# The perceived depth from disparity as function of luminance contrast

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**Does human vision show the contrast invariance expected of an ideal stereoscopic system for computing depth from disparity? We used random-dot stereograms to investigate the luminance contrast effect on perceived depth from disparity. The perceived depth of disparity corrugations was measured by adjusting the length of a horizontal line to match the perceived depth of the corrugations at various luminance contrasts. At each contrast, the perceived depth increased with disparity up to a critical value, decreasing with further increases in disparity. Both the maximum perceived depth and the disparity modulation level where this maximum occurred changed as a sigmoid function of luminance contrast. These results show that perceived depth from disparity depends in a complex manner on the luminance contrast in the image, providing significant limitations on depth perception at low contrasts in a lawful manner but that are incompatible with existing models of cortical disparity processing.**

## Introduction

Binocular disparity occurs when an object in the scene projects to different locations in the left and right eye images. Because such location differences vary with the distance between the object and the observer's fixation plane, an observer can use the binocular disparity to estimate the depth of an object in a scene. Because disparity is a purely geometric cue, an ideal stereoscopic system would compute the depth from disparity independently of the luminance contrast of the disparity cue and exhibit contrast invariance. Such contrast invariance is important because objects in natural scenes have a wide range of contrasts relative to their backgrounds (Marr, 1982). Moreover, variations in luminance contrast can be produced by changes in illumination and atmospheric conditions, particularly in the case of the disparities of shadow edges.

On the other hand, luminance contrast is a well-known distance cue in the form of aerial perspective, by which contrast is reduced by the distance through that atmosphere that the light has to travel, with lower contrast implying increased distance from the viewer. Thus, disparity and luminance contrast provide different sources of the distance information for an object.

In this study, we investigated the effect of luminance contrast on perceived depth from disparity. Currently, there are no consistent results concerning the effect of luminance contrast on perceived depth. Schor and Howarth (1986) used stimuli whose luminance was defined by a difference of two Gaussian functions (DoG) and a depth-matching paradigm. They found that there was no luminance contrast effect on apparent depth when the spatial frequency of the DoG stimulus was greater than $\sim$1 cy/° but that perceived depth for a given disparity decreased with contrast below that DoG frequency. Similarly, Fry, Bridgman, and Ellerbrock (1949) used a depth-matching paradigm to measure the apparent distance of a rectangular target that was 5 m away from the observer. Their results showed that the apparent distance of the target increased with the

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reduction of contrast. Rohaly and Wilson (1999) tested the perceived depths of a sixth derivative of the Gaussian function (D6) pattern with either crossed or uncrossed disparity of 4 arc min. They found that, at low contrast, the matched disparity was less than 4 arc min for the crossed stimuli but greater than 4 arc min for uncrossed stimuli. Thus, in all cases, the stimuli tended to appear farther away at low contrast levels. Such mismatches were reduced as contrast was increased to give veridical depth matches at high contrast. They did not measure the relative perceived depth as a function of target disparity.

One measurement that may be related to the disparity contrast is stereoacuity, which is the measure the ability of an observer to detect the disparity difference between two objects. Here, consistent contrast effects specific to the stimulus conditions are known. Ogle and Weil (1958) measured the stereoacuity of a test line at different luminance levels against a uniform background. They found that the stereoscopic threshold remained the same regardless of the luminance contrast except for a slight increase when the contrast was reduced to near threshold. Lit, Finn, and Vicars (1972) used a two-rod Howard-Dolman device, in which an observer viewed two rods in front of a uniform background through an aperture, to test the stereoacuity with different target-background luminance combinations, and they also reported that contrast had little effect on stereoacuity. On the other hand, using vertical sine-wave gratings as stimuli, Legge and Gu (1989) found that the stereoacuity was inversely proportional to the square root of stimulus contrast. Halpern and Blake (1988) and Heckmann and Schor (1989), using the 10th derivative of Gaussian luminance distribution (D10) stimuli and sinusoidal grating targets, respectively, also reported that stereoacuity varied with a power function of contrast. For random-dot stereogram stimuli, Cormack, Stevenson, and Schor (1991) found that the stereocuity was proportional to the square root of contrast when the stimulus contrast was above ~5× the contrast threshold, whereas stereoacuity became proportional to the cube root of contrast when the contrast was below ~5× contrast threshold.

It should be noted that the earlier studies that reported no luminance contrast effect on stereoacuity defined contrast from the luminance difference between the test pattern and the background (Ogle & Weil, 1958), whereas the later studies (Halpern & Blake, 1988; Heckmann & Schor, 1989; Legge & Gu, 1989; Cormack et al., 1991) defined contrast as the luminance difference between regions within the periodic test patterns. Thus, one may conclude that stereoacuity depends on the luminance contrast within the test pattern but not on the luminance contrast between the test pattern and the background.

