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**Citation**

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The absence of depth constancy in contour stereograms

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Abstract. Stereoscopic surfaces constructed from Kanizsa type illusory contours or explicit luminance contours were tested for three dimensional (3D) shape constancy. The curvature of the contours and the apparent viewing distance between the surface and the observer were manipulated. Observers judged which of two surfaces appeared more curved. Experiment 1 allowed eye movements and revealed a bias in 3D shape judgment with changes in apparent viewing distance, such that surfaces presented far from the observer appeared less curved than surfaces presented close to the observer. The lack of depth constancy was approximately the same for illusory contour surfaces and for explicit contour surfaces. Experiment 2 showed that depth constancy for explicit contour surfaces improved slightly when fixation was required and eye movements were restricted. These experiments suggest that curvature in depth is misperceived, and that illusory contour surfaces are particularly sensitive to this distortion.

1 Introduction
Stereoscopic depth from binocular disparity is ambiguous unless it is scaled by some measure of viewing distance. The result is that the same magnitude of disparity can be associated with many different depth extents, depending on the distance to fixation. This inherent ambiguity in binocular input could have profound effects on judgments of shapes that vary in depth. There are many ways that the visual system could disambiguate disparity information. The most straightforward strategy is to obtain a measure of viewing distance from one of several cues available either in the image or in the state of the system. So, for example, the vergence angle of the eyes or the state of accommodation when viewing a three-dimensional (3-D) object could, in principle, be used to scale disparity. Other strategies depend specifically on the task or the stimulus. Consider an experimental task that requires a depth match to be made between stimuli at two distances. If the visual system assumes that the two stimuli are the same size, then the ratio of distances could be estimated from the angular extent of each stimulus and used to scale disparity (Glennerster et al 1996). Likewise, a change in vergence angle could also be used to estimate a distance ratio. Both strategies would allow an observer to perform the task even when the absolute distance to each surface is not known.

Despite the strategies that could be used, there is considerable evidence that human observers fail to show perfect depth constancy, even at viewing distances less than 2 m (Foley and Richards 1972; Johnston 1991; Tittle et al 1995; Bradshaw et al 1996; Glennerster et al 1996). This failure of depth constancy can be thought of as a perceptual distortion of physical space, or, congruently, as an incorrect mapping of physical space onto perceptual space (Todd et al 1998). The distortion of perceptual space does not appear to be random; rather, errors tend to occur in a particular direction. Many investigators have found that observers judge a stereoscopic object or surface with a fixed disparity to have more depth when presented close to the viewer and less depth when presented further away. If one assumes that this perceptual distortion is due to a misestimation of viewing distance (Foley 1980; Johnston 1991), then viewing distances are overestimated when the surface is close and underestimated when the surface is far.
Recent studies of stereoscopic depth constancy used random-dot stereograms as stimuli. Luminance contours alone, however, are just as effective in specifying shape-in-depth (Harris and Gregory 1973; Gregory and Harris 1974). Even illusory contours, which contain very little binocular disparity, generate the perception of 3-D surfaces and shape. Is the depth specified by dichoptic contours (either explicit luminance contours or illusory contours) subject to the same stereoscopic distortions as found with other types of display? One study by Carman and Welch (1992) suggests that illusory contours do show 3-D shape constancy. Carman and Welch presented Kanizsa-type illusory-contour stereograms of curved, cylindrical surfaces. They varied the distance of the illusory surface from its inducers by shifting the surface portions in each half-image towards or away from one another. This manipulation adds relative disparity between the inducers and the curved surface, and is perceived as a change in the distance to the surface. Observers viewing these stereograms reported the shape of the illusory surface to be unchanged despite the manipulation of apparent distance. On the other hand, Watanabe and colleagues (Redies and Watanabe 1993; Watanabe et al 1995) found that both illusory and explicit contours failed to exhibit 3-D shape constancy. They used an Ehrenstein grid to induce illusory circular contours, then tilted the display in depth. They found that, as the degree of tilt increased, the illusory circles became increasingly deformed. Replacing the illusory contours with luminance contours decreased the distortion, but did not eliminate it.

