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Correlation Effect on Stereo Transparency

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Abstract—Stereo transparency is one of the important phenomena for the computational study of binocular stereopsis, because this perception raises a fundamental issue of how binocular disparities are represented in the brain. We investigate the perceptual property of stereo transparency with a specific stereogram generated by overlapping two 'identical' dot patterns in different depths. This stereogram has potential matches leading to a unitary surface perception as well as transparency perception, and which surface is perceived in this ambiguous stereogram would reflect the property of the transparency detection mechanism in human stereopsis. The result suggests that the depth perception in this stereogram is affected by the correlation between overlapping patterns within a small area the size of which was approximately equal to the receptive field size in early visual cortex.

1. Introduction

Transparency perception is a challenging problem for the theory of the early visual processing in the brain. Transparency perception indicates that the human visual system can naturally deal with overlapping, or multi-valued, visual quantities and suggests that a simple model reconstructing a single-valued field of a visual quantity (such as a disparity map) cannot model the early visual processing in the brain.

In recent years, the human ability to transparency perception in binocular stereopsis has been studied intensively. Many psychophysical studies for stereo transparency employed a stereogram generated by overlapping two random dot patterns with different disparities. Fusing this type of stereogram, observers can perceive two overlapping disparities simultaneously. Here we investigate the transparency detection mechanism for binocular stereopsis by using a specific stereogram as illustrated in Fig.1. The stereogram shown in Fig.1a was composed of two identical dot patterns in different depths. In this stereogram, the geometrically paired dots in each surface were projected on nearby positions as shown in Fig.2a. This stereogram can be regarded as a random-dot version of the double-nail illusion [3] and a stereo version of the locally-paired-dot (LPD) stimuli [1, 6, 7] that was used to investigate the neural mechanism for transparent motion detection. This stereogram has potential matches leading to a unitary (or non-transparent) surface perception as well as transparent surface perception, and these matching candidates are exclusive if the uniqueness constraint holds [4]. Which surface is perceived in this type of stereograms would reflect the property of the stereo mechanism in the brain. Fusing this stereogram, we can only perceive a single surface. This perception is not surprising, especially in light of the previous results concerning the double-nail illusion. Similar to the double-nail illusion, this perception can be interpreted by simple models employing the smoothness constraint.

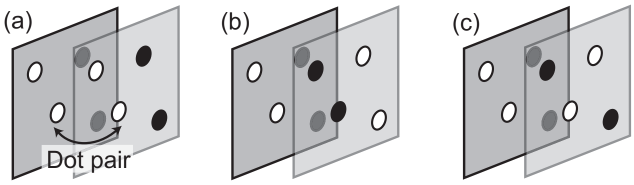

Figure 1: Examples of the stereograms generated by overlapping two identical dot patterns. (a) All geometrically paired dots have the same contrast polarity. (b) All paired dots have the opposite contrast polarity. (c) A half of dot pairs has the opposite contrast polarity, while another half the same.

When an additional segregation cue for overlapping surfaces is provided, does the visual system overcome the inability to detect transparent surfaces in this ambiguous stereogram? In Fig.1b, a surface segregation cue was provided by reversing the signs of contrast of paired dots. In this stereogram, two overlapping patterns have opposite signs of contrast, while dot positions of two patterns are identical. In this case, there is no alternative match leading to a unitary surface perception, and it is expected that the contrast reversal might act as a surface segregation cue (Fig.2b). Fusing this stereogram, although observers might perceive two overlapping surfaces, this perception would be unstable because binocular rivalry occurs. This perception indicates that the contrast reversal does not act as a surface segregation cue as expected. In this stereogram, the disparity detection mechanism in the human visual system tends to detect rivalrous matches with zero disparity rather than stable matches leading to stereo transparency.

