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Effects of Temporal Frequency and Contrast on Spatial Frequency Characteristics for Disparity Threshold

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We measured disparity threshold for identifying the depth direction as a function of spatial frequency with various temporal frequencies and stimulus contrasts using drifting gratings. The results showed that disparity threshold depended little on temporal frequency with the exception of high temporal frequencies ($\geq$10 Hz) independently of stimulus contrast. Contrary to temporal frequency, contrast substantially influenced spatial frequency characteristics. The disparity threshold was approximately constant with change in spatial frequency with slight increase at high spatial frequencies for contrasts higher than 0.2 when the threshold is expressed by phase difference between the left and right eye images (phase disparity). The phase disparity threshold had a negative peak at a spatial frequency between 1 and 5 c/deg (band-pass) for contrasts lower than 0.2. We discuss possible differences in the underlying mechanisms to determine disparity threshold below and above temporal frequency of 10 Hz.

Key words: temporal frequency, spatial frequency, contrast, disparity threshold, stereo acuity, stereopsis, phase disparity

1. Introduction

Stereopsis is the sense of depth derived from binocular disparities between the left and right retinal images. Several studies have shown that spatial frequency is one of crucial factors for determining the disparity threshold (or stereo acuity).[1–5] For example, Schor and Wood showed that the disparity threshold increased with the decrease of spatial frequency (size-disparity correlation) below 2 c/deg while approximately constant at frequencies higher than 2 c/deg.[5]

Such a dependency of disparity threshold on spatial frequency is likely related to the spatial frequency channels,[6–8] with which the visual system analyze the retinal images dividing several spatial frequency components. If there are several channels that are sensitive to different spatial frequencies and if the channel that is sensitive to low spatial frequencies are sensitive to large disparities, disparity threshold with lower spatial frequency stimulus is expected to be high. This is supported by the fact that contrast sensitivity for stereopsis depends on spatial frequency.[8–10] Smallman and MacLeod showed that the peak spatial frequency of contrast sensitivity function for depth identification decreased with the increase of disparity.[9]

Contrary to spatial frequency, much fewer studies have investigated effect of temporal frequency on stereopsis. Patterson measured stereo acuity for different spatiotemporal frequencies using counter-phase flickering gratings. He found that stereo acuity slightly reduced with the change of temporal frequency from 5 to 20 Hz when the stimulus spatial frequency was high, while stereo acuity was approximately constant when the stimulus spatial frequency was low.[11] Similarly, Kimura *et al.* reported that contrast sensitivity slightly decreased with temporal frequency when the stimulus spatial frequency was high using spatially filtered random-dot stereograms.[8,12] These results suggest some effect of temporal frequency on stereo acuity or sensitivity. However, these results are not sufficient to understand how spatial frequency characteristics change with temporal frequency because of the limited number of spatiotemporal frequency and contrast conditions. In this study, we investigated the effect of temporal frequency on spatial frequency characteristics for disparity threshold to investigate the spatiotemporal characteristics of the underlying mechanism of stereopsis. If more than one mechanisms with different spatial frequency tunings contribute to stereopsis, the spatial frequency characteristics for disparity threshold may change with temporal frequency. Contrast sensitivity for pattern detection show that band-pass spatial frequency tunings at low temporal frequency and low-pass spatial frequency tunings at high temporal frequency[13,14] and their results can be explained by contribution of multiple mechanisms with different spatial and temporal frequency tunings. Similar dependency of sensitivity on temporal frequency is possible for stereopsis. We also investigated the effect of stimulus contrast since contrast is another important factor to determine disparity threshold[3,4,15] and there is possible interaction between the effects of temporal frequency and contrast.

2. Experiments

Stimulus display consisted with four squares filled with sinusoidal gratings arranged in a 2 × 2 array with gaps to separate them (Fig. 1). The stimulus size was 4.3 deg × 4.3 deg (128 × 128 pixels) and gap size was 0.3 deg (10 pixels) in visual angle. The gratings in the upper right and the lower left squares had the same disparity that was opposite of those in the other two squares (i.e., upper left and lower right had crossed disparity and upper left and lower right had uncrossed disparity or vice versa). The observers responded which pair appeared to be closer to them. The stimulus of a 2 × 2 array was used for the following reason.[8] If there is one stimulus at the center of the disparity, the stimulus tends to be seen in front of the background even without disparity difference from the background. If there are one pair of stimuli arranged vertically, the upper stimulus tends to be perceived farther