In this paper, we examine shape-in-depth judgments while the apparent distance to a stereoscopic surface is changed. Depth is specified by disparate stereoscopic contours. Two types of contour were used throughout: explicit, luminance-defined contours and illusory contours. The curvature of the contours was manipulated, and the observers’ task was to make judgments about the depth curvature of the resulting stereoscopic surfaces. The aim was to determine whether the disparity from both illusory and explicit contours is subject to 3-D shape distortions, and to investigate the role of eye movements in depth constancy.

2 Experiment 1: Shape from stereo with explicit-contour and illusory-contour surfaces
2.1 Method
2.1.1 Stimuli. Kanizsa-type stereograms depicting curved surfaces were displayed on a 19-inch high-resolution Sigma Designs gray-scale monitor. The monitor was driven by a Macintosh Quadra 840 AV. Displays were viewed through a mirror stereoscope from a distance of 195 cm (see figure 1). At this viewing distance, a single pixel subtended 25 s of arc. The convergence angle ($2^\circ$) to the virtual image of the screen plane of the monitor is given by:

![Diagram of stereoscopic viewing apparatus](image)

**Figure 1.** Schematic top down representation of the stereoscopic viewing apparatus. Two sets of half-silvered mirrors were used to control vergence, and the septum insured that each half image was presented to only one eye. The dashed lines show the path of light from the monitor to the observer. The solid lines represent the lines of sight to the virtual image.
\[ \alpha = 2 \arctan \left( \frac{I}{2D} \right), \]  
(1)

where \( I \) is the interocular distance and \( D \) is the distance from the observer to the monitor. With 6 cm taken for \( I \) and 195 cm for \( D \), the convergence angle to the virtual screen was 1.76°. Figure 2 shows the viewing geometry.

Examples of stimuli are shown in figure 3. We generated 2 types of stereogram, differing only in whether the contours were defined explicitly by a luminance edge, or

\[ \delta_{\text{standing}} = \beta \quad \alpha \]
\[ \delta_{\text{curvature}} = \gamma \quad \beta \]

**Figure 2.** Top down view of the stereo geometry for the experimental setup. Dashed lines represent the stimulus (which would have a square profile when viewed from above). \( D \) viewing distance, \( I \) interocular separation, \( \alpha \) convergence angle to the screen, \( \beta \) convergence angle to the back of the surface, \( \gamma \) convergence angle to the front of the surface, \( \delta_{\text{standing}} \) standing disparity from the monitor to the back of the surface, \( \delta_{\text{curvature}} \) curvature disparity from the back of the surface to the front of the surface.

![Illusory contour and explicit contour stereograms like those used in experiment 1. The left pair of images is arranged for cross fusion, the right pair for parallel fusion. Both contour types depict a textureless surface curving out of the page toward the observer. (a) The illusory contour stereogram is shown with a greater curvature than the explicit contour stereogram. (b) The viewing distance manipulation. Surface portions in the top stereogram are shifted horizontally relative to the bottom stereogram.](image-url)
implicitly by Kanizsa-type inducers. In the right half-image of an explicit-contour display, a white rectangle (luminance 83.3 cd m\(^{-2}\), dimensions 2.25 deg horizontally by 1.5 deg vertically) appeared on a black background (luminance 1.53 cd m\(^{-2}\)). The stereoscopic shape of this surface was manipulated by altering both vertical contours of the left half-image, which was otherwise identical to the right half-image. Each vertical contour in the left half-image was aligned with the long axis of an ellipse, the height of which equaled the height of the rectangle. The vertical contours were then replaced with the curved contours from the right edge of the ellipse. The resulting stereoscopic percept was a smooth-surface patch curving out towards the observer in orthographic projection.

