

# Perceptual enhancement of suprathreshold luminance modulation in stereoscopic patterns

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**Previous studies have shown that the binocular summation of luminance contrast signals depends on the parameters involved in stereopsis when the luminance contrast is at the detection threshold. However, less attention has been paid to the perception of luminance modulation in stereoscopic patterns at suprathreshold contrast. To address this issue, we determined the contrast of stereoscopic patterns at the perceptual match to a standard contrast as a function of binocular disparity. The matched contrast was close to the standard contrast at 0 degrees disparity, but decreased as disparity deviated from 0 degrees, suggesting that sufficient disparity perceptually enhances luminance contrast. The reduction of matched contrast was more evident for uncrossed disparities than for crossed disparities, which almost disappeared when the contrast was near the threshold and also occurred when vertical disparity was introduced. We argue that the perceptual enhancement of the luminance contrast is due to the weaker interocular suppression for stimuli with large disparities.**

## Introduction

Binocular viewing is superior to monocular viewing based on a variety of visual performance measures, including luminance increment thresholds, contrast sensitivity, flicker fusion thresholds, visual acuity, and reaction times (see for reviews: [Blake & Fox, 1973](#); [Blake, Sloane, & Fox, 1981](#)). This advantage is called binocular summation. Previous studies have shown that binocular summation depends on various parameters involved in stereopsis. Whereas binocular contrast sensitivity is approximately 1.5 times higher than monocular sensitivity for observers with normal stereopsis ([Campbell & Green, 1965](#); [Legge, 1984](#); [Meese, Georgeson, & Baker, 2006](#)),

stereoblind observers have similar contrast sensitivity between binocular and monocular viewing conditions ([Lema & Blake, 1977](#)). [Thorn and Boynton \(1974\)](#) and [Westendorf and Fox \(1977\)](#) found that binocular summation in detection thresholds for luminance contrast fell to the level of probability summation, that is, the ratio between the binocular and monocular sensitivities was approximately 1.2 when stimuli had too large of a binocular disparity to yield single vision. Moreover, [Rose, Blake, and Halpern \(1988\)](#) reported that the binocular summation exceeded the probability summation even in disparity ranges over which stereoscopic depth perception occurred without a fused single percept, suggesting that a mechanism for stereopsis underlies the binocular summation for luminance contrast as well. Whereas these studies typically focus on near-threshold perception, less attention has been paid to the relationship between stereopsis and binocular summation above the contrast threshold.

A number of studies have conducted suprathreshold matching experiments to examine how signals contained in two monocular images are combined to form a single percept. In terms of brightness matching, [Levelt \(1965\)](#) demonstrated that the binocular effective luminance basically equaled the average luminance of two monocular stimuli, but that the luminance in one eye, especially in the dominant eye, almost determined the effective luminance without binocular averaging (winner take all) when the luminance in the other eye was much smaller. However, the binocular effective luminance always followed the winner take all rule when dark disks were presented on a light background and when light or dark disks were presented on a gray background ([Anstis & Ho, 1998](#); [Ding & Levi, 2017](#)). [Legge and Rubin \(1981\)](#) reported trends similar to those observed by [Levelt \(1965\)](#) in the appearance of the suprathreshold luminance contrast, although the

Citation: Maehara, G., & Murakami, I. (2020). Perceptual enhancement of suprathreshold luminance modulation in stereoscopic patterns. *Journal of Vision*, 20(12):8, 1–11, <https://doi.org/10.1167/jov.20.12.8>.

<https://doi.org/10.1167/jov.20.12.8>

Received June 10, 2020; published November 19, 2020

ISSN 1534-7362 Copyright 2020 The Authors



latter studies suggested that the winner take all rule is a closer description of contrast matching for dichoptic stimuli (Baker, Wallis, Georgeson, & Meese, 2012; Ding, Klein, & Levi, 2013). Huang, Zhou, Zhou, and Lu (2010) manipulated the vertical phase shift between two horizontal gratings presented dichoptically, and found that the matched contrast, namely the luminance contrast of a reference stimulus that was judged to have the same contrast as that of the stimulus in question, was invariant irrespective of the interocular phase shift. Baker et al. (2012) extended the above study by Huang et al. (2010) within a wider range of contrasts and phase shifts. High contrast stimuli (16%–32% Michelson contrast) appeared to have slightly higher contrasts at middle phase shifts (around 90 degrees), whereas the stimulus appeared more veridical at in-phase (around 0 degrees) and antiphase (around 180 degrees) shifts. In addition, low-contrast stimuli (2%–4% Michelson contrast) appeared to have monotonically reduced contrasts as the interocular phase shift increased. Based on these results, Baker et al. (2012) proposed a model of phase-dependent interocular suppression followed by a summation of excitatory signals over the eyes, phases, and space. These suprathreshold matching experiments deliberately tested the situation where stimuli had no horizontal disparity, because their research focused on how the visual system combines information from corresponding retinal points in the two eyes.

Harwerth, Smith, and Levi (1980) reported that simple reaction times for suprathreshold grating patterns were shorter under binocular viewing than under monocular viewing at low luminance contrasts (around 1%–10% Michelson contrast). Additionally, this binocular advantage disappeared when dichoptic stimuli were presented to noncorresponding retinal points. This suggests that stimulation at corresponding retinal points is essential for suprathreshold binocular summation to improve reaction time. It should be noted, however, that stimulus positions were vertically displaced to exclude the effects of stereopsis. Thus, it remains unclear how the appearance of the luminance contrast interacts with the horizontal displacement. Legge and Rubin (1981) mentioned that binocular contrast matches seemed unlikely to change with disparity (see their note 3). This could be valid in their experiment wherein full-field grating patterns were presented as stimuli; however, whether this is also the case for more localized stimulations remains to be tested. Therefore, in the present study, we examined luminance contrast perception in a situation wherein stimuli elicit stereoscopic perceptions while they are locally presented at noncorresponding retinal points displaced horizontally.