However, even taking account of this distinction, it is still difficult to infer the effect of luminance contrast effect on perceived depth in a scene based on these prior studies. First, stereoacuity measurement is based on the performance near threshold and provides no direct information about the suprathreshold percept. Second, as shown in signal detection theory (Green & Swets, 1966; Chen & Tyler, 2001), the threshold measurement constituting stereoacuity depends not only on the intensity of the stimulus but also on the internal noise. Thus, stereoacuity is also limited by the level of noise in the stereo system, not just the relationship between disparity and the depth percept. Conversely, the studies that measured perceived depth as a function of contrast for barlike stimuli did not assess the overall perceived depth of the disparity structure of stereoscopic scenes.

Here, we report the first study of the luminance contrast effect on perceived depth using the random-dot stereograting paradigm originally developed by Tyler (1974). We used stereograting patterns modulated in depth, either as a unipolar depth change or as corrugated surface, and measured the perceived depth difference between the furthest and nearest points on the test pattern. We determined the perceived depth magnitude as a function of both the disparity modulation amplitude and the luminance contrast of the dots.

# Method

## Observers

Three observers (all in their 20s) participated in this study, including one of the authors and two observers who were naïve to the purpose of this study until debriefed by an author upon completion of the experiment. All of the observers had a normal or corrected-to-normal visual acuity (20/20). The use of human participants was approved by the Research Ethic Committee of National Taiwan University and adhered to the principles set by the Helsinki Declaration.

## Apparatus

The stimuli were presented on a 17-inch cathode ray tube monitor, which was controlled by an ATI Radeon HD 5770 video card on a 2.8-GHz Mac Pro computer. The monitor had a spatial resolution of 1024 (H) × 768 (V) and a refresh rate of 60 Hz. The monitor was calibrated to achieve a linear gray scale with a mean luminance of 30 cd/m$^2$. At a viewing distance of 100

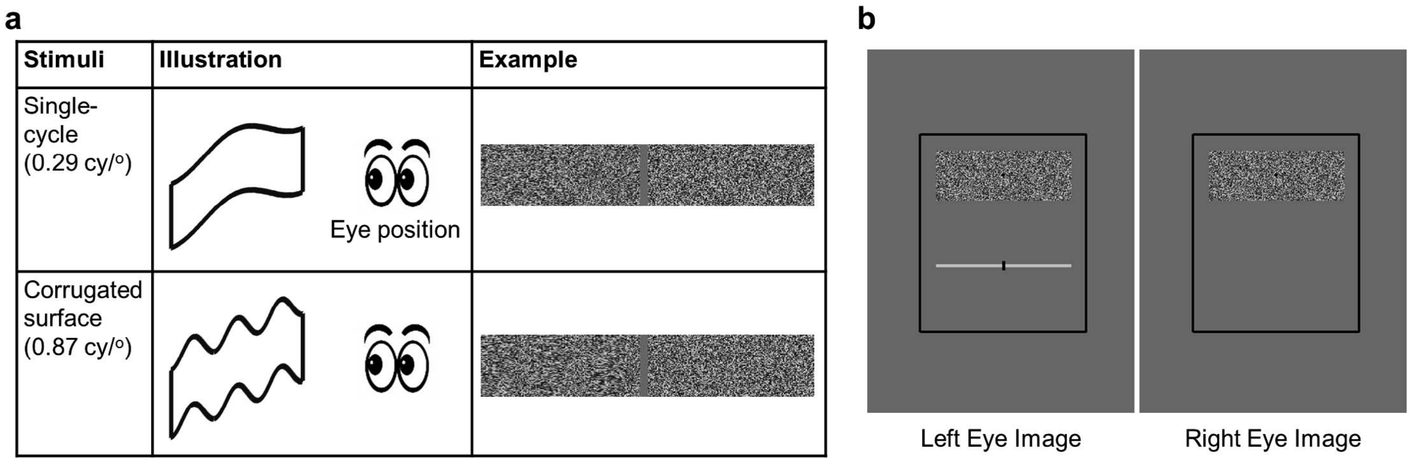


Figure 1. Methods. (a) Specification of the stimuli. (b) Display configuration. The left- and right-eye images were presented simultaneously on the screen and viewed through the stereoscope. A horizontal black line was shown below either the left- or the right-eye stimulus for observers to use for matching to their perceived depth difference within the stereo stimulus.

cm, one pixel on the screen extended 0.019° × 0.019° (about 1.1 arc min per pixel).