Illusory-contour displays were constructed from explicit-contour displays by centering inducing elements at the corners of the surface and changing the background color to white. The diameter of each inducing element was 0.88 deg.

The curvature of a surface was manipulated by changing the length of the short axis of the ellipse; a small length yielded a nearly flat surface and a long length generated a very curved surface. We used 5 radial lengths, ranging from 11 to 23 pixels in 3-pixel steps. The curvature disparity (\(\delta_{\text{curvature}}\)) produced by these displays was calculated by determining the change in convergence angle between the back corner of the surface (angle \(\beta\) in figure 2) and the peak of the surface (angle \(\gamma\) in figure 2). Curvature disparity, then, is equal to \(\gamma - \beta\). At the viewing distance of 195 cm, the 5 radial lengths yielded disparities of 6.8, 8.7, 10.5, 12.4, and 14.3 min of arc, respectively.

The viewing distance from the observer to the back corner of the surface was manipulated by moving the surface portions of the left and right half-images closer together, as illustrated in figure 3b. Note that this manipulation adds relative disparity between the contours of the surface and the inducers. The inducers were not shifted and therefore always appeared in the plane of the virtual screen. The surface portions of the half-images were shifted towards each other from this zero-disparity position by 2 to 26 pixels in 6-pixel steps. The manipulation yielded 5 ‘standing disparities’ from the plane of the virtual screen to the back corner of the surface. The standing disparity (\(\delta_{\text{standing}}\)) is equal to the change in convergence angle from the plane of the virtual screen (angle \(\alpha\)) to the back corner of the surface (angle \(\beta\)). Standing disparity therefore equals \(\beta - \alpha\) (see figure 2). At the viewing distance of 195 cm, the 5 standing disparities equaled 1.2, 5.0, 8.7, 12.4, and 16.1 min of arc, respectively.

Given \(\alpha\) and \(\delta_{\text{standing}}\), a viewing distance can be calculated for each standing disparity. Equation (1) was rearranged to yield:

\[
D_{\text{back}} = \frac{I}{2 \tan(\beta/2)},
\]

(2)

where \(D_{\text{back}}\) is the viewing distance to the back of the surface, \(I\) is again an interocular distance of 6 cm, and \(\beta = \alpha + \delta_{\text{standing}}\). This calculation yielded 5 viewing distances: 193, 186.5, 180.5, 174.8, and 169.4 cm. These manipulated viewing distances are shown schematically in figure 4. A similar procedure can be used to calculate the viewing distance to the peak of the surface (\(D_{\text{peak}}\)):

\[
D_{\text{peak}} = \frac{I}{2 \tan(\gamma/2)},
\]

(3)

where \(\gamma = \alpha + \delta_{\text{standing}} + \delta_{\text{curvature}}\). By subtracting equation (3) from equation (2), the depth of a surface can be calculated. The depth of the surface with 8.7 min of arc of standing disparity and 10.5 min of arc of curvature disparity, for example, is 16.5 cm.

2.1.2 Procedure. A session comprised 10 presentations of each of the 5 radii of curvature at each of the 5 apparent viewing distances for both illusory-contour surfaces and explicit-contour surfaces, yielding 500 trials. On each trial, two surfaces appeared,
Figure 4. A schematic cross section of the stimulus display. The dashed lines indicate the 5 viewing distances. The reference surface ($\delta_{\text{curvature}} = 10.5$ min of arc) appears at the top, and a test surface ($\delta_{\text{curvature}} = 6.8$ min of arc) at the bottom.

The absence of depth constancy in contour stereograms

separated vertically by 2.3 deg. The method of constant stimuli was used, so one of the surfaces was the reference. The reference surface appeared on the top portion of the screen on a random half of the trials and always contained 10.5 min of arc curvature disparity and always appeared at a viewing distance of 180.5 cm. The depth of the reference surface, as calculated above, was 16.5 cm. The other surface was the test surface, drawn randomly from the pool of 50 test stimuli (2 contour types $\times$ 5 radii of curvature $\times$ 5 apparent viewing distances). The task was to indicate with a button press which surface (top or bottom) looked more curved in depth. Because there were 2 contour types, separate sessions were run with either the illusory surface or the explicit surface as the standard. This created 4 contour-type conditions: illusory reference illusory test (II); illusory reference explicit test (IE); explicit reference illusory test (EI); and explicit reference explicit test (EE). We conducted 3 sessions for each of these conditions, yielding 30 observations per data point.

