A textured surface appears slanted about a vertical axis when the image in one eye is horizontally enlarged relative to the image in the other eye. The surface appears slanted in the opposite direction when the same image is vertically enlarged. Two superimposed textured surfaces with different horizontal size disparities appear as two surfaces that differ in slant. Superimposed textured surfaces with equal and opposite vertical size disparities appear as a single frontal surface. The vertical disparities are averaged. We investigated whether vertical size disparities are averaged across two superimposed textured surfaces in different depth planes or whether they induce distinct slants in the two depth planes. In Experiment 1, two superimposed textured surfaces with different vertical size disparities were presented in two depth planes defined by horizontal disparity. The surfaces induced distinct slants when the horizontal disparity was more than \( 6 \text{ arcmin} \). Thus, vertical size disparities are not averaged over surfaces with different horizontal disparities. In Experiment 2 we confirmed that vertical size disparities are processed in surfaces away from the horopter, so the results of Experiment 1 cannot be explained by the processing of vertical size disparities in a fixated surface only. Together, these results show that vertical size disparities are processed separately in distinct depth planes. The results also suggest that vertical size disparities are not used to register slant globally by their effect on the registration of binocular direction of gaze.

Keywords: stereopsis, slant, vertical disparity


**Introduction**

Horizontal size disparities provide information about the slant of a surface about a vertical axis. Consider a surface directly in front of an observer, slanted with respect to the gaze-normal plane (in this case, the frontal plane) as in Figure 1a. The left eye’s image is horizontally compressed relative to the right eye’s image. We will denote a horizontal size disparity as the percentage difference between the horizontal extents of the two images, signed positive when the left eye’s image is larger than the right eye’s image.

Horizontal size disparity increases as slant increases. However, the disparity produced by a given slant changes with distance. It also changes with azimuth. Therefore a given horizontal size disparity corresponds to surfaces with different slants at different locations. For example, the two surfaces in Figure 1 have the same horizontal size disparities but surface (a) is centered on the midline while surface (b) is at an azimuth of \( \gamma \). It can be seen that the surfaces have different slants. Distance and azimuth must be taken into account if slant is to be judged accurately (Backus et al., 1999).

In theory, distance and azimuth could be indicated by eye-position signals. But they could also be provided by the pattern of vertical disparities produced by the surface because vertical disparity varies with distance and with eccentricity. There is considerable evidence that vertical disparities are used to interpret horizontal disparities produced by slanted surfaces (Stenton, Frisby, & Mayhew, 1984; Rogers & Bradshaw, 1993, 1995; Kaneko & Howard, 1996; Backus et al., 1999; Frisby et al., 1999; Gårding et al., 1995; Banks, Hooge, & Backus, 2001; Berends & Erkelens, 2001; Serrano-Pedraza & Read, 2009). However, theories differ over how vertical disparities are used in this process. For example, Mayhew and Longuet-Higgins (1982) and Gårding et al. (1995) proposed theories in which vertical disparities are used to obtain information about binocular eye position. On the other hand, Gillam and Lavergne (1983), Kaneko and Howard (1996) and Backus et al. (1999) proposed theories in which vertical disparities are used to obtain information about distance and azimuth. Both types of
information – binocular eye position and surface location – can be used to scale horizontal disparities to recover surface slant. The reason why vertical disparities are used to provide eye position information in some theories and surface location in others stems from the use of different coordinate systems in the two cases (Read, Phillipson, & Glennerster, 2009; Howard & Rogers, 2012). In principle, vertical disparities can provide both eye position signals and surface location information. An important question, which we address in the present study, is whether vertical disparities used in slant perception are used “directly” to signal surface azimuth, or “indirectly” to signal gaze eye position.