The third stereogram (Fig.1c) was generated by intermingling above two stereograms, that is, a half of paired dots has the same signs of contrast and another half was reversed. When fusing, two overlapping surfaces could be easily perceived rather than Fig.1b. Why stereo transparency appears stably when only a half of paired dots has

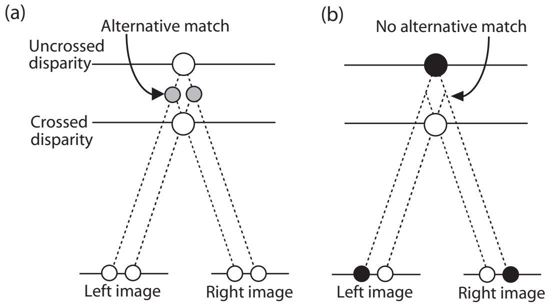

Figure 2: Candidate matches generated by dot pairs with (a) the same and (b) the opposite contrast polarities.

the opposite contrast polarity? This phenomenon cannot be explained by simply assuming that the contrast reversal acts as a cue for surface segregation, because, if the assumption is correct, we should easily perceive overlapping surfaces when all paired dots have the opposite signs of contrast rather than when only a half of paired dots has the opposite contrast polarity.

In this paper, we carried out a parametric study to reveal the property of the depth perception in this stereogram. The experimental results showed that the depth perception in this stereogram is affected by the contrast reversal ratio, or correlation, between overlapping patterns within small regions the widths of which were nearly equal to the receptive field sizes in early visual cortex. This result suggests that the contrast reversal between two identical patterns modulates the activities of each neuron, and this modification would have a crucial effect on the transparency detection.

2. Experiment 1: effect of the contrast reversal ratio

In Introduction, we described the depth perception in the ambiguous stereograms with the typical contrast reversal ratios at 0%, 50%, and 100%. In Experiment 1, we examine the effect of the contrast reversal ratio more precisely.

2.1. Method

2.1.1. Apparatus

Stimuli were generated by an ELSA Quadro FX3000 graphic board and presented on a NANAO T766 CRT monitor at a viewing distance of 100 cm, leading a spatial resolution of 49.9 pixels/deg. To provide independent stimulation of the eyes, the graphic board was synchronized with stereoscopic liquid crystal glasses (MacNaughton NuVision 60GX) at 120 Hz. Observers seated in front of the monitor with their heads supported by a chin-rest. The experimental room was darkened, but the light from the monitor provided dim illumination.

2.1.2. Observers

Three observers were participated in the experiment; one was the author, and the others were naive to the conceptual basis of the experiments.

2.1.3. Stimuli

The stimuli were composed of a red fixation cross and two stereograms plotted within square areas subtending 5 deg. The fixation cross was located at the center of the display and was presented throughout an experiment. In each trial, two stereograms were presented simultaneously and centered 4 deg either side of the fixation cross; one was an ambiguous stereogram, and the other a simple random-dot stereogram (RDS) with a single disparity. Which side an ambiguous stereogram was presented at was chosen at random from trial to trial.

Each stereogram consisted of 700 dots (0.06 deg diameter; density 27 dots/deg^2). A half of dots was bright (L = 6.82 cd/m^2) and the others dark (L = 1.72 cd/m^2); the luminances were measured through the stereo glasses. The luminance of a grey background was L_{mean} = 4.29 cd/m^2, making Weber contrasts, $|L - L_{\mathrm{mean}}|/L_{\mathrm{mean}}$, of both bright and dark dots against the background about 0.6. The ambiguous stereogram was generated by overlapping two dot patterns each of which consisted of 350 dots. The two patterns had disparities of ±0.12 deg, and the dot distributions of them were identical. Therefore, this stereogram also had potential matches leading to single surface perception with a disparity of 0 deg. The RDS consisted of randomly distributed dots. In each trial, the disparity of an RDS was selected randomly from 9 different levels between −0.10 deg and +0.22 deg; a positive and a negative value represents a crossed and an uncrossed disparity, respectively.

2.1.4. Procedure

A two-alternative forced choice (2AFC) procedure with the method of constant stimuli was used to examine the depth perception in the ambiguous stereograms. Observers indicated which stereogram, presented in the left side or the right side, had a nearer disparity via a key press. Therefore, if observers perceive two overlapping surfaces separately, the nearest disparity obtained by this experiment should be +0.12 deg, whereas the disparity should be 0 deg if observers detected alternative matches leading to unitary surface perception. Stereograms were presented for 2 s in one trial, and no feedback was given. In Experiment 1, we used 11 levels of contrast reversal ratios selected between 0% and 100% in a step of 10%. Therefore, the number of combinations of the ambiguous stereogram and the RDS was 99 (11 levels of the contrast reversal ratios × 9 levels of the RDS disparities). In each session of the experiment, these 99 conditions were presented in random order, and all observers carried out 20 sessions to obtain the result.