Experiments were conducted in a well-lit room. On the first trial of a session, the observer adjusted the mirrors of the stereoscope so that the frame of the monitor in each half-image was fused. No fixation point was given. Trials were untimed and vergence eye movements were allowed. This procedure provided two cues to absolute distance in addition to room layout: vergence angle and changes in vergence angle. After a response was registered, the next display immediately appeared on the screen. No feedback was given.

2.1.3 Observers. Four observers aged between 24 and 30 years served as subjects. Each had normal or corrected-to-normal vision, and each was tested for stereoaecuity to 20 s of arc. Two observers (CJ and DV) were practiced in making psychophysical judgments, while the remaining two (LC and VA) were not. All but one observer (DV) were naive as to the purpose of the experiments. All observers consented to participation and were debriefed following the conclusion of the experiments.

2.2 Results

Figure 5 shows a set of representative psychometric functions for one of the four observers (observer CJ). A separate line is plotted for each of the 5 viewing distances, and each of the 4 reference test conditions is shown in a separate panel. Each psychometric
function increases monotonically with increasing radii of curvature, indicating sensitivity to depth curvature.

The effect of changing viewing distance can be seen by comparing the black symbols (larger viewing distances) with the gray triangles (reference viewing distance) and white symbols (smaller viewing distances). The pattern in each plot shows that stimuli at the largest apparent viewing distances (black symbols) are associated with a low probability of a "more curved" response, and stimuli at the smallest viewing distances have the highest probability of producing a "more curved" response.

To summarize the effect of viewing distance on perceived shape, we estimated, by using a probit technique, the mean and standard deviation of each psychometric function for each observer and contour condition. A $\chi^2$ test was used to check the goodness-of-fit for each function. The vast majority of $\chi^2$ values were well below one, indicating excellent fits and reliable estimation of the means and standard deviations.

The mean of the fitted psychometric functions is the point of subjective equality (PSE), measured in minutes of arc of disparity. The PSE is a disparity match to the reference stimulus. Recall that disparity scales as the reciprocal of the square of viewing distance; to compensate for viewing distance, disparity must decrease as viewing distance increases. The dashed line in figure 6 shows how the disparity matches to the reference (i.e., the PSEs) should change as the apparent viewing distance changes if depth constancy is to be maintained. This prediction was calculated by finding the curvature disparity ($\delta_{curvature}$) necessary to generate the reference depth of 16.5 cm at each apparent viewing distance. The solid lines are the disparity matches made by the four observers. The depth-constancy prediction and the data have opposite trends; it is clear that observers are not matching disparities in a way that maintains depth constancy.

Another way to examine the data is to calculate the depth match of the test stimuli based on the disparity PSEs at each viewing distance. This is calculated, as shown in section 2.1.1, by finding the viewing distance to the back of the surface [equation (2)] and subtracting the viewing distance to the peak of the surface [equation (3)]. Thus, the depth match equals the distance to the back of the surface minus the distance.
The absence of depth constancy in contour stereograms

Figure 6. Disparity matches to the reference surface plotted as a function of the viewing distance for experiment 1. Data from the illusory reference—illusory test condition (II) are shown. The dashed line marks the disparity matches necessary for depth constancy. Although not obvious over this small range of viewing distance, the depth constancy prediction is not a straight line. All four observers make systematically biased disparity matches.