The experimental control and the stimuli generation were written in MATLAB R2010a (MathWorks, Natick, MA) with the PsychToolbox-3 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007). Observers viewed the stimuli through a four-mirror Wheatstone stereoscope in a dark room. Two images, one for the left eye and one for the right eye, were presented simultaneously on the monitor side by side. The mirrors of the stereoscope reflected the left image to the left eye and the right image to the right eye, allowing the observers to fuse the left- and right-eye images effectively into one stereoscopic image. The observer's head was stabilized by a chin rest.

## Stimuli

The test patterns were random-dot stereograms extending 1.27° (V) by 3.44° (H) with a dot size of 0.019° by 0.019°. The dot luminance at position (x, y), L(x, y) was determined by $L_0 * (1 + C * U(x, y))$, where U(x, y) was a random number drawn from a uniform distribution ranging from −1 to 1, $L_0$ was the background luminance, and C was the Weber contrast parameter. The luminance contrast of the test patterns varied from 5% to 80% (or −26 dB to −1.9 dB) in factors of 2, making five contrast levels with equal log spacing.

The disparity between the left- and the right-eye patterns was modulated horizontally according to a 0.29 or 0.87 cy/° cosine wave to create the percept of either a single cosine cycle or a three-cycle corrugated surface (see Figure 1a). The disparity of each point with horizontal position $x$ ranged from −1.72° to 1.72°, in the rectangular stimulus, $d_x$, was

$$d_x = D \cdot \cos(2\pi \cdot x \cdot sf) \quad (1)$$

where $D$ is the maximum test disparity and $sf$ is the spatial frequency of the stimulus. $D$ was set to values from 0 to ±20 arc min for the pairs of near and far directions. For the near direction, the test patterns contained a crossed disparity in the middle of the test pattern, whereas for the far direction, the test patterns contained an uncrossed disparity in the middle. We used positive signs to indicate test disparities in the near direction and negative signs for test disparities in the far direction.

## Procedure

There were 75 conditions (15 test disparities × 5 contrast levels) in this study. Each condition was repeated 4 to 12 times until stable results were achieved. All the conditions were randomly presented to the observers. In each trial, the left- and the right-eye patterns were presented on a uniform gray background. A zero-disparity fixation point was presented in the center of both images, and a 4.20°(H) × 4.96°(V) black rectangular frame (0.057° wide) was presented around the stimulus to help the observer to fuse the images and stabilize the horopter. The observers were allowed to move their eyes freely during the experiment.

A white horizontal bar with an adjustable black center region was placed below the fixation in either the left- or right-eye image. The task for the observers was to adjust the length of black region in this horizontal bar to match the perceived peak-to-trough depth difference in the test patterns (see Figure 1b). The observers adjusted the horizontal line rightward when