If one image of a surface is magnified horizontally to produce a horizontal size disparity, the surface appears to slant away from the eye with the wider image. If the same image is magnified vertically to produce a vertical size disparity, the surface appears to slant in the opposite direction. This is the “induced effect” described by Ogle (1938). The two effects cancel when one image is magnified in both directions, as happens in anisometropia. Thus the perceived slant of a surface depends on the combined effects of horizontal size disparity and vertical size disparity (e.g., Frisby, 1984; Backus et al., 1999). The induced effect is evidence that vertical size disparities are used to interpret horizontal size disparities. However, it is not known whether vertical size disparity disambiguates horizontal size disparity by providing information about eye positions or about stimulus azimuth. The two alternatives may be distinguished by examining how vertical size disparities are processed over the binocular visual field as we explain next.

Horizontal size disparities are resolved within each small region. They are averaged only within an area subtending a few minutes of arc (Parker & Yang, 1989). Kaneko and Howard (1997) reported that dissimilar vertical size disparities applied to various regions of a large frontal surface produced different slants across the surface as long as the regions subtended at least approximately 20°. More recently, Serrano-Pedraza, Phillipson, and Read (2010) found wide individual differences, with regions as small as 3° in some observers.

A stereogram containing dots with a horizontal size disparity intermingled with dots with zero disparity appears as two intersecting surfaces with different slants. A stereogram containing dots with a vertical size disparity intermingled with dots with zero disparity appears as a single surface with an induced slant based on the ratio of dots with disparity to dots with zero disparity (Stenton et al., 1984; Kaneko & Howard, 1996; Porrill et al., 1999). Thus intermingled vertical size disparities are averaged over a surface in one depth plane but it is not known whether they are averaged across two surfaces at different depths. That is the question we examine in this paper.

Evidence that vertical size disparities are averaged over depth would support the conclusion that vertical size disparities signal eye gaze direction, not surface azimuth. In contrast, evidence that vertical size disparities are processed independently within surfaces at different depths would indicate that vertical size disparities signal surface azimuth directly, not eye gaze direction.

Introducing a horizontal gradient of vertical disparity into a frontal surface induces curvature about the vertical meridian (Rogers & Bradshaw, 1995; Frisby et al., 1999; Berends & Erkelens, 2001). This curvature induced effect indicates that horizontal gradients of vertical disparity are used to compensate for change in
horizontal disparity curvature with distance (Gårding et al., 1995). Duke and Howard (2005) introduced different horizontal gradients of vertical disparity into each of two frontal surfaces separated in depth and found distinct curvature induced effects when the surfaces were separated by a horizontal disparity as little as 10 arcmin. Thus, the horizontal gradients of vertical disparity were not averaged over surfaces at different depths. This result suggests that the vertical disparities are used to determine the distance of a surface directly, not through the mediation of coding the convergence angle of the eyes.

In the present study we examined whether vertical size disparities are averaged over depth and thus whether vertical size disparities are used directly to determine surface azimuth or indirectly to determine gaze direction.

### Experiment 1

**Method**

**Stimuli**

Stereoscopic images were generated by a PC computer (ASUSTek Computer, Inc., Taiwan) and rear projected onto two large screens, (Xeed SX60 projectors, Canon, Inc., Japan; Da-Tex screens, Da-Lite Screen Company, Inc., Indiana, USA) one on each side of the observer. The images were anti-aliased to increase their effective resolution. When viewed through two orthogonal mirrors, the images fused into a single image, 70° wide and 60° high, which appeared to be straight ahead in the frontal plane at a distance of 1 m.

The observer’s head was supported on a chinrest. An occluder on each side of the head limited the field of view of each eye to its own image. Nothing other than the projected images was visible.

The stereoscopic stimuli were planar arrays of white texture elements on a black background. The texture elements subtended approximately 1.3° and were separated by approximately 6.6° with added random displacement of up to 1°. The random displacement and variable shapes of the texture elements prevented false fusions.