to the surface peak. Recall that the reference surface has a depth of 16.5 cm. If depth constancy holds, then depth matches to the reference surface at all viewing distances would equal approximately 16.5 cm. The dashed lines in Figure 7 show the depth-constancy prediction and the solid lines show the depth matches for each observer. The error bars are standard errors of the mean (SEMs). Across observers and contour-type conditions, the same pattern of distortion is found. Specifically, observers require less depth to match the reference at near apparent viewing distances. Note that this pattern indicates that depth is overestimated at near apparent viewing distances and underestimated at far apparent viewing distances. Stated another way, surfaces near the observer are stretched in depth, and surfaces far from the observer are flattened. This

Figure 7. The depth match points of subjective equality (PSEs) as a function of apparent viewing distance. Each panel shows the data from four observers in a single reference—test contour condition as in Figure 5. Error bars are standard errors of the mean. The dashed line shows the depth of the reference surface; if depth constancy holds, all depth matches would lie on this line. Arrows mark the depth matches made at the reference distance. Observers perceive surfaces stretched in depth at near distances (requiring under 16.5 cm depth to match), while surfaces at far distances (requiring more than 16.5 cm depth to match) are perceived as flattened.
distortion is in the same direction as that found by other investigators (Foley 1980; Johnston 1991; Glennerster et al 1996).

A two-way (viewing distance × reference test contour type) within-subjects ANOVA was performed on the depth-match data. The effect of viewing distance was significant ($F_{3,12} = 7.72$, $p < 0.001$), indicating that the slopes of the fitted data are different from zero. The effect of reference test contour type was also significant ($F_{3,9} = 8.29$, $p = 0.006$). To understand this effect, consider the depth match at the reference distance (180.5 cm, the midpoint of each function in figure 7). This point indicates the depth matches made to the reference curvature at the reference viewing distance. If the reference stimulus was perceived veridically, the data at this point would fall on the dashed line. For the II and EE conditions, this is approximately true. The perceived depth of the reference in the IE and EI conditions, however, is not veridical. All of the data points are shifted downwards in the IE condition, indicating that an explicit-contour test surface required less depth to match the illusory reference. In other words, explicit-contour surfaces were stretched in depth relative to illusory-contour surfaces. The pattern in the EI condition is reciprocal: the functions are shifted upwards, indicating that more depth is required to match the explicit-contour reference relative to illusory-contour test surfaces. Thus, the upward and downward shifts of the functions in the IE and EI conditions account for the main effect of reference test contour type.

The interaction between viewing distance and reference test contour type was not significant ($F_{3,12,36} = 1.35$). This outcome indicates that the magnitude of the shape distortion is the same for all contour types. The slopes of the fitted lines, which also indicate the magnitude of shape distortion, are similar to one another. The mean slopes (and SEMs) for each condition in figure 7 are 0.42 (0.10), 0.30 (0.19), 0.38 (0.06), and 0.34 (0.09), corresponding to the II, IE, EI, and EE conditions, respectively.

The above analysis assumes that each of the viewing distances is accurately perceived by observers. An alternative assumption is that the visual system uses an incorrect

![Figure 8](image-url)

Figure 8. Scaling distance plotted as a function of viewing distance for experiment 1. Each panel shows the data from four observers in a single reference test contour condition, as in figure 7. The dashed line with slope equal to one marks the ratio where the viewing distance and scaling distance are equal. The slopes of the best fitting lines to each observer's data are negative, indicating that viewing distance is overestimated when the stimulus appears close and underestimated when the stimulus appears far.
measure of viewing distance to scale disparity. Studies of depth constancy often include a calculation of the distance misestimation, called ‘scaling distance’. Given a depth match to a reference surface with known disparity, the scaling distance is the distance to the surface required in order to perceive the depth specified by the match. The important point is that a scaling distance analysis assumes that, rather than a shape distortion due to misestimation of the depth curvature of the surface, the error is in the perceived distance to the surface. In figure 8 the scaling distance is plotted as a function of the viewing distance. If depth constancy holds, the data would fall on a line with slope equal to one. This prediction is shown with a dashed line in figure 8. Regression lines have been fitted to each observer’s data; among all observers and contour conditions, the slopes of the fitted lines are negative. The mean slope (and SEM) for each contour-type condition in figure 8 is $-1.97 \ (0.68)$, $-1.12 \ (0.68)$, $-1.20 \ (0.27)$, and $-1.21 \ (0.57)$, corresponding to the II, 1E, EI, and EE conditions, respectively. Negative slopes indicate that viewing distance is overestimated when the surface appears close to the observer and underestimated when the surface appears farther away. This distance misestimation is in the same direction as found by Johnston (1991), but the magnitude of the effect is much larger. At the closest and farthest viewing distances, for example, the distance misestimation can be 50 cm or larger.