To estimate the nearest depth perceived in an ambiguous stereogram, a psychometric function was fitted to the data with psignifit 2.5.41, a software package that implements the maximum-likelihood method [8]. A logistic function

$$F(x;\alpha,\beta) = \frac{1}{1+\exp\left(\frac{\alpha-x}{\beta}\right)} \tag{1}$$

was employed as a psychometric function. α and β are the position (corresponding to the point of subjective equality; PSE) and spread (or slope) parameters of the function.

2.2. Result and discussion

Figure 3a shows the average PSEs for the nearest depths perceived in the ambiguous stereogram. The depth perception in the ambiguous stereogram was affected by the contrast reversal ratio. An ANOVA showed that this effect was significant ($F_{10,20} = 8.18$, $p < 0.01$), and post hoc multiple comparisons with Tukey's test showed that the PSEs with the contrast reversal ratios of 0% and 100% were significantly different from others ($p < 0.05$).

When the contrast reversal ratio was 0%, the average PSE was 0.001 deg. This depth perception corresponded to the disparity of alternative matches (0 deg) that led to unitary surface perception, and this result confirms the description in Introduction section.

On the other hand, the average PSE at the contrast reversal ratio of 100% was 0.029 deg. The long error bar in Fig.3a indicates that the individual difference in this condition was greater than others. This result suggests that the depth perception in this condition was unreliable. As described in Introduction, it was hard to perceive transparency when the contrast reversal ratio was 100%, since binocular rivalry occurred. The binocular rivalry led to unstable depth judgments in experiments. Therefore, the average PSE is insufficient to discuss the depth perception in this condition. Figure 3b directly shows that observers could not perform the task stably in this condition. This graph shows the mean spread parameters of the fitted psychometric functions. The spread parameter, or the slope, of the psychometric function provides a measure of the precision of judgments. As shown in Fig.3b, the spread parameter in the case of 100% was greater than others. An ANOVA showed that the effect of the stimulus type on the spread parameter was significant ($F_{10,20} = 3.16$, $p < 0.05$), and multiple comparisons with Tukey's test indicated there were significant differences between 100% and others ($p < 0.05$). This result indicates that the precision of the depth judgment in the case of 100% was poorer than others.

When the contrast reversal ratios were between 10% and 90%, the obtained PSEs were similar to the disparity of the nearer surface in the ambiguous stereogram (+0.12 deg). This result indicated that, to detect overlapping disparity from the ambiguous stereograms, it is necessary that both two types of pairs, the same and the opposite contrast pairs, coexisted in the stimuli. The contrast reversal ratios of 0% and 100% are the specific cases that the ambiguous stereograms only contain the same and the opposite contrast pairs, respectively. In these cases, the human stereo mechanism tends to detect matching candidates with zero disparity. Especially in the case of 100%, observers preferred the matching candidate with zero disparity even if the correspondences were rivalrous.

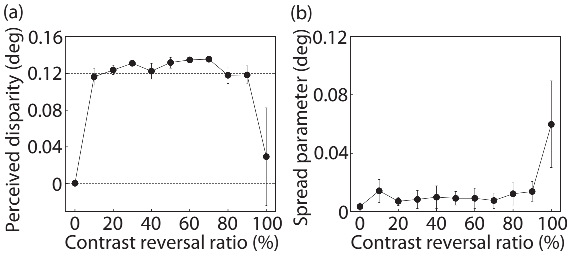

Figure 3: Results of Experiment 1. (a) Average PSEs for the nearest depths perceived in the ambiguous stereograms are plotted as a function of the contrast reversal ratio. (b) Spread parameters (β) of psychometric functions. In both graphs, error bars represents ±1 S.E.

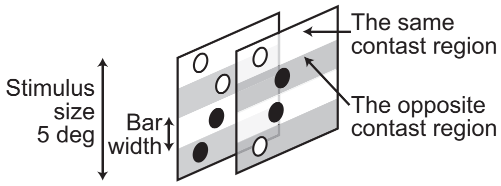

Figure 4: Schematic illustrations of dot arrangements of the ambiguous stereograms used in Experiment 2. The same and the opposite contrast pairs were located in white and dark regions, respectively.