The purpose of this study was to investigate how the state of stereopsis derived from horizontal disparities in suprathreshold binocular stimuli influences the perceptual impression of luminance modulation seen in the cyclopean percept, hereafter termed “perceived

contrast” for the sake of simplicity. To address this issue, we varied binocular horizontal disparities to determine the luminance contrast of stereoscopic stimuli at the perceptual match to a certain fixed contrast, hereafter called “standard contrast” owned by a reference stimulus. If binocular summations of contrast and stereopsis share the same mechanism, or more specifically, monocular contrast responses to stereoscopic patterns are summed in a local stereopsis mechanism, the matched contrast would be constant regardless of disparity as long as stereoscopic perception occurs. If, instead, binocular summation of contrast occurs independent of the stereopsis processing and requires stimulation at corresponding retinal points in the two eyes, the perceived contrast would become lower, and the matched contrast would therefore become higher as the disparity increases. Furthermore, it is also possible that the matched contrast lowers even more with increasing disparity. Stereoscopically disparate stimuli are projected onto noncorresponding retinal points in the two eyes. As such, if interocular suppression involves a retinotopically local process, stereoscopically disparate stimuli would elicit somewhat weaker suppression than stimuli projected to corresponding retinal points. This could result in an increase in perceived contrast and, therefore, a decrease in matched contrast.

## Methods

### Observers

Ten observers, including one of the authors (G.M.), participated in the main experiment using the staircase method. Nine of the 10 observers also participated in the follow-up experiment using the method of constant stimuli. Another group of 10 observers, including 5 observers from the first group, participated in additional experiments (vertical-disparity and monocular-stimulation experiments described near the end of the Results section). All observers had normal or corrected-to-normal visual acuity with normal stereopsis and provided full informed consent. The present study followed protocols that were approved by the institutional ethics committee and were in accordance with the Declaration of Helsinki.

### Apparatus

Stimuli were generated using a ViSaGe MKII Stimulus Generator (Cambridge Research System Ltd., Kent, UK) with 14-bit gray-level resolution and were presented on a CRT video monitor (Mitsubishi Electric RDF223H). The display resolution was 800 × 600 pixels with a refresh rate of 100 Hz. The observers viewed the screen through a mirror stereoscope (Chuo

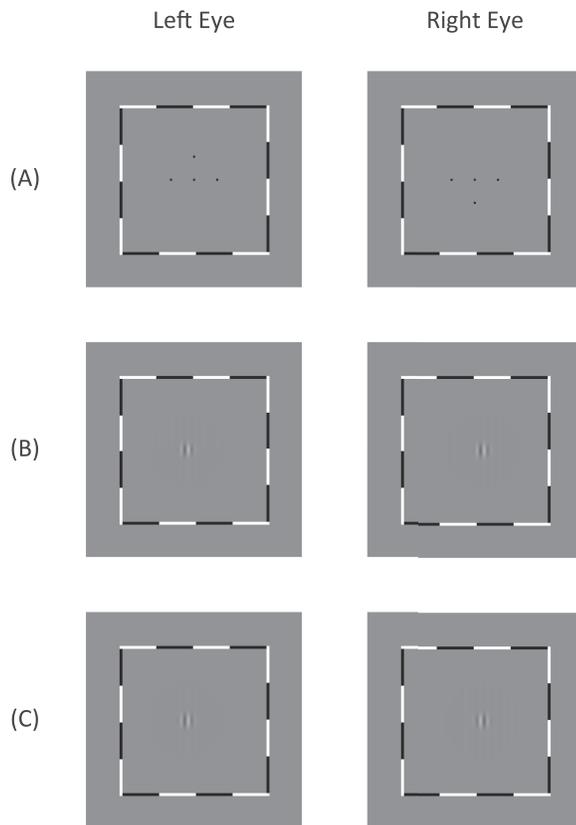


Figure 1. Stimulus examples. **(A)** Fixation dot and Nonius dots. **(B)** In-phase stimulus at 1 degree disparity. **(C)** Antiphase stimulus at 1 degree disparity. The phase of sinusoidal modulation was shifted by 180 degrees for the right eye.

Precision Industrial, Tokyo, Japan). The presentation areas on the monitor subtended a visual angle of 13 degrees height and 13 degrees width for each eye. The viewing distance was 57 cm.

## Stimuli

Figure 1 illustrates the stimuli used in the present experiment. A black fixation dot was presented at the center of the presentation area for each eye (Figure 1A). Two dots flanked the fixation dot at 1.5 degrees to the left and right. Nonius dots in the left and right eyes were placed 1.5 degrees above and below the fixation dot, respectively, for precise binocular alignment. In addition, a square frame subtending 9.9 degrees was presented to each eye to aid binocular fusion throughout testing.

We used Gaussian-windowed sinusoidal luminance gratings (Gabor patterns) as standard and comparison stimuli. Figure 2 shows the luminance profiles of the stimuli. The gratings had a spatial frequency of 2 c/deg and were oriented at 0 degrees (i.e. vertical stripes). In the in-phase condition, the phases were 0 degrees at the center of the Gaussian window (i.e. equivalent to

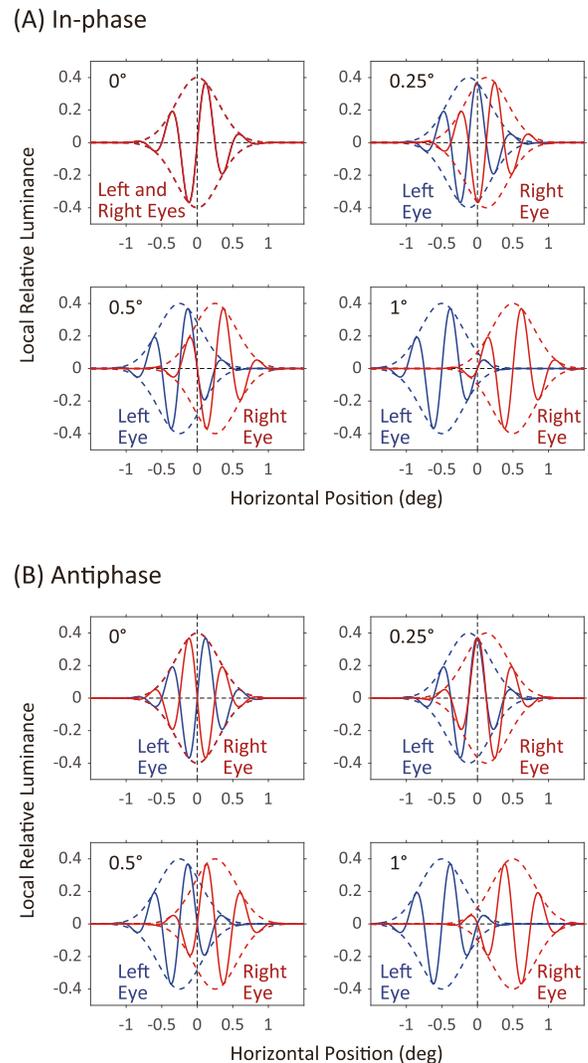


Figure 2. Luminance profiles of the stimuli at different uncrossed disparities (positive disparities). Dashed lines illustrate the Gaussian windows (envelope). Local luminance relative to the background luminance is plotted on a linear scale. The stimulus contrast is  $-8$  dB (40%) as an example. The left-eye and right-eye images should be switched for crossed disparities (negative disparities). **(A)** Stimuli for the in-phase condition. **(B)** Stimuli for the antiphase condition.

the sine function) for both eyes (Figures 1B and 2A). In the antiphase condition, the phase was shifted by 180 degrees for one eye, resulting in inverted luminance modulations between eyes (Figures 1C and 2B). The standard deviation of the Gaussian function was 0.3 degrees. Because the stimuli for the left and right eyes overlapped very little at the largest disparity (bottom right panels of Figures 2A, B), the perceived depth of these stimuli must have been driven by envelope disparity and not by phase disparity in line with the data of the Wilcox and Hess (1995) study. The mean luminance of the stimuli was  $32.1$  cd/m<sup>2</sup>. The luminance contrast was defined as the relative amplitude of the carrier grating before contrast reduction by the

Gaussian envelope and was expressed in dB re 1. Thus, the actual Michelson contrast between light and dark bars nearest to the center of the Gaussian window was always lower than the nominal contrast value by 0.71 dB (by a factor of 0.92). Because 1 dB is equivalent to 1/20 of a log unit of contrast, 0 dB, –20 dB, and –40 dB will correspond to 100%, 10%, and 1%, respectively.

Binocular disparity was defined as the relative shift in the horizontal position between the patterns projected to the left and right eyes. The left eye and right eye images were shifted in directions opposite to each other, such that a 1 degree uncrossed disparity, for example, was attained by shifting the left eye image by 0.5 degrees to the left and right eye image by 0.5 degrees to the right. Not only the Gaussian windows (envelopes) but also the sinusoidal gratings (carriers) were shifted in position by the same amount.

The disparity of the comparison stimulus was manipulated as an independent variable ranging from –1 degrees to 1 degree of the visual angle where negative and positive disparities indicate crossed and uncrossed ones, respectively. The contrast of the comparison stimulus was also variable. The standard stimulus, which served as a fixed reference throughout each session, had a fixed standard contrast and was always presented at the center of the presentation area at 0 degrees disparity and in phase between eyes.

## General procedure

By using the two-interval forced-choice task, we determined the contrast of the comparison stimulus at the perceptual match to the standard contrast owned by the standard stimulus. Observers initiated each trial by pressing a key when the Nonius and fixation dots appeared vertically aligned. The dots disappeared at the beginning of the trial. After 500 ms of a blank display at the mean luminance, the standard stimulus at a fixed standard contrast and at 0 degrees disparity was first presented (first observation interval), followed by the presentation of a comparison stimulus at a variable contrast and at a variable disparity (second observation interval). These two intervals were separated by 500 ms of a blank display at the mean luminance. In each presentation, the contrast of each stimulus was temporally modulated with a raised cosine function with a cycle of 510 ms. Observers judged which stimulus had a higher contrast.

## Experiment using the staircase method

There were seven levels of disparity (–1 degrees, –0.5 degrees, –0.25 degrees, 0 degrees, 0.25 degrees, 0.5 degrees, and 1 degree). The contrast of the standard

stimulus was set at either –8 dB or –26 dB (40% or 5%, respectively) in separate sessions. The contrast of the comparison stimulus was varied according to the one-up one-down staircase method with a step size of 1.5 dB. One staircase began at 6 dB above the standard contrast and another one began at 6 dB below it. Each staircase terminated after six reversals. The matched contrast was determined by averaging the last four reversals of two such interleaved staircases (eight reversals in total). Each session consisted of seven blocks, each of which contained a pair of staircases devoted to one of the seven disparity levels. The order of the blocks was randomized. Observers first completed the sessions under the in-phase condition. If the results exhibited any significant effect of disparity, we successively tested the antiphase condition. Note that the level at 0 degrees disparity under the in-phase condition served as the control condition. Matched contrast in this condition was expected to be equal to the standard contrast because both the standard and comparison stimuli were presented in phase at 0 degrees disparity, and any deviation from the standard contrast must stem solely from the two-interval forced-choice paradigm that could produce a constant error called time-order error (Hellström, 1985). Hence, all matched contrasts were evaluated in reference to that in this control condition.

One potential concern in the above manipulation was that stimuli were presented more frequently at 0 degrees disparity than at other disparities because the stimulus in the first interval was always presented to the fovea. Therefore, contrast adaptation could be greater at 0 degrees disparity than at others. This raised the possibility that contrast sensitivity reduction affected the matched contrast. To exclude this possibility, additional blocks were conducted to retest the in-phase condition at 0 degrees and 1 degree disparities on different days. Consequently, the number of stimulus presentations within the day of testing was equal between the two levels of disparity in each block. Furthermore, we added a supplementary condition where a 0 degree-disparity stimulus presented in the first interval and a variable-disparity stimulus presented in the second interval behaved as the comparison and standard stimuli, respectively, with respect to contrast manipulation; that is, the first stimulus had a variable contrast, whereas the second stimulus had a fixed contrast.

We also tested a monocular presentation condition in which one of the monocular images in the comparison stimulus in the original experiment was presented to one eye, while the other eye viewed a blank field at the mean luminance. The image was placed at 0 degrees or 0.5 degrees temporal eccentricity, which corresponded to the monocular image position in the original binocular stimuli with 0 degrees or 1 degree disparity, respectively. The standard stimulus was presented to

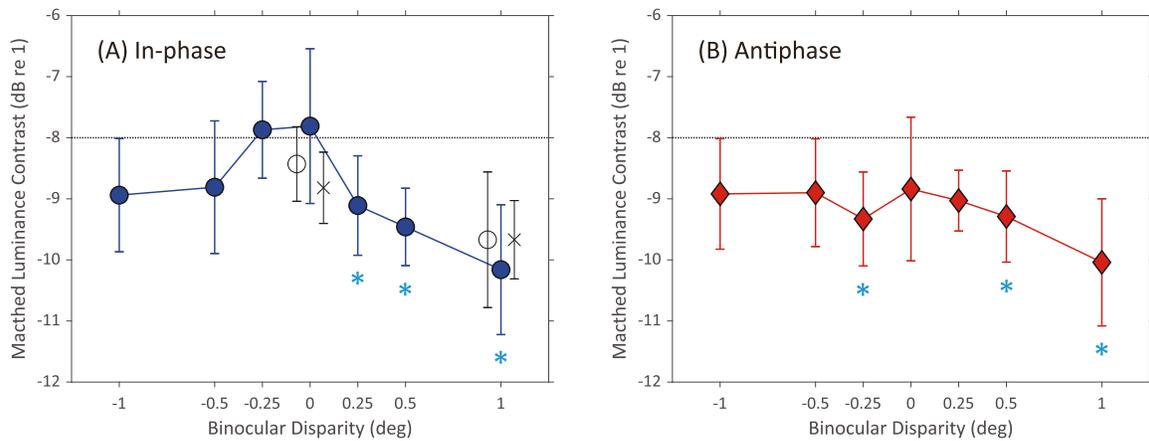


Figure 3. The luminance contrast at the perceptual match to the standard contrast ( $-8$  dB) owned by the standard stimulus presented at 0 degrees disparity and in phase between eyes. Compared with the control condition (at 0 degrees disparity under the in-phase condition), matched contrasts were significantly lower in the conditions marked by the asterisks ( $p < 0.05$ ). Error bars indicate 95% confidence intervals. (A) Results under in-phase conditions. Open circles represent the matched contrasts that were retested on separate days. Crosses represent the matched contrasts measured using the method of constant stimuli. Their plots are horizontally shifted to avoid overlapping. (B) Results under antiphase conditions.

both eyes, as in the original experiment. One block was conducted at each eccentricity (0 degrees or 0.5 degrees) for each eye, resulting in a total of four blocks. Eye dominance was tested for each observer by using the Miles test with a tube, and the monocular image was delivered to each observer's dominant or nondominant eye in separate sessions.

### Experiment using the method of constant stimuli

A subset of the conditions tested in the original experiment with the staircase method was also tested using the method of constant stimuli for further validation. The procedure within each trial was identical to that of the experiment using the staircase method, except for the following modifications. The standard stimulus had a fixed contrast at  $-8$  dB and was presented at 0 degrees disparity. The disparity of the comparison stimulus was set at 0 degrees or 1 degree of the visual angle. The contrast of the comparison stimulus was varied from  $-14$  dB to  $-5$  dB in 1.5 dB increments. A block consisted of 5 trials each at  $-14$  dB and  $-5$  dB, and 10 trials each at  $-12.5$  dB,  $-11$  dB,  $-9.5$  dB,  $-8$  dB, and  $-6.5$  dB (hence, 60 trials in total). The order of the trials was randomized within a block. Observers completed four blocks in a session devoted to one of the two levels of disparity. That is, each matched contrast was determined based on 240 trials. Sessions for 0 degrees and 1 degree disparities were conducted on different days to avoid any imbalance in adaptation levels.

Moreover, we measured the matched contrasts under two additional experimental conditions. In the vertical-disparity condition, two comparison stimuli were displaced vertically instead of horizontally. The orientation of the carrier gratings was 90 degrees (i.e. horizontal stripes). In the monocular-disparity condition, the comparison stimulus with 1 degree disparity in the main experiment, namely, two vertical Gabor patches displaced horizontally by 1 degree, was presented to the same eye, while the other eye viewed a blank field. The comparison stimulus with zero disparity in the main experiment was mimicked by a single Gabor patch monocularly presented at the fovea. The aim of this experiment was to test whether or not two adjacent stimuli appear to have a higher contrast than one stimulus. The standard stimuli were presented to the two eyes in the same way as in the main experiment. The presentation of the comparison stimuli was counterbalanced among observers with respect to eye dominance and across the left and right eyes.

## Results

### Experiment using the staircase method

For each binocular disparity, the mean luminance contrast at the perceptual match to the standard contrast of  $-8$  dB at 0 degrees disparity is plotted in Figure 3. As shown in Figure 3A (left panel), the matched contrast decreased as the disparity deviated from 0 degrees under the in-phase condition. In addition, the contrast at 0 degrees disparity

(−7.81 dB) at the perceptual match to itself was statistically indistinguishable from the veridical (−8 dB), indicating that the time-order error inherent in the two-interval forced-choice task turned out to be negligible in the present experiment. Compared with the in-phase condition, the antiphase condition showed lesser differences in the matched contrast among different disparities (Figure 3B). To confirm these trends, we subjected all data to a 2-way repeated-measures analysis of variance (ANOVA) with phase (in-phase or antiphase) and disparity as factors. As expected, the main effect of disparity was significant,  $F(6, 54) = 6.44$ ;  $p < 0.001$ , whereas the main effect of phase was not,  $p > 0.05$ , although their interaction was significant,  $F(6, 54) = 2.96$ ;  $p = 0.014$ . The significant interaction suggests that the matched contrast yielded statistically reliable changes across different disparities in the in-phase condition but not in the antiphase condition.

However, the 95% confidence intervals (CIs) in the antiphase condition were below the actual value of the standard contrast (−8 dB) when the stimuli were presented with disparities (error bars in Figure 3B except at 0 degrees), indicating that the matched contrast was significantly lower than the standard contrast. Compared with the results under the in-phase condition (see Figure 3A), the absence of the disparity effect under the antiphase condition might be due to a reduction in matched contrast at −0.25 degrees and 0 degrees disparities.

To confirm which conditions yielded significant reduction in matched contrast, we subjected the data in the in-phase and antiphase conditions to Dunnett's multiple-comparison tests, where the point at 0 degrees disparity under the in-phase condition was used as the control condition. The matched contrast was significantly lower at 0.25 degrees, 0.5 degrees, and 1 degree disparities under the in-phase condition (−9.11, −9.46, and −10.2 dB, respectively, and marked by the asterisks in Figure 3A) and at −0.25 degrees, 0.5 degrees, and 1 degree disparities under the antiphase condition (−9.33, −9.29, and −10.0 dB, respectively, and marked by asterisks in Figure 3B) compared with the control condition. The 95% CIs of these differences ranged from 0.0287 to 2.56, 0.384 to 2.92, 1.08 to 3.61, 0.255 to 2.79, 0.215 to 2.75, and 0.965 to 3.50, respectively. The in-phase and antiphase conditions produced similar results at 0.5 degrees and 1 degree disparities, supporting the notion that envelope disparity drove the perceived depth in these conditions.

The lowest matched contrast was observed at the 1 degree disparity of in-phase and antiphase conditions. The reduction in the matched contrast was possibly larger for the uncrossed disparity than for the crossed disparity. Supporting this notion, there was a significant difference in the matched contrast between −1 degrees and 1 degree disparities (−8.94 and −10.2 dB) in the

in-phase condition,  $t(9) = 2.93$ ,  $p = 0.017$ , although the difference was not significant in the antiphase condition,  $p > 0.05$ .

Taken together, these results demonstrate that the contrast was perceived as higher for stimuli with sufficiently large disparities than for the in-phase stimulus at 0 degrees disparity, and that this enhancement effect could be prominent for uncrossed disparities, regardless of the interocular phase matching.

To exclude the possibility of long-term contrast adaptation that might have built up during sessions within a single day as a potential confounding factor, we next retested contrast matching of the in-phase stimuli at 0 degrees and 1 degree disparities each within a single day. The results are plotted in Figure 3A with open circles. The mean matched contrast was still significantly lower at 1 degree (−9.67 dB) than at 0 degrees (−8.43 dB),  $t(9) = 2.61$ ,  $p = 0.028$ . In addition, a separate experiment was performed, wherein we switched the roles of comparison and standard stimuli and measured the matched contrast in the same manner. That is, the first stimulus at 0 degrees disparity was presented as the comparison stimulus, meaning that its contrast varied according to the staircase protocol, whereas the second stimulus at either 1 degree or 0 degrees disparity was presented as the standard stimulus with the standard contrast (−8 dB). This methodological change predicted a higher rather than a lower matched contrast for 1 degree disparity than for 0 degrees disparity, given that perceived contrast was higher for 1 degrees disparity than for 0 degrees disparity. As expected, in this subsidiary experiment, we found that the matched contrast became significantly higher at 1 degree disparity (−6.22 dB) than at 0 degrees (−7.27 dB),  $t(9) = 2.67$ ,  $p = 0.026$ . These results confirm that disparity, rather than contrast adaptation, contributed to the elevation in perceived contrast.

For the monocular presentation condition wherein the comparison stimulus was presented to only one eye, but the standard stimulus was presented to both eyes, we subjected the data to a 2-way repeated-measures ANOVA with eccentricity (0 degrees and 0.5 degrees eccentricities) and eye (dominant and nondominant eyes) as factors. One of 10 observers showed unstable eye dominance and was thus excluded from the analysis of the monocular presentation condition. There were no significant differences between 0 degrees (−8.28 dB) and 0.5 degrees eccentricity (−8.75 dB) and between the dominant (−8.81 dB) and nondominant (−8.22 dB) eyes,  $p > 0.05$ . The interaction was also not significant ( $p > 0.05$ ). The mean matched contrasts at 0 degrees and 0.5 degrees eccentricity are plotted in Figure 4 (blue upward-pointing triangles). These results support the notion that stereoscopic presentation, rather than mere presentations of monocular images at designated

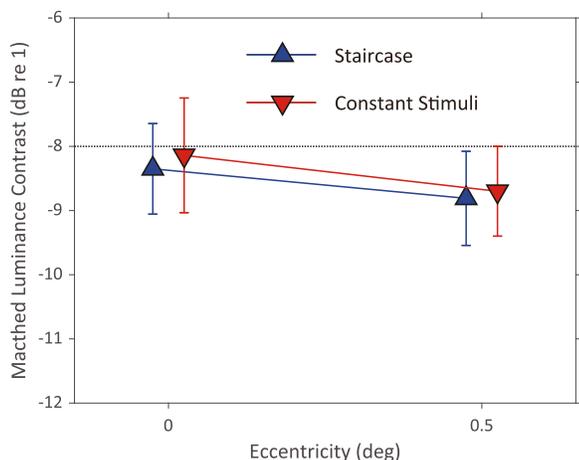


Figure 4. The monocular luminance contrast at the perceptual match to the binocular standard contrast (−8 dB). The matched contrasts were measured using the staircase method (blue upward-pointing triangle) or the method of constant stimuli (red downward-pointing triangle). Their plots are horizontally shifted to avoid overlapping. Error bars indicate 95% confidence intervals.

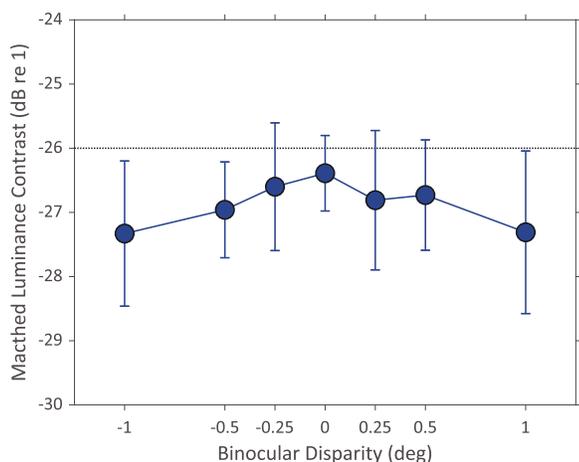


Figure 5. The luminance contrast at the perceptual match to the standard contrast (−26 dB) under the in-phase condition. Error bars indicate 95% confidence intervals.

eccentricities, caused a reduction in matched contrast in the original experiment.

Figure 5 shows the results after the standard contrast was reduced to −26 dB. When Figure 5 is compared with Figure 3A, it becomes apparent that the reduction in matched contrast was smaller here. Consistently, a repeated-measures ANOVA yielded no significant main effect of disparity ( $p > 0.05$ ), suggesting that the perceptual enhancement of luminance contrast was more notable for the stimuli at high contrasts of approximately −8 dB ( $\approx 40\%$ ), but negligible at low contrasts of approximately −26 dB ( $\approx 5\%$ ). Due to

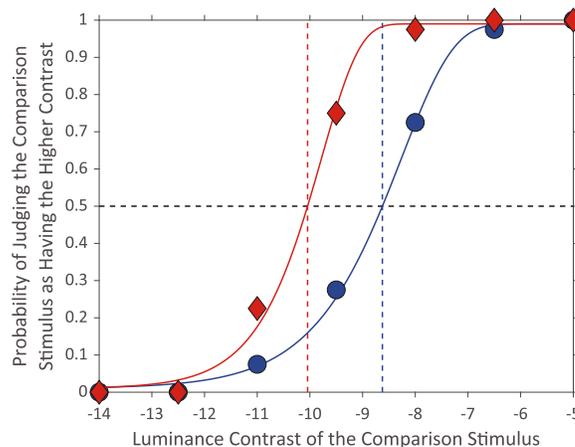
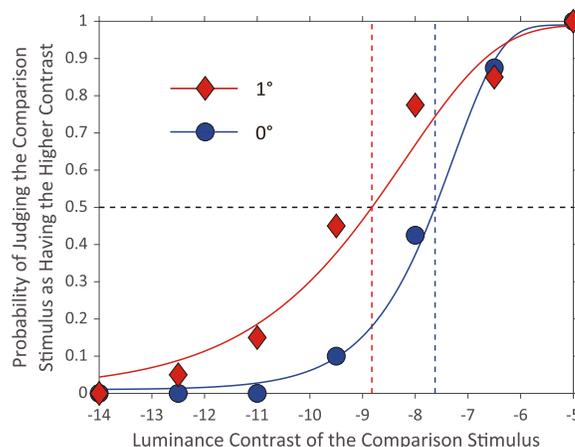


Figure 6. Psychometric functions for two typical observers (top and bottom panels) in the experiment using the method of constant stimuli. The binocular disparity of the comparison stimulus was set at either 0 degrees (blue circles) or 1 degree (red diamonds). Smooth curves show the fitted psychometric functions. Vertical dashed lines indicate the matched contrast.

the lack of significant differences among different disparities, we did not test the antiphase condition for the −26 dB standard contrast.

### Experiment using the method of constant stimuli

To validate the main message from the original experiment, we also determined the matched contrast for a subset of conditions by using a different psychophysical protocol, namely the method of constant stimuli. Figure 6 illustrates the psychometric functions for two typical observers when the binocular disparity of the comparison stimulus was set at either 0 degrees (blue circles) or 1 degree (red diamonds). As in the original experiment, the standard stimulus was always presented at a fixed standard contrast (−8 dB) and at 0 degrees disparity. We fitted the

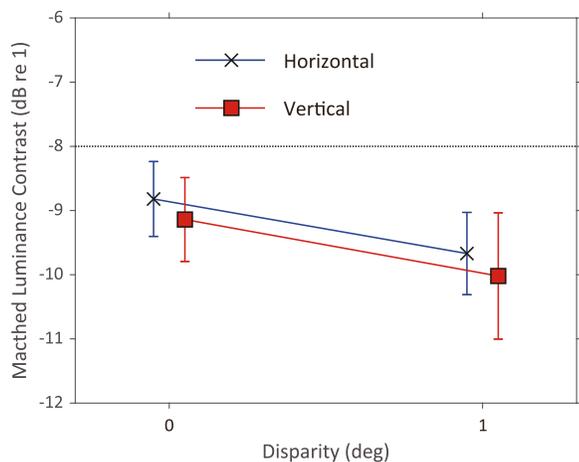


Figure 7. The luminance contrast at the perceptual match to the standard contrast ( $-8$  dB) for horizontal and vertical disparities (crosses and red squares, respectively). The matched contrasts were measured using the method of constant stimuli. Their plots are horizontally shifted to avoid overlapping. Error bars indicate 95% confidence intervals.

log-Quick function to the data using the Palamedes toolbox (Kingdom & Prins, 2016). The smooth curves in the figure correspond to the best-fit models. The matched luminance contrast was defined as the point at which the curve crossed the 50% line. By simply glancing at the figure, it becomes evident that the function shifted leftward when the comparison stimulus was at 1 degree disparity, resulting in a reduction of matched contrast.

Figure 7 shows the mean matched contrasts at 0 degrees and 1 degree disparities when the comparison stimuli were displaced horizontally (crosses; also plotted in Figure 3A;  $n = 9$ ) or vertically (red squares;  $n = 10$ ). To examine whether the aforementioned findings for disparity are only applicable to horizontal disparity or the same effects also occur for vertical disparity, we subjected the data to a 2-way ANOVA with disparity (0 degrees or 1 degree) as a within-group factor and displacement-orientation (horizontal or vertical) as a between-group factor. The mean matched contrast was significantly lower for the 1 degree disparity ( $-9.86$  dB) than for the 0 degrees disparity ( $-8.99$  dB), as revealed by the significant main effect of disparity,  $F(1, 17) = 45.0$ ;  $p < 0.001$ , whereas the main effect of the displacement-orientation factor or their interaction was not significant ( $p > 0.05$ ). These results indicate that the stimuli with vertical as well as horizontal disparity produced a reduction in the matched contrast.

To examine whether the presentation of two shifted images is a sufficient condition or dichoptic presentation is required, dichoptic stimuli used in the main experiment were presented monocularly. Thus, the stimulus for the 0 degrees disparity was mimicked

by a single monocular Gabor patch at the fovea and that for the 1 degree disparity was mimicked by two monocular Gabor patches shifted from each other by 1 degree (presented at  $\pm 0.5$  degrees horizontal eccentricities). The mean matched contrasts at 0 degrees and 0.5 degrees eccentricity are plotted in Figure 4 (red downward-pointing triangles). The results showed no significant differences between the “0 degrees disparity” ( $-8.14$  dB) and “1 degree disparity” ( $-8.70$  dB) conditions,  $t(9) = 1.79$ ,  $p > 0.05$ , indicating that the spatial proximity of stimuli was not sufficient to yield a reduction in matched contrast.

Altogether the perceptual enhancement of the luminance contrast required a dichoptic stimulation with two patches separately presented to the two eyes, and the patches could be shifted horizontally or vertically between the two eyes to produce the effect.

## Discussion

The present study determined the luminance contrast of stereoscopic patterns at the perceptual match to a fixed contrast, owned by a standard stimulus, as a function of binocular disparity. Compared with the standard stimulus at  $-8$  dB contrast and at 0 degrees disparity, the matched contrast of the in-phase stimulus, which had luminance modulations in the same phase between eyes, was virtually veridical at 0 degrees disparity and decreased as the disparity deviated from 0 degrees (see Figure 3A). The reduction was significant at 0.25 degrees, 0.5 degrees, and 1 degree. This effect could not be attributed to artifacts from long-term contrast adaptation at the fovea because a significant reduction in matched contrast was robustly observed even when the number of stimulus presentations was equal between 0 degrees and 1 degree disparities (see Figure 3A, open circles). Moreover, there was no significant difference between the monocular matching contrast at 0 degrees and 0.5 degrees eccentricity, indicating that the reduction in matched contrast requires a stereoscopic presentation. In other words, the reduction in the matched contrast was not attributable to the spatial proximity of stimuli. These results suggest that sufficiently large disparities enhance the perceived luminance contrast of suprathreshold stimuli.