2.3 Discussion

The perceived depth curvature in contour stereograms increased monotonically as the curvature disparity increased. All observers, however, showed a shape distortion with changes in viewing distance. This distortion is in the same direction as has been reported in the literature: surfaces closer to the observer appeared more curved in depth than surfaces farther away. There was little difference in the magnitude of the effect between illusory contours and explicit contours; both contour types failed to produce depth constancy. This outcome suggests that illusory and explicit contours are treated equally by the visual system at the level where depth from disparity is recovered. If one assumes that this distortion is due to a misestimation of viewing distance, then observers overestimate viewing distance when the surface appears close and underestimate viewing distance when the surface appears more distant.

If the lack of depth constancy is due to a misestimation of viewing distance, then the outcome may not be surprising. Estimates of depth constancy for tasks that require a measure of viewing distance vary over the entire range of constancy. What is curious about the current results, however, is the magnitude of the effect. The scaling distances required to account for perceived surface depth are not only incorrect, as suggested by previous work, but incorrect to such a degree that they are inverted. It is difficult to believe that observers were making such large errors in viewing distance. Rather, we suggest that the shape distortions we find are not due to a misestimation of viewing distance.

An additional concern about the scaling-distance analysis in figure 8 is that it does not allow a measure of depth constancy to be calculated. Typically, depth constancy is expressed as the ratio of slopes between the scaling distance and the prediction of perfect depth constancy (Howard and Rogers 1995; Glennerster et al 1996). Because the slope of the prediction line equals one and the slopes of the scaling distances are typically less than one, the proportion of depth constancy is given by their ratio. The negative slopes associated with the scaling distances in the current experiment, however, prevent a meaningful estimate of depth constancy from being calculated in this way. An equivalent estimate of depth constancy ($C$), however, can be calculated from the slopes of the depth-match data in figure 7:

\[
C = \tan(45^\circ - \theta),
\]

(4)
where $\theta$ is the angle formed by a fitted data line and the horizontal prediction line. The cosine of $\theta$ would provide a ratio of the two slopes and therefore a measure of depth constancy; cosine $\theta$, however, gives an inflated value of depth constancy, relative to those reported using the scaling-distance strategy, because the cosine of angles smaller than $45^\circ$ is close to 1 and relatively constant. A more appropriate measure involves comparing the data with a prediction line with slope equal to one. Such a prediction line would form a $45^\circ$ angle with respect to the horizontal, and the tangent of this angle is one. Simply transforming the values in figure 7 with an anticlockwise rotation until the slope of the prediction line equals one does not solve the problem, since the data line would then have a slope greater than one. Rather, subtracting $\theta$ from $45^\circ$ yields a new angle which can then be compared to the tangent of the $45^\circ$ prediction line, yielding a measure of depth constancy equivalent to those used in previous work. Using this procedure, we calculated the proportion of depth constancy averaged over observers (and SEMs) to be 0.35 (0.11), 0.52 (0.13), 0.39 (0.06), and 0.45 (0.10) for the II, IE, EI, and EE conditions, respectively. These constancy values are slightly higher than Johnston’s (1991) estimate of 0.30 but lower than the 0.70 to 0.75 estimated by Glennerster et al (1996).

It has been suggested that a change in eye position is more important for scaling depth than static eye position (Foley and Richards 1972; Glennerster et al 1996). The current experiment allowed observers to change vergence and thus estimate viewing distance over multiple fixations. Further, the shape-judgment task used here required only the ratio of viewing distances to be estimated for depth scaling, rather than the absolute viewing distance. Despite the availability of vergence information, depth constancy was clearly not obtained. For comparison, however, it is necessary to know the extent of depth scaling when eye movement is restricted.

3 Experiment 2: Fixation and eye-movement control

The stimuli in experiment 1 were presented without a fixation point, and observers were freely allowed to make vergence eye movements. Does the perceived depth in contour stereograms change when vergence movements are restricted? One hypothesis is that because the strategy of estimating the ratio of viewing distances based on vergence eye position cannot be used when eye movements are not allowed, depth constancy should get worse when static eye position is maintained. Experiment 2 was conducted as a fixation and eye-movement control.

3.1 Method

The same stimuli and procedure were used as in the previous experiment, with the following exceptions. First, the stimulus set was reduced such that only 3 curvatures and only 3 apparent viewing distances were used. Curvature disparities of 6.8, 10.5, and 14.3 min of arc were used, corresponding to the least, standard, and most curved surfaces. Likewise, apparent viewing distances of 169.4, 180.4, and 193 cm were used, corresponding to surfaces that appeared closest, at the reference distance, and furthest from the observer. The second difference in procedure from the previous experiment was in the contour-type combinations presented. For this experiment, only the illusory reference illusory test (II) and the explicit reference explicit test (EE) conditions were shown. Third, the two authors served as observers. Fourth, a gray fixation cross was added to each of the displays. This cross subtended 0.5 deg horizontally and vertically, and appeared at the depth of the inducing elements. At the beginning of each trial, the fixation cross appeared at mid-height between the top and bottom display surfaces. Observers were instructed to maintain fixation on the cross. When the observer was ready, she pressed a button that initiated the drawing of the display. The display required about 600 ms to draw; after this period had elapsed, an addi-
tional period of 500 ms was allotted to view the stimuli while maintaining fixation. Note that, although observers did not voluntarily change fixation, 500 ms is sufficient for a vergence eye movement to occur. After this viewing period, the display was removed and the observer made a response.

Because LW did not participate in experiment 1, this observer completed extra conditions where no fixation point was given and unlimited eye movements were allowed. These data are referred to as the 'no-fixation comparison'. For observer DV, the appropriate data from experiment 1 were used for no-fixation comparisons.

3.2 Results and discussion

Individual psychometric functions were analyzed as before, resulting in disparity PSEs. These PSEs were then transformed into depth matches [calculated as before from equations (1) and (2)] and fitted with straight lines. The data appear in figure 9. Filled symbols refer to the conditions in which fixation was required and eye movements were restricted; open symbols refer to the no-fixation conditions on the same set of axes for easy comparison. As in figure 7, the thick dashed line marks the depth-constancy prediction. Both observers show the shape distortion found in experiment 1 for all conditions. Because there were only two observers, an ANOVA was inappropriate; rather, the conditions were compared by simply examining the slopes of the fitted data functions. If restricting eye movements decreases depth constancy, then the magnitude of the shape distortion should increase in the fixation condition. This outcome is observed for illusory-contour displays (left panel). In the no-fixation condition (right symbols), the mean slope is 0.32 with a SEM of 0.13; in the fixation condition (filled symbols), the mean slope is 0.58 with a SEM of 0.18. For explicit-contour displays (right panel), however, a trend in the opposite direction is found. In the no-fixation condition (unfilled symbols), the mean slope is 0.33 with a SEM of 0.15; in the fixation condition (filled symbols), the mean slope is 0.17 with a SEM of 0.13. This pattern of results suggests an interaction between contour type and fixation condition. Adding a fixation point and restricting eye movements increases the shape distortion for illusory contours, but tends to decrease the distortion for explicit contours. Consistent with this analysis, depth constancy (calculated as before and averaged across the two observers) was worst in the condition with illusory contours and a fixation requirement ($C = 0.27$), and best in the condition with explicit contours and a fixation requirement ($C = 0.71$). The remaining two conditions yielded intermediate depth-constancy values of 0.51 and 0.52.