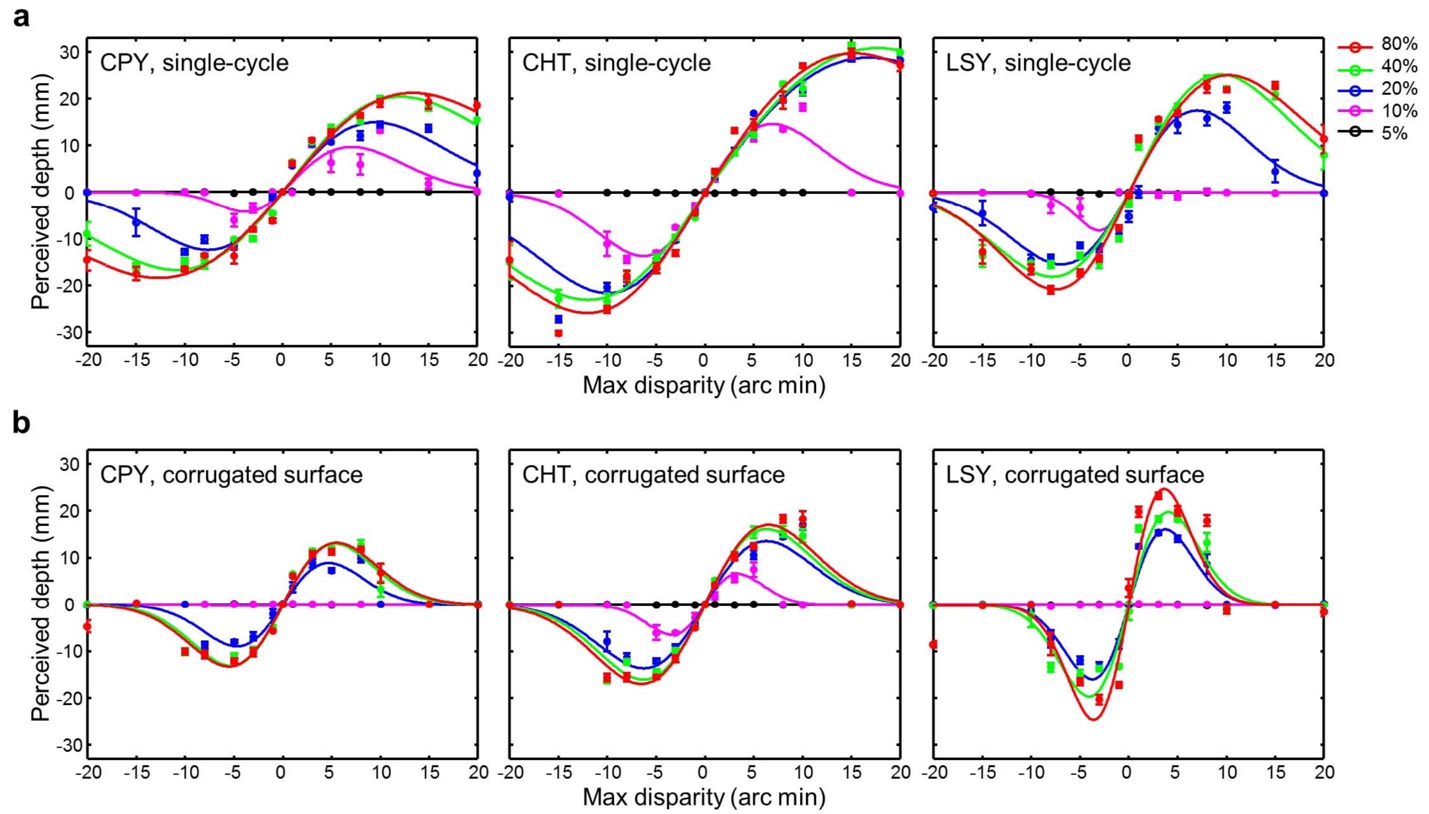


Figure 2. Effect of luminance contrast on perceived depth from binocular disparity in (a) the single-cycle condition and (b) the corrugated surface condition. Matched perceived depth is plotted as a function of the max disparity manipulation for the three observers. Error bars represent one standard error of the means. A positive ordinate value indicates a crossed disparity at the center of the stimulus, whereas a negative value indicates an uncrossed disparity at the center of the stimulus. The data were fit with the first derivative of a Gaussian function separately for the two sides. The colored solid curves represent the fits for each luminance contrast level indicated in the color key.

the stimulus contained a crossed disparity in the midline and leftward when it contained an uncrossed disparity. The test pattern was presented on the screen until the observers were satisfied with their adjustment. Each data point was the average of at least four measurements. The average time for the observers to make a satisfactory match was 11.24 s.

## Results

Figure 2a shows the matched perceived depth for the single-cycle stimuli (0.29 cy/°) for each observer. A positive value of test disparity indicates a crossed disparity at the midline of the stimulus, whereas a negative one indicates an uncrossed disparity at the midline of the stimulus. At 5% contrast (or −26 dB), the observers were not able to perceive any depth in the stimulus even though the stimulus was visible for two of them (see the Appendix). Beyond that contrast, at each contrast level, the perceived depth first increased with the magnitude of disparity up to a critical value and then decreased gradually with further increase in the magnitude of disparity. These disparity effects were similar for both far and near disparities. However, at any given test disparity, perceived depth decreased as luminance contrast was reduced. The pattern of results was similar across the three observers. These findings suggest that not only the disparity but also the luminance contrast of the stimuli affect our perception of depth.

Figure 2b shows the matched perceived depth for the corrugated stimuli (0.87 cy/°) for each observer. Qualitatively, the data here are similar to the results for the single-cycle stimuli. At each contrast level, the matched perceived depth first increased with disparity and then decreased with further increases in disparity. However, the decrease in perceived depth began when the disparity exceeded about 5 arc min, which was smaller than the 10 arc min value for the single-cycle stimuli. This result was consistent with the phenomenological reports of the observers, who reported that it was more difficult to see depth in the binocular images of corrugated stimuli than in the single-cycle stimuli when disparity was large.