Baker et al. (2012) reported a similar elevation of perceived contrast when there was a large vertical phase offset (around 90 degrees) between two monocular horizontal gratings at the fovea. They ascribed this effect to the attenuation of interocular suppression in the presence of a phase difference. The process of interocular suppression is generally thought to be retinotopically local because simultaneous stimulations at corresponding retinal points elicit strong interocular suppression, resulting in binocular rivalry (Blake,

1989). Because stimuli with large binocular disparities are projected to noncorresponding retinal points, it is possible that our stimuli with sufficiently large disparities yield weaker interocular suppression, thus enhancing the contrast.

Disparity had no significant effect in the antiphase condition in which the luminance modulations were antiphase between eyes, whereas the matched contrast was significantly lower at  $-0.25$  degrees,  $0.5$  degrees, and  $1$  degree disparities than that of the control condition (see Figure 3B). Therefore, there is not enough evidence to conclude that there was no elevation of perceived contrast under the antiphase condition. There is also a possibility that the antiphase stimuli lowered the interocular suppression and elevated the perceived contrast even at  $0$  degrees disparity. Although Baker et al. (2012) stated that the perceived contrast was veridical under the antiphase condition in the range of high contrast, a close inspection of their results revealed that the perceived contrast of antiphase stimuli increased as the standard contrast increased. Moreover, one of the three observers in their study showed an elevation of perceived contrast at  $-9.9$  dB (32%) of the standard contrast. Thus, it remains to be further examined which factors (binocular disparity, phase mismatch, or both) elevate the perceived contrast of antiphase stimuli.

The perceptual enhancement of the luminance contrast was more modest for crossed disparities than for uncrossed disparities, regardless of interocular phase matching in the in-phase condition (see Figure 3A). Researchers have reported differences between crossed and uncrossed disparities based on a variety of measurements, including stereoblindness, fusional limits, stereoacuity, and temporal sensitivity (see for a review Mustillo, 1985). Such differences may cause the asymmetry of matched contrasts in the present experiment, although the exact mechanism is unclear. One possible explanation is the difference in the fusional limits. According to Woo (1974), the limiting disparity for fusion (threshold for diplopia) was smaller in the crossed direction than in the uncrossed direction. If binocular summation is larger for fused single vision than for double vision, as was suggested by Thorn and Boynton (1974) and Westendorf and Fox (1977), perceived contrast could be lower for crossed disparities than for uncrossed disparities, which would result in an asymmetry of matched contrast.

The vertical disparity caused the same reduction in the matched contrast as the horizontal disparity. It is also known to yield depth perception, although its functional role is controversial (see for a review Matthews, Meng, Xu, & Qian, 2003). According to Gonzalez, Relova, Perez, Acuña, and Alonso (1993), 30% of V1 cells and 40% of V2 cells in the foveal areas of the monkey visual cortex responded to both horizontal and vertical disparities. Therefore, it is possible that the

visual system integrates luminance-contrast responses elicited by stimuli with vertical as well as horizontal disparities and that it results in the perceptual enhancement of the luminance contrast. However, in a previous study, binocular summation in contrast detection thresholds fell to the level of probability summation at  $0.5$  degrees of vertical disparity, a value comparable to the horizontal fusion limit (Rose et al., 1988). Moreover, the binocular advantage in the simple reaction time disappeared when stimuli were presented with a vertical disparity (Harwerth et al., 1980). Perceptual decisions concerning stereoscopic perception and contrast detection may depend on different types of visual signals. Contrast thresholds for depth identification were higher than contrast detection thresholds (Simmons & Kingdom, 1997). Observers took  $0.3$  to  $6$  seconds to obtain stereoscopic perception even after training (Ramachandran & Braddick, 1973). These previous studies suggested that the stereopsis process is not optimally involved in contrast detection tasks.

An elevation of perceived contrast may be observed when stereoscopic images are artificially synthesized from 2D images by adding binocular disparity information (e.g. Fukiage, Kawabe, and Nishida, 2017). Our measurements using the method of constant stimuli indicated that the perceived contrast was  $1.1$  times higher at  $1$  degree uncrossed disparity. This elevation value is near increment thresholds for contrast discrimination within a range of high contrasts (Legge & Foley, 1980; Maehara & Goryo, 2005; Meese et al., 2006). Thus, the observers would possibly notice subtle changes in the appearance of the luminance contrasts of stereoscopic patterns even if the actual contrasts were kept constant. This might be one of the factors causing a sense of artificiality in synthesized 3D images and virtual reality spaces. In normal scene viewing, objects outside of our fixation tend to appear blurred because they are often located in different depth planes and are therefore defocused. We tentatively speculate that the perceptual enhancement of luminance contrasts in stereoscopic patterns may function as a perceptual compensation for a reduction of local luminance contrast in blurred objects.

## Conclusion

This paper has dealt with how binocular disparity affects the perceived luminance contrasts of suprathreshold stereoscopic patterns. We found that the perceived contrast was approximately  $0.87$  dB higher ( $1.1$  times increase) at  $1$  degree disparity. The shift in the perceived contrast with disparity was systematic but within a barely discriminable range; perceptually, it is a small effect. This effect almost disappeared when

the contrast of the stimuli was near the threshold. The elevation in perceived contrast was more modest for crossed disparities than for uncrossed disparities. The perceptual enhancement of the luminance contrast could be due to weaker interocular suppression for the stimuli with binocular disparities.

*Keywords:* luminance contrast, stereopsis, interocular suppression, binocular summation

## Acknowledgments

IM was supported by JSPS KAKENHI Grants-in-Aid for Scientific Research on Innovative Areas (18H05523).

Commercial relationships: none.

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