Although this is the simplest explanation consistent with the facts, it is still rather complicated and this may explain why it has eluded researchers for a half century.

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Acknowledgements—This work was supported by AFOSR Research Grant 93NL366 and by the NSF Research Grant DBS-9309820. We thank Jim Crowell, Tom Freeman, Jitendra Malik, Cliff Schor, and Raymond van Ee for comments.