To provide a quantitative analysis of the results, we fit the matched depth difference ($L_c$) at each luminance contrast level, c, with the first derivative of a Gaussian function for the two sides of the data separately,

$$L_c = \alpha_c \cdot D \cdot e^{-\frac{D^2}{2 \cdot \sigma_c^2}} \quad (2)$$

where $D$ is the parameter from Equation 1 controlling disparity between the left- and right-eye images, $\alpha_c$ is the scaling factor of the function for contrast level $c$, and $\sigma_c$ is the variance parameter of the Gaussian for contrast level $c$. The least square fits are shown as the smooth curves in Figure 2 and colored the same as the corresponding data points. Notice that none of the observers perceived any depth at the 5%, or –26 dB, luminance contrast level, nor at 10% in several cases. Thus, we simply set the fitted $\alpha_c$ to zero for these conditions. This first derivative Gaussian function accounts for 90.4% to 97.5% of variance in the data for the three observers.

To test whether the crossed and uncrossed disparities have similar values, we fit a version of the model in which both $\alpha_c$ and $\sigma_c$ were the same for the crossed and uncrossed disparities. This reduction in fitting parameters significantly reduced the fit of the single-cycle surface conditions, $F(24, 177) = 6.99$, $p < 0.001$, but did not explain significantly less variance for the corrugated surface conditions, $F(24, 177) = 0.73$, $p = 0.81$. Thus, the contrast effect was similar between the near and far disparities in corrugated surface stimuli, whereas it was significantly biased toward greater perceived depth for far disparities in the single-cycle stimuli.

To test whether the perceived depth was veridical, we also set $\alpha_c$ at 1 for all contrast levels, still allowing $\sigma_c$ to be a free parameter. That is, the maximum perceived disparity to a pattern is set to be proportional to the physical disparity but not dependent on the luminance contrast. Such a reduced model provides a much worse account to the data, $F(24, 402) = 80.33$, $p < 0.001$. Thus, the luminance contrast has a highly significant effect on perceived depth. Similarly, if we fix $\sigma_c$ to be the same for all contrast level with $\alpha_c$ as a free parameter, this reduced model also has a worse fit to the data, $F(18, 402) = 6.68$, $p < 0.001$. Because the peak position and bandwidth of the derivative of Gaussian function depends on $\sigma_c$, this comparison shows that the peak position of the perceived depth is significantly dependent on luminance contrast.

From the fit parameters, we extracted the amplitude, or the max perceived depth (*Amp*), and the peak position (*PP*) of the fit curves. Based on the derivative of Equation 2, the peaks occurred when the disparity D $= \sigma_c$. Substituting D with $\sigma_c$ in Equation 2, the peak amplitudes are given by

$$Amp = \alpha_c \cdot \sigma_c \cdot e^{-\frac{1}{2}} = 0.6065 \cdot \alpha_c \cdot \sigma_c \quad (3)$$

Figure 3a plots the peak amplitudes (*Amp*) as a function of luminance contrast for the three observers. For both single-cycle (blue circles and curves) and corrugated stimuli (red circles and curves), the amplitude increases as a sigmoid function of luminance contrast. We formalized this function according to

$$Amp = A_{max} \cdot \frac{c^p}{c^p + z_1^p} \quad (4)$$

where $A_{max}$ is the maximum perceived depth experienced by the observer, $p$ is an exponent parameter, and $z_1$ is an additive constant. The exponent $p$ was much greater than unity (a linear increase in maximum perceived depth with contrast), ranging from 2.76 to 4.84 for the single-cycle stimuli with near disparities, from 2.43 to 5.77 for the single-cycle stimuli with far disparities, and from 3.19 to 8.13 for the corrugated stimuli. The asymptotic amplitude for the single-cycle stimuli was greater than that for the corrugated condition in two observers but not for the third one. The half-height point, represented by $z_1$, for the single-cycle condition was significantly smaller (shift = 3.1%, or –30 dB, two-tail pair-comparison, $t[2] = -4.76$, $p = 0.02$) than that for the corrugated condition. This suggests that the mechanism underlying the depth perception for the single-cycle stimuli is more susceptible to luminance contrast.

Figure 3b plots the peak positions for perceived depth as a function of luminance contrast. Similarly for both single-cycle (blue circles and curves) and corrugated stimuli (red circles and curves), peak position increased with contrast level as a sigmoid function of the same form as Equation 4,

$$PP = P_{max} \cdot \frac{c^q}{c^q + z_2^q} \quad (4)$$

where $PP$ is the peak position, $P_{max}$ is the disparity where the maximum perceived depth occurs, $q$ is an exponent, and $z_2$ is an additive constant**.** The exponent $q$ ranged from 2.13 to 4.25 for the single-cycle stimuli with near disparities, from 2.69 to 26.80 for the single-cycle stimuli with far disparities, and from 4.99 to 9.92 for the corrugated stimuli. At every contrast level, the peak position for the single-cycle was greater than that for the corrugated surface. The scaling parameter $P_{max}$ also showed a significant difference between two spatial frequency conditions (two-tail pair-comparison, $t[2] = 7.45$, $p = 0.01$). That is, the corrugated surface does not support as much depth perception as a single-cycle of the same amplitude. The half-height point, represented by $z_2$, however, showed no significant difference (two-

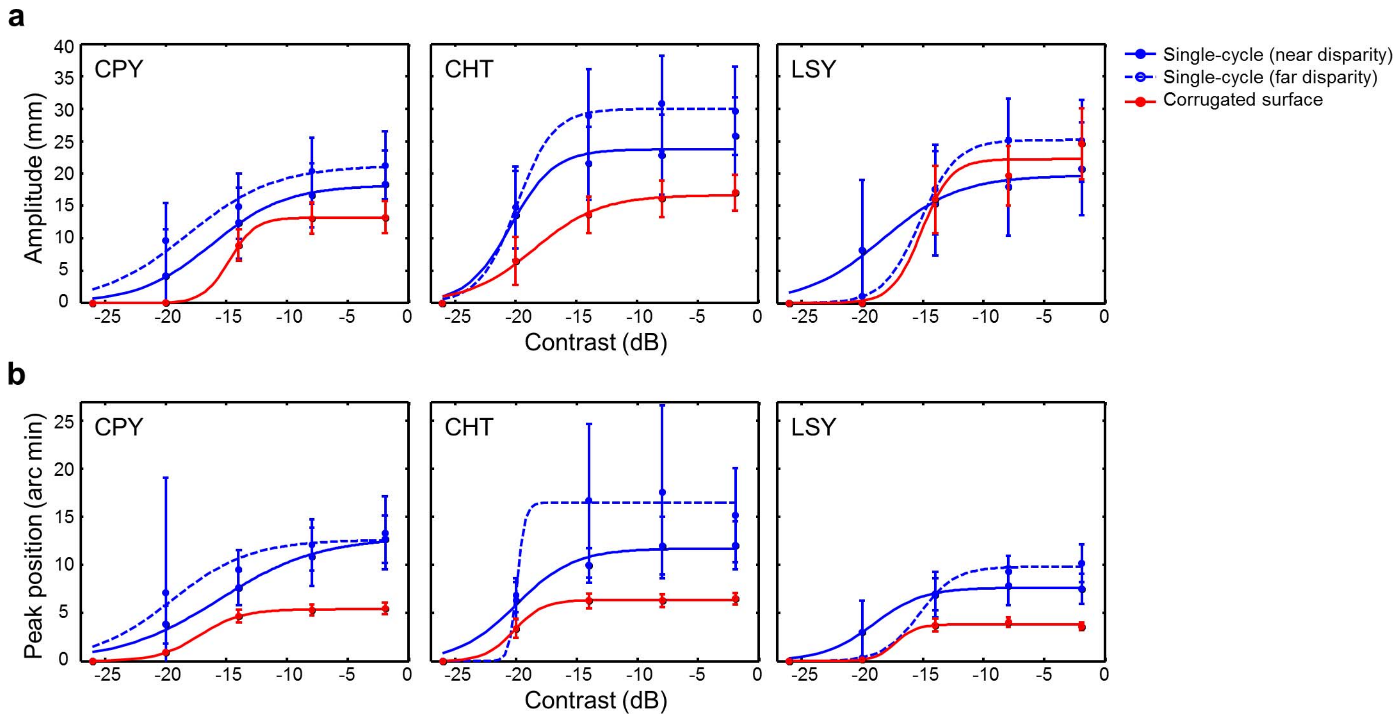


Figure 3. (a) Amplitude (*Amp*) and (b) peak position (*PP*) as a modified normalization function of the luminance contrast. Each panel represents one observer. The blue curves are for the single-cycle stimuli, and the red curves are for the corrugated surface stimuli. Error bars represent 95% confidence interval estimated by the chi-square method (Bevington & Robinson, 2003).

tail pair-comparison $t[2] = 0.86$, $p = 0.24$) between the single-cycle and the corrugated conditions.

To further test whether the depth impression at small disparities was veridical, we also extracted the slope of the fit curves at zero disparity ($S_0$), based on the derivative of Equation 2 at the disparity $D = 0$ where the slope $S_0 = \alpha_c$. If the depth impression were veridical, the perceived depth in millimeter, by the geometry of binocular disparity (Cormack & Fox, 1985), should be 2.35 times the disparity in arc min given our experimental setup. Hence, the slope at zero disparity should be 2.35 in all conditions and for all the observers. As shown in Figure 4, the slope at different luminance contrast levels (data points) approximates an initial linear increase with disparity under many conditions but tends to have a steeper than veridical slope at high contrasts (especially for the single-cycle stimulus) and falls to zero slope at very low contrasts.

## Discussion

We investigated the effect of luminance contrast on perceived depth over a wide range of binocular disparities. The results showed that perceived peak-to-trough depth depends on both luminance contrast and disparity modulation in the image. At each contrast level, the perceived depth first increased up to a peak

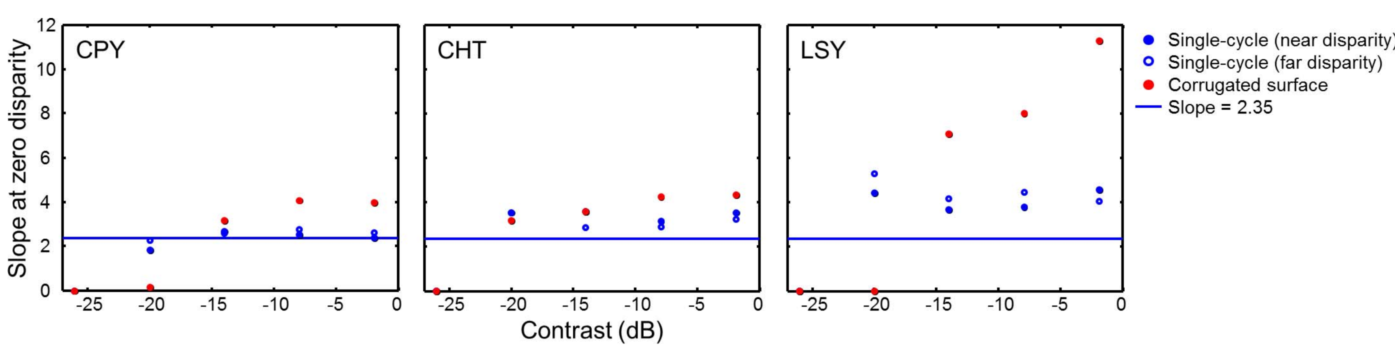


Figure 4. The slope of the fitted function at zero disparity ($S_0$) for all observers. The blue dots are for single-cycle stimuli, and the red dots are for corrugated surface stimuli.

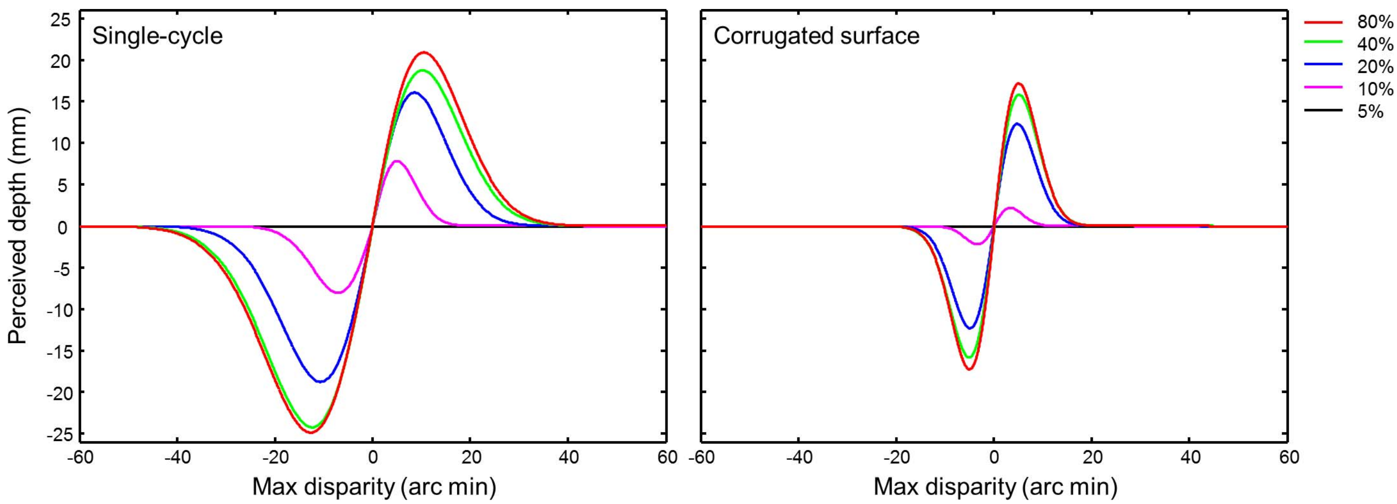


Figure 5. Perceived depth as a function of disparity and contrast, averaged across the three observers. Left panel: single-cycle stimuli; right panel: corrugated stimuli.

value and then decreased gradually with further increase in the magnitude of disparity modulation (Figure 2). The disparity effect was similar for far and near disparities in corrugated surface conditions but was biased toward greater perceived depth for far disparities in single-cycle conditions. Such matching functions are consistent with both the psychophysical and functional imaging response functions of Backus, Fleet, Parker, and Heeger (2001) for rectangular cyclopean targets and bear a resemblance to the cyclopean disparity tuning function of complex cells in the striate cortex (Poggio, Motter, Squatrito, & Trotter, 1985).

There was a considerable interaction between luminance contrast and disparity: Both the maximum perceived depth and the disparity modulation level where this maximum occurred changed as a sigmoid function of luminance (Figure 3). Such a compressive sigmoid function implies that a contrast gain control mechanism is involved in this contrast effect. There was also a spatial frequency effect. The dynamic range of the maximum perceived depth for the single cycle (0.29 cy/°) occurs at lower luminance contrasts than that for the corrugated surface (0.87 cy/°). The peak depth for the single cycle occurs at greater disparity modulation than that for the corrugated surface. This result is consistent with the original finding of Tyler (1974) that the peak sensitivity for disparity corrugations is at about 0.4 cy/° and would have fallen by about a factor of about 2 by 0.9 cy/°. To specify a typical function for perceived depth over disparity and contrast, we averaged the fits in the empirical data across the three observers and extended the fits across the maximum disparity for any visible depth (±1°). The disparity and contrast dependence of the perceived depth is shown in Figure 5.

There was, however, a significant interaction between luminance contrast and disparity, such that both the maximum perceived depth difference and the disparity modulation level where this maximum occurred changed as a sigmoid function of luminance (Figure 3). Such sigmoid behavior implies that a contrast gain control mechanism is involved in this contrast effect, providing strong contrast dependence below about 10% contrast (–20 dB) and approximate contrast constancy of perceived depth above it. Moreover, the contrast gain control parameters exhibit a strong dependence on the disparity modulation spatial frequency (Figure 3), implying the presence of long-range spatial integration across local disparity processing elements. This pattern of behavior implies that the results cannot be explained by a disparity energy model, which would predict no luminance contrast effect on perceived depth difference (Ohzawa, DeAngelis, & Freeman, 1990; Fleet, Wagner & Heeger, 1996; Qian, 1997; Qian & Zhu, 1997; Ohzawa, 1998; Read, Parker, & Cumming, 2002).

There is evidence that a low-contrast stimulus appears to be farther away as a whole than a high-contrast one with the same disparity (Fry et al., 1949; Rohaly & Wilson, 1999). This effect is consistent with the covariation between distance and atmospheric scattering (Da Vinci, 1802; Fry et al., 1949), which makes distant objects hazy and thus low contrast. This holistic distance effect cannot explain our results, however. What we measured was the perceived difference between the nearest and furthest points of a stimulus. At low contrast, both points would appear further from the observer, and thus such haze effect would not predict our differential depth reduction results. Hence, our luminance contrast effect should come from a different source.

## Conclusion

Our results show that the perception of depth differences from binocular disparity depends on both the relative disparity and the luminance contrast in random-dot stereogram images. At each contrast level, the perceived depth first increases with the magnitude of disparity modulation up to a critical value and then decreases gradually with further increases in the magnitude of disparity modulation. The disparity effect was similar for both far and near disparities but progressively weakened as contrast was reduced.

*Keywords: stereopsis, depth matching, gain control, disparity modulation*

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# Appendix

We tested the stereo contrast threshold for each observer to make sure that they could perceive the stimuli at each contrast level. The stimuli were rectangular random-dot stereograms with zero disparity variation. We used a temporal two-alternative forced-choice (2AFC) paradigm with the Psi adaptive threshold-seeking algorithm (Kontsevich & Tyler, 1999) to estimate the contrast threshold at the 75% accuracy response level for each observer. A target stereogram was randomly presented in either of the two intervals, whereas a mean luminance blank was presented in the other. The task for the observers is to indicate which interval contained the target. The results are shown in Table A1. For the three observers, the stereo contrast thresholds were about 3.06% to 6.27%, which suggested that the 5% contrast level was the near-threshold condition for the observers to detect the stereo stimuli.

| | Stereo contrast threshold | |
|---|---|---|
| Observer | Mean | Standard error |
| CPY | 6.27% | 0.39% |
| CHT | 3.06% | 0.26% |
| LSY | 4.55% | 0.17% |

Table A1. Stereo contrast thresholds for the three observers.