3. Experiment 2: effect of spatial position

In Experiment 2, we examine whether the spatial positions of the same and the opposite contrast pairs affect the depth perception in the ambiguous stereograms. The size of the stereograms used in the experiment (5 × 5 deg) was relatively larger than the receptive field sizes in primary visual cortex. If transparency perception in this stereogram requires that individual binocular neurons receive both the same and the opposite contrast pairs simultaneously, the two types of pairs have to be plotted in spatially neighbors. In the present experiment, we locate the two types of dot pairs in spatially segregated regions and examine the effect on depth perception.

3.1. Method

Figure 4 shows the schematic illustrations of dot arrangements employed in Experiment 2. Each ambiguous stereogram was divided into an even number of horizontal bars of equal width. In the experiment, we used 8 levels of bar numbers between 4 and 18 in a step of 2. The same and the opposite contrast pairs were attributed to the odd and the even bars, respectively. Because the stimulus size was 5 deg, each bar width became 1.25 deg when the number of bars was 4. At the maximum bar number, each bar width was 0.28 deg. As the bar width decreases, the stimulus became similar to the ambiguous stereograms in Experiment

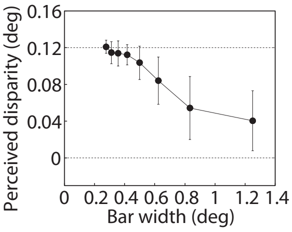

Figure 5: Result of Experiment 2. The average PSEs for three observers are plotted as a function of the bar width.

1. Therefore, when the bar width was sufficiently small, the PSE should become 0.12 deg. On the other hand, when the bar width was broad, many binocular neurons can only receive one of two types of pairs. If it is necessary for transparency detection that each neuron receives both two types of pairs simultaneously, observers would perceive zero disparity and rivalrous regions arranged in alternately. In this case, the PSE would be 0 deg.

In this experiment, to maximize dot homogeneity, each bar had the equal number of dots, and therefore, the contrast reversal ratio was fixed at 50%. The number of combinations of the ambiguous stereogram and the RDS was 72 (8 levels of bar numbers × 9 levels of the RDS disparities). In each session, these 72 conditions were presented in random order, and all observers carried out 20 sessions.

3.2. Result and discussion

Figure 5 represents the average PSEs for the nearest disparities in our corrugated stimuli. When the bar widths were small, the PSEs were nearly equal to the nearest disparity in the ambiguous stereogram (0.12 deg). However, as the bar width increased, the PSE decreased toward zero disparity. An ANOVA showed that the effect of the bar width was significant ($F_{7,14} = 6.92$, $p < 0.01$), and multiple comparisons with Tukey's test indicated there were significant differences between the PSEs the bar widths of which were 0.42 deg or smaller and the PSEs the bar widths of which were 0.83 deg or higher ($p < 0.05$).

In Experiment 2, the proportion of contrast reversed pairs was fixed at 50%. Therefore, the present result showed that only the coexistence of both the same and the opposite contrast pairs in a stimulus was insufficient to detect two overlapping disparities from the ambiguous stereogram, and it is necessary to locate these pairs in nearby positions. The maximum bar widths that could lead to stereo transparency (0.42 deg) are similar to the receptive field sizes in striate cortex [2]. When the bar widths were smaller than the receptive field sizes, individual binocular neurons could receive the same and opposite contrast pairs simultaneously. This result suggests that the calculations within individual neurons, rather than cooperative interactions between neurons, influence the transparency detection in the ambiguous stereogram.

4. Conclusions

In the present study, we have examined the depth perception in the stereograms generated by overlapping two identical dot patters. These stereograms have potential matches leading to transparency and non-transparency perceptions, and which depth perception occurs from these stimuli would reflect the transparency detection mechanism in human stereo vision. The present results did not reveal the neural mechanism for stereo transparency *in detail*, but could provide a clue for investigating how the binocular neurons represent overlapping disparities. The results suggest that the perceptual properties in the ambiguous stereograms depend on the responses of individual neurons and that the contrast reversal provide a crucial effect on the decoded information. Therefore, examining how the contrast reversal modulate the responses of binocular neurons, we could investigate the encoding strategy for transparency situations. Future research should include physiological study and/or computational analysis with the spatiotemporal energy model [5] to examine how binocular neurons respond to the ambiguous stereograms.

Acknowledgments

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