![Figure 9](image-url)

**Figure 9.** The depth match points of subjective equality (PSEs) for two observers as a function of viewing distance. II illusory reference illusory test; EE explicit reference explicit test. The fixation conditions of experiment 2 are shown with filled symbols and solid lines; no fixation comparisons are shown with unfilled symbols and thinly dashed lines. Error bars are standard errors of the mean. The thick dashed line shows the depth of the reference surface; if depth constancy holds, all depth matches would lie on this line.
Restricting eye movements did not have the simple effect on depth constancy that we hypothesized. We found evidence that eye movements both improve depth constancy and make it worse, depending on the contour type. Only cautious conclusions should be drawn, given the small number of observers. If the effects found in this experiment are real, there are two possible explanations for the difference in depth constancy with contour type. One possibility is that, when eye movements are restricted, the strategy of estimating the ratio of viewing distances based on the ratio of vergence angles is no longer reliable. Rather, disparity must be scaled by a single measure of absolute viewing distance. For illusory-contour displays, restricted eye movements led to less depth constancy. This suggests that, in experiment 1, observers are indeed scaling disparity using a vergence-angle-ratio strategy. The small improvement in depth constancy found in experiment 2 when explicit contours are presented suggests that disparate luminance contours can be scaled with either the multiple-vergence or the single-vergence strategy. A second possibility (and one that could be compatible with the first) is that illusory contours are simply less robust than explicit contours. The inherent positional ambiguity in illusory-contour displays may make this kind of contour particularly subject to depth distortions.

4 General discussion
These experiments clearly show that shape-in-depth can be recovered from disparate binocular contours, but that the shape is subject to systematic distortions when the apparent viewing distance is varied. This shape distortion is in the same direction as that found by Johnston (1991) with random-dot stereograms that varied in physical viewing distance. It is consistent with the report of Watanabe et al (1995) who used Ehrenstein grid displays, and conflicts with Carman and Welch's (1992) report of view stability with 3-D illusory-contour shapes. A unique contribution of the current paper is the finding that, when eye movements are allowed, the shape distortion is the same for both illusory-contour and explicit-contour displays.

The stereograms used in these experiments contained disparity information only at the edges. Although the task was to judge the shape of the resulting surface, it could be argued that observers used only the contours when making shape judgments. It could be, for example, that observers were responding to monocular curvature information. If this were true, then a shape distortion with changes in apparent viewing distance would not be expected. Because the manipulation of apparent viewing distance leaves monocular curvature intact, the shape distortion must be due to the binocular edges. This does not preclude the possibility, however, that observers based their judgments only on binocular contours rather than on the surface. We consider this unlikely for two reasons. First, observers were instructed to attend to the surface rather than the contours, and they reported judging the shape of a salient, smoothly curved surface. Second, because previous research has shown that the local shape of the interpolated surface from contour stereograms is largely dependent on the 3-D shape of the contours (Carman and Welch 1992; Vreven and Welch 1998), global shape judgments of the kind required here would not be expected to differ between the contours and the surface.

The current experiments suggest that 3-D shape from contour stereograms fails to show depth constancy. The finding of a similar magnitude of shape distortion for both illusory and explicit contours in experiment 1 supports the idea that both contour types are coded by the same neural machinery (von der Heydt et al 1984). On the other hand, there were differences in the perceived depth of illusory-contour and explicit-contour displays in experiment 1 and, unlike illusory-contour displays, explicit-contour displays yielded greater depth constancy in experiment 2. Thus, our results are more in line with Watanabe and colleagues, who suggest that illusory contours are not capable of carrying the same ‘strength’ of disparity signals as explicit contours.
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