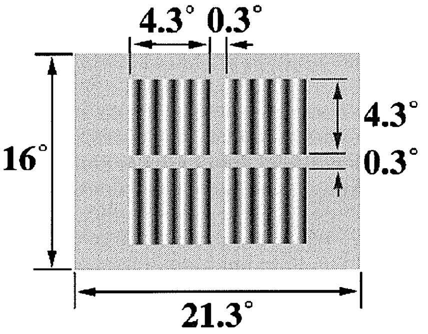


Fig. 1. The fused-image of the experimental stimuli.

in depth than the lower one. The 2 × 2 stimulus arrangement canceled the influence of these undesired depth biases. We did not choose stimulus pair arranged horizontally because we think disparity change along vertical axis is important for detecting relative disparity between vertical gratings.

2.1 *Apparatus*

Stimuli were generated on a color monitor (Sony GDM-FW900) under the control of a graphic board (Cambridge Research, VSG 2/3). The frame rate of the display was 120 Hz and spatial resolution was 640 × 480 pixels. Dichoptic separation was achieved by viewing the display through a pair of goggles (Crystal EYES3) switching on and off alternatively between the two eyes at a rate of 120 Hz in synchrony with the frame refresh of the display, so effective frame rate to each eye was 60 Hz. The average luminance of the display was 6.3 cd/m^2 when viewed through the opened shutter of the goggles and the luminance was 0.5 cd/m^2 when viewed through the closed shutter. This light through the closed shutter changes the retinal disparity. The amount depends on the disparity set by the computer and that was between 7.6 and 7.7% in our thresholds. Disparity thresholds in the following section were the values compensated this effect. Viewing distance was 82 cm, with which 1 pixel of the display corresponded to 2 min of arc. A chin rest was used to stabilize the observer's head. The experiments were carried out in a dark room.

2.2 *Procedure*

A two alternative forced choice response, which of the two diagonal pairs of the patches appeared closer, procedure was used. Threshold disparity for depth detection was measured by a staircase procedure. A staircase procedure controlled stimulus disparity by 2-up-1-down staircase, in which disparity was assumed to converge at the value that gives 70.7% correct responses. The one step of disparity change was 1.12 dB. Fifteen reversals were measured in a staircase and the median of the last five reversals was calculated as the threshold for the session. Motion direction was randomly chosen on each trial. Observers received no feedback concerning the validity of their response.

Six spatial frequencies (0.23, 0.47, 0.94, 1.88, 3.75 and 7.5 c/deg) and six temporal frequencies (0.15, 0.4, 1.53, 4, 10 and 20 Hz) were used. The stimuli contrasts varied between 0.02 and 1 for each of the conditions. The stimulus presentation duration was fixed at 1 s. Two observers, the first author (SL) and a naive observer (JK), participated in the experiment. Both observers had corrected to normal visual acuity, normal stereopsis and no history of any visual disorders. Each observer ran three sessions in each conditions.