One of the basic stereograms was constructed from two arrays with bold texture elements. The other was constructed from two arrays with fine texture elements. Each stereogram presented alone created a surface in the frontal plane. When the two stereograms were superimposed, a horizontal disparity between them created two surfaces in different depth planes, as in Figure 2. The two surfaces could be distinguished because of the difference in the texture elements. The texture elements of the two surfaces were relatively displaced horizontally and vertically so that they did not overlap when superimposed. One surface (the “fixed surface”) was presented at a fixed distance of 1 m. The other surface (the “offset surface”) was presented with each of nine levels of horizontal disparity with respect to the fixed surface. The disparity offsets were ±40, ±20, ±10, ±5 and 0 arcmin, which are well within the range that provides good stereopsis (Blakemore, 1970).

In one surface the left eye’s image was vertically magnified 4% relative to the right eye’s image. We call this a +4% vertical size disparity. In the other surface the right eye’s image was vertically magnified 4% relative to the left eye’s image. We call this a −4% vertical size disparity. Each surface presented alone appeared to slant because of the induced effect created by vertical disparity. The theoretical slant, \( \sigma \), produced by a given vertical size ratio (VSR: the ratio of the vertical subtense of the left and right eye’s image) is given by the following equation,

\[
\sigma = -\tan^{-1}\left[\frac{D}{I} \ln VSR\right]
\]

where \( D \) is viewing distance and \( I \) is the interocular distance (Backus et al., 1999). In this equation, \( \sigma \) is measured with respect to the gaze-normal plane, which can be considered a frontal plane in this experiment since the display is straight in front of the observer. Theoretically, at a distance of 1 m, a +4% vertical disparity should produce a slant of approximately −30° (left-side-near) and a −4% disparity should produce a slant of approximately +30° (right-side-near). The superimposed surfaces are a form of cue-conflict stimulus because the vertical size disparities considered separately in each surface predict opposing slants but the relative horizontal disparities between the surfaces indicate that they are parallel.

Observers performed a slant-matching task. On each trial an observer was shown either a single test surface with +4% or −4% vertical size disparity or the same surface superimposed on the surface with opposite vertical disparity and different texture elements. When the observer pressed a button, the initial stimulus was replaced by a single comparison surface with zero vertical disparity at a distance of 1 m. The comparison surface had the same texture elements as the test surface. Thus, it was clear which of the initial superimposed surfaces was the test surface.

Observers used a keypad to adjust the slant of the comparison surface until it matched the slant of the test surface with the same texture elements. The slant of the comparison surface was altered by changing the horizontal magnification of the left eye’s image relative to that of the right eye’s image. Observers were free to alternate between viewing the test and comparison
surfaces as often as they wished. Observers pressed a key to advance to the next trial when the slants of the comparison and test surfaces were judged to be the same.

Observers

There were four observers between 20 and 30 years of age. All had stereoacuity of 20 arcsec or better, measured with the Titmus Randot Stereotest. Observer PD was an author, and the other three were naïve as to the purpose of the experiment.

Procedure

Each observer completed four experimental sessions, each consisting of 38 trials: two single-surface trials and 36 superimposed-surface trials. The single surfaces were presented once with positive vertical disparity and once with negative vertical disparity. Superimposed surfaces were presented with each of the nine horizontal-disparity offsets. In one pair of conditions the observer adjusted the slant of the offset surface: once when it had positive vertical size disparity and once when it had negative disparity. In a second pair of conditions the observer adjusted the slant of the fixed surface, once with positive and once with negative vertical size disparity. Stimuli in each of the 38 trials were presented with one of the four combinations of types of texture element and position, which were randomly distributed over the four sessions.

Predictions

Figure 3 shows three different predictions for the perceived slants of superimposed surfaces with opposite vertical size disparities. Perceived slant is indicated by the horizontal size disparity of the comparison stimulus. Figure 3a shows predicted perceived slants assuming that vertical size disparities are processed within each surface separately. The graphs indicate roughly equal but opposite induced effects in the two surfaces throughout the range of horizontal-disparity offsets.

Figure 3b shows predicted perceived slants assuming that vertical size disparities are averaged over a narrow range of horizontal disparity offsets. This pattern is predicted if vertical size disparities directly signal surface azimuth, not eye gaze direction.

Figure 3c shows predicted perceived slants assuming that vertical size disparities are averaged over a wide range of horizontal disparities. This pattern is predicted if vertical size disparities directly signal the angle of eccentric gaze, not surface azimuth.

Results and discussion

Equal and opposite vertical magnifications predict equal and opposite induced slants, which should require equal and opposite settings of horizontal size disparity of the comparison surface to match them. Indeed, ANOVAs revealed no significant difference in the magnitude of induced slants between the two vertical magnification conditions either for the fixed surface ($F(1,3) = 0.411$, $p = 0.567$) or for the offset surface ($F(1,3) = 1.96$, $p = 0.256$). Therefore we combined the data across the positive and negative vertical-disparity conditions for the fixed and offset surfaces. Results for the four observers are shown in Figure 4a–d. The observers produced qualitatively similar results. The group mean data are shown in Figure 4e.

First consider the results for the single surfaces, each of which produced induced slant. The magnitude of the induced slant was about 28% of the theoretical value. This is similar to findings from some studies of induced effects (Duke & Howard, 2005) but smaller than others (Berends & Erkelens, 2001). A possible reason for the partial induced effect is that the induced slant conflicted
with perspective and accommodation, both of which signaled zero slant. Banks and Backus (1998) demonstrated that perspective cues reduce the size of the induced effect. Watt, Akeley, Ernst, and Banks (2005) showed that monocular slant perception is reduced when texture cues conflict with the accommodative blur. However, they found that perception was accurate when their displays were viewed binocularly. Another reason for the partial induced effect is that gaze eye position signals are used to scale horizontal size disparities in slant perception (Backus & Banks, 1999, Backus, Banks, van Ee, & Crowell, 1999). The magnitude of the induced effect should be a compromise between slants predicted by the use of vertical size disparities and the use of eye position signals to scale horizontal disparities. Backus et al. (1999) estimated the relative contribution of vertical size disparities and eye position to be about 80:20% in stimuli that provided a reliable vertical size disparity signal.

Next consider the results for the superimposed surfaces. The first point to note is that when two surfaces with opposite vertical magnifications were superimposed in the same depth plane (zero offset) all the texture elements of the two surfaces appeared to lie on the same frontal surface. This demonstrates that vertical size disparities were not processed independently within the two superimposed surfaces, even though their
texture elements were not the same (Figure 3a). Our data are consistent with previous reports that vertical size disparities within a single depth plane are averaged (Stenton et al., 1984; Porrill et al., 1999).

The second and most important point is that the induced effects in the two surfaces became increasingly different with increasing horizontal disparity between the surfaces. ANOVAs revealed that the effect of horizontal disparity was statistically significant for both the fixed surface \((F(8,24) = 4.973, p = 0.001)\) and the offset surface \((F(8,24) = 6.830, p < 0.0005)\). A difference in slant between the two surfaces was evident even for the smallest horizontal-disparity offset \((\pm 5\) arcmin). A paired-samples t-test revealed that the difference in settings, averaged across +5 and −5 arcmin horizontal disparity offset conditions, is statistically significant; \(t_3 = 2.793, p = 0.034\) (one-tailed test). As the horizontal disparity offset between the surfaces increased, slant settings tended toward those obtained when each surface was seen alone, being almost equal to them at an offset of \(\pm 40\) arcmin.

Although the induced slants are smaller than predicted on the basis of disparity, the results resemble the predictions shown in Figure 3b. The data show that vertical size disparities are averaged only within a very narrow range of horizontal disparities (less than \(\pm 5\) arcmin). With larger horizontal disparities, observers perceived the slant of each surface using the vertical size disparities in each surface separately, not the average vertical size disparity of the two surfaces. These results can be interpreted as evidence that vertical size disparities are processed separately in distinct depth planes. However, they could also be interpreted as evidence that vertical size disparities are ineffective away from the horopter. Informally, we observed that the appearance of the stimuli did not seem to change when fixating the near or far surface, which suggests that the visual system uses vertical size disparities both within and outside the plane of fixation. Experiment 2 was designed to test whether vertical size disparities are effective away from the horopter.

### Experiment 2

In Experiment 1 the observer’s eye movements were not constrained. Therefore, we could not be sure whether observers processed vertical size disparities separately in different depth planes or whether disparities were effective in only the fixated surface.

In Experiment 2 we examined whether vertical size disparities are effective in eliciting an induced slant effect in surfaces offset in depth from the horopter. We used brief presentations to prevent observers from changing their fixation from a fixation cross to an offset surface. Both horizontal and vertical disparities must be measured reliably to produce the induced effect (Duke et al., 2006). It is known that horizontal disparities are registered between pairs of elements away from the horopter and with brief exposures (Andrews, Glennerster, & Parker, 2001) but we are not aware of any studies demonstrating that vertical size disparities are registered away from the horopter with brief exposures.

To further test the hypothesis that vertical size disparities are processed separately in surfaces at different depth planes we also examined whether the induced effect in the offset surface is influenced by the presence of a surface in the plane of fixation.

### Method

**Stimuli**

Stimuli were stereograms of surfaces similar to those in Experiment 1. As in Experiment 1, they had 0% horizontal size disparity so their horizontal disparities corresponded to frontoparallel surfaces. One surface (the “offset surface”) was offset from a central fixation cross by a horizontal disparity of −20 arcmin (crossed disparity). This was the intermediate offset value tested in Experiment 1. The offset surface had one of five different vertical size disparities: ±4%, ±2% and 0%. The fixation cross was continuously present at a distance of 1m and included vertical flanking nonius lines.

On a given trial, observers fixated the central cross and ensured the nonius lines were aligned. When ready, they pressed a key to flash the offset surface for 123 ms, i.e., less than the latency of vergence, which can be as little as 130 ms and typically around 160 ms (Rashbass & Westheimer, 1961). The offset surface could not be flashed again for two seconds as a precaution against vergence eye movements. The observer was free to flash the surface several times until they were able to confidently judge its slant. Observers used the same slant matching procedure as in Experiment 1 to match the perceived slant of the offset surface.

The offset surface was seen either with 1) the fixation cross present, or 2) the fixation cross and another surface (the “fixed surface”) present in the plane of fixation. The “fixed surface” was physically frontoparallel, i.e., its horizontal and vertical size disparities were both 0%. This surface was visible throughout the trial but not present while the observer viewed the adjustable surface. We refer to the two conditions as “fixed surface absent” and “fixed surface present” conditions respectively.

The fixed and offset surfaces were clearly distinguished by bold and fine elements respectively. Elements were circles, approximately 1.3° in diameter. We used circles rather than the selection of shapes used in Experiment 1 as it seemed easier to judge surface slant at brief exposures when elements were uniform.
Observers

There were four observers between 22 and 38 years of age. All had stereoacuity of 30 arcsec or better, measured with the Titmus Randot Stereotest. Observer PD was a participant in Experiment 1. The other three were naive as to the purpose of the experiment.

Procedure

Each observer completed two experimental sessions, each consisting of 25 trials. The offset surface was presented five times at each of the five levels of vertical size disparity, and in both “fixed surface absent” and “fixed surface present” conditions. Stimuli were randomly ordered throughout.

Predictions

Figure 5 shows the predicted theoretical slant of the offset surface. Figure 5a shows the predicted slant if vertical size disparities are ineffective in surfaces away from the horopter. In this case, the predicted slant of the offset surface is zero at all levels of vertical size disparity, both when the offset surface is seen alone or in the presence of the fixed surface.

Figures 5b and 5c show the predicted slant if vertical size disparities are effective off the horopter. Figure 5b shows predictions if vertical size disparities are processed separately in different depth planes. In this case, the slant of the offset surface is predicted from its vertical size disparities. Its vertical size disparities are processed independently from those in the fixed surface so predictions for the fixed surface present and absent are identical.

Figure 5c shows the predicted slant if vertical size disparities are pooled over surfaces at different depths. In this case, the slant of the offset surface in the “fixed surface absent” condition is predicted from its vertical size disparities (±5%). When the offset surface is seen in the presence of the fixed surface, its slant is predicted from the mean vertical size disparity of the two surfaces (±2%). Thus, the gradient of the predicted slants in the “fixed surface present” condition is half that of the “fixed surface absent” condition.

Results and discussion

Results of Experiment 2 are shown in Figure 6. The results for each of the four observers are shown in Graphs a-d, and the group mean is shown in Graph e. The results for the four observers were qualitatively similar. The graphs show that all observers perceived the vertical size disparity induced effect in the offset surface, and this was similar in both “fixed surface present” and “absent” conditions. An ANOVA revealed that the effect of vertical size disparity was statistically significant ($F(4,12) = 19.164, p < 0.0005$). The induced slant in the offset surface was not significantly affected by the presence or absence of the fixed surface, either as a main effect ($F(1,3) = 2.306$) or in interaction with the vertical size disparity of the offset surface ($F(4,12) = 0.557$).

For all observers the magnitude of the induced effect, as indicated by the slope of the data, was less than the full amount predicted from the vertical size disparities of the offset surface (diagonal dashed lines in Figures 5 and 6). As in Experiment 1, possible
reasons why we did not find the full effect include the contribution of conflicting gaze eye-position signals used in horizontal disparity scaling and perspective and focus cues, which specified zero slant. There were individual differences but, for each observer, the magnitude of the induced effects in the “fixed surface absent” and “present” conditions were similar. On average, these values were 38% and 33% respectively. A one-tailed paired-samples t-test revealed no significant effect of the presence or absence of the fixed surface on the slope of the data ($t_3 = -1.109$). This suggests that the vertical size disparities of the offset surface were processed independently of those in the fixed surface. Aside from the reduced effect overall, the data resemble predictions in Figure 6b. This shows predictions if vertical size disparities are effective off the horopter and are processed separately in different depth planes.

We can conclude from these results that 1) observers use vertical size disparities in surface slant perception when the surface is offset in depth from fixation and 2) there is no evidence that vertical size disparities are pooled across surfaces separated in depth. Consequently we can conclude that the depth-specific processing of vertical size disparities in Experiment 1 cannot be attributed to a failure to process vertical size disparities in surfaces away from the horopter; instead the results suggest that vertical size disparities are processed separately in different depth planes.

**General discussion**

In Experiment 1 we examined how vertical disparities are used to scale horizontal disparities when two surfaces are presented simultaneously in different depth planes defined by different horizontal disparities. In this way, we examined the depth-plane specificity of the processing of vertical size disparities.

We presented two superimposed textured surfaces with opposite vertical size disparities and varied the horizontal disparity between them. We found that vertical size disparities were averaged when the two surfaces were close to being at the same depth. Since the texture elements of the two surfaces were different, we conclude that the form of the texture elements did not influence how the vertical disparities were processed. When the surfaces were separated by $\pm 5$ arcmin of horizontal disparity observers perceived two surfaces with opposite induced effects. Informally, we observed that the appearance was the same whether the observer fixated on the near or on the far surface. This suggests that the visual system uses vertical size disparities both inside and outside the plane of fixation. We confirmed that vertical size disparities are used outside the plane of fixation in Experiment 2, using briefly presented induced-effect stimuli off the horopter. Thus we can conclude from our results that the visual system processes vertical size disparities in surfaces at different depths and does so separately for surfaces at different depths.

Our results indicate that while vertical size disparities are averaged over large areas in one depth plane they are processed separately in different depth planes defined by different horizontal disparities. This suggests that vertical size disparities are used to compensate for surface azimuth directly, as proposed by Gillam and Lawergren (1983), Kaneko and Howard (1996), and Backus et al. (1999). If vertical size disparities were
used in this way it would be a good strategy to process them separately at different depths. If they were averaged across different depths then, for example, the pooled vertical size disparity produced by two adjacent surfaces at different depths falling on the same retinal integration region would be incorrect for both surfaces. This situation would be very common, given that retinal integration regions are several degrees in size (Kaneko & Howard, 1997; Serrano-Pedraza et al., 2010).

Our results are contrary to theories in which vertical disparities are pooled from points at different depths. Gärding et al. (1995) proposed that vertical disparities are pooled within retinal regions to provide regional estimates of binocular eye position parameters. In their theory, vertical disparities are pooled regionally from points that can be at different depths. In their analysis, vertical disparities do not vary with scene depths but instead vary with eye position. Using all the points within a retinal region would provide the most reliable estimates for binocular eye position parameters, which could then be used to scale horizontal size disparities of surfaces at any depth. However, our results indicate that vertical size disparities are processed separately in different horizontal disparity-defined depth planes.

The present results provide evidence that vertical size disparities directly provide information about the azimuth of surfaces. However, this does not mean that they cannot be used to register eye gaze direction. Gaze direction can be obtained indirectly by combining vertical size disparities and their retinal eccentricity. Duke, Oruç, Qi, and Backus (2006) and Liu, Berends, and Schor (2005) demonstrated that adaptation to vertical size disparities recalibrates eye position signals used in stereoscopic slant perception. This suggests that vertical size disparities provide, whether directly or indirectly, information about direction of gaze.

The depth-specificity that we have found for processing vertical size disparity is also seen in processing horizontal gradients of vertical size disparity. This component of the latitudinal vertical disparity field directly signals the distance to surfaces and is thus another essential scaling parameter (Rogers & Bradshaw, 1993). Duke and Howard (2005) found the horizontal-disparity specificity of this component to be less than ±10 arcmin. Both of these results indicate that vertical disparities are used to estimate the azimuth and distance of surfaces directly, rather than indirectly through an estimation of eye position. Allison, Howard, and Fang (2000) found that vertical disparities that drive vertical vergence are integrated over ±3° of horizontal disparity. Thus vertical disparities are averaged over a larger range of horizontal disparities for the purpose of driving vertical vergence than for the purpose of scaling horizontal disparity.

The present study examined the role of vertical size disparities in stereoscopic slant perception. Vertical size disparities may also play a role in direction perception. A few studies have examined this. Banks, Backus and Banks (2002) examined whether vertical size disparities influenced the judged direction of a target, using an unseen pointer device and found no evidence that vertical size disparities are used for direction judgment. Berends, van Ee, and Erkelens (2002) measured the apparent straight-ahead point of a spot within in a display containing vertical size disparities but found only a very small effect and only after 5 minutes of adaptation to the stimulus. Ishii (2009) used a pointer device and examined direction judgments for surfaces with different combinations of horizontal and vertical size disparities. They aimed to weaken the contribution of eye position signals during the task by having observers adopt an extreme gaze posture for several seconds beforehand. They found evidence for a small contribution of vertical size disparity in the task, but only when combined with an equal horizontal size disparity. It therefore seems that vertical size disparities do not contribute to direction judgments unless other signals become unreliable. It is not known whether vertical disparities contribute to direction judgments by providing information about surface azimuth directly or indirectly through estimation of gaze eye position.

In summary, our results provide evidence that vertical size disparities are processed independently at different horizontal disparities in stereoscopic slant perception. It may be that neural connections necessary for integration of vertical size disparities across different horizontal disparities do not exist. Our results and those of Duke and Howard (2005), suggest that, in stereopsis, vertical disparities are used to directly correct for the location of surfaces relative to the head, rather than binocular eye position.

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