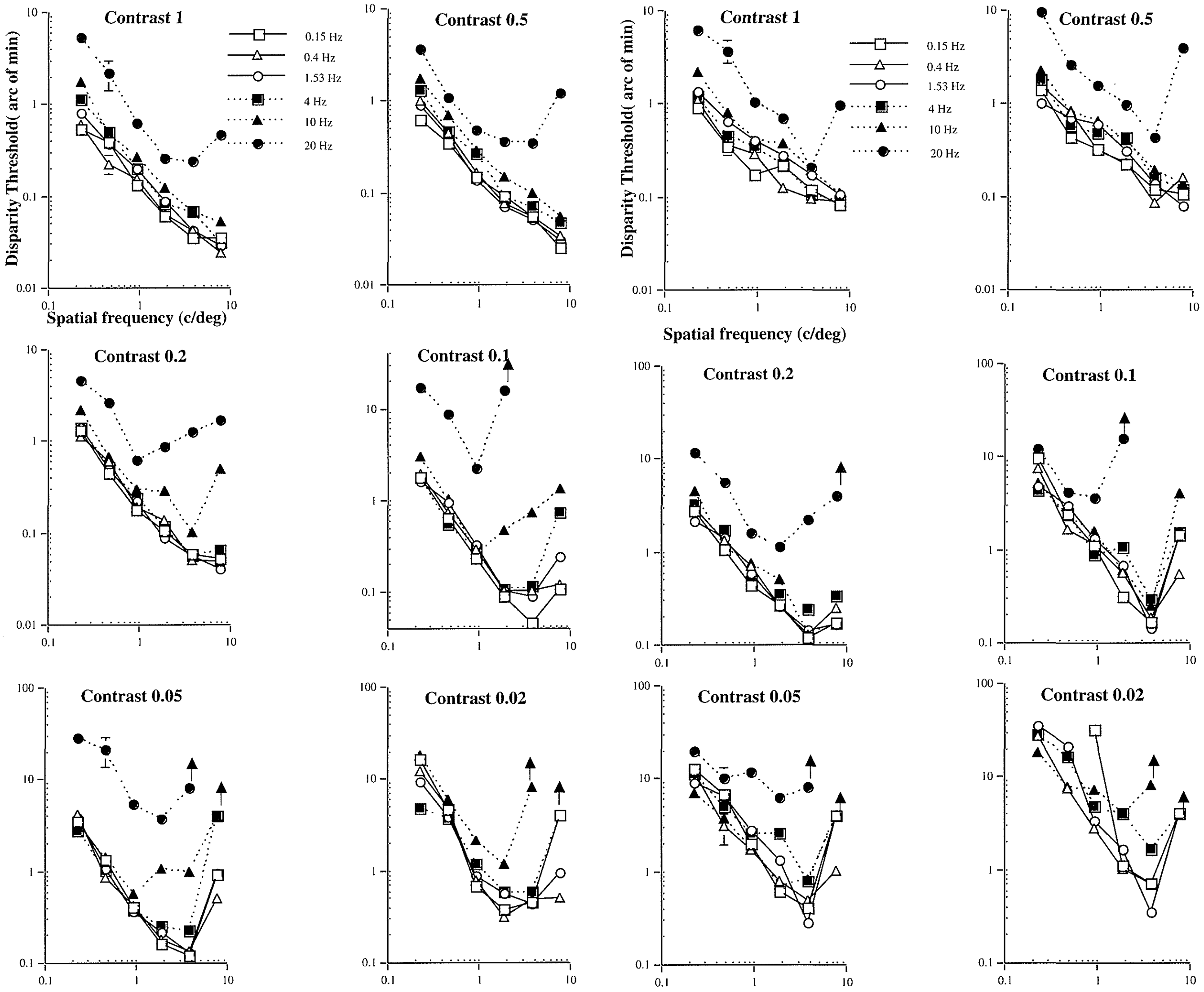
3. Results

Figure 2 shows disparity threshold as a function of spatial frequency for two observers. Symbols represent the different temporal frequencies and different plots show the results of different contrasts. Error bar occasionally attached to a datum point indicates a typical standard error of mean. General tendency of the results is similar between the observers although the results of the naive observer (JK) are somewhat noisier. The disparity threshold depended little on temporal frequency with the exception of high temporal frequencies (10 and 20 Hz) in all contrast conditions. On the contrary, the spatial frequency characteristics are different among different contrast conditions as well as absolute values. Independently of temporal frequency except higher than 10 Hz, disparity threshold decreased with the increase of spatial frequency when stimulus contrast was high (>0.2) while the disparity threshold had negative peak at a spatial frequency between 1 and 5 c/deg when stimulus contrast was low (<0.2). To show the effect of contrast, Fig. 3 plots the spatial frequency characteristics for each contrast in 0.4 Hz condition as an example. We can summarize the results as the disparity threshold depends on the stimulus contrast but depends little on temporal frequency.

4. Discussion

The present experiment revealed how spatial frequency, temporal frequency and contrast influence on disparity threshold. Temporal frequency did not influence disparity threshold unless higher than 10 Hz. Independently of the temporal frequency, disparity threshold decreased with the increase in spatial frequency when stimulus contrast was high (>0.2) while it had a minimum at a spatial frequency between 1 and 5 c/deg when stimulus contrast was low (<0.2). When temporal frequency was high, the threshold function showed a minimum at a middle spatial frequency similar to when contrast was low. One possible interpretation of this similarity between conditions of high temporal frequency and low contrast is the reduction of the effective contrast at high temporal frequency. In general, reduction of contrast sensitivity at high temporal frequencies should reduce the effective contrast of the stimulus. A high contrast stimulus at high temporal frequency can be as less effective as a low contrast stimulus at low temporal frequency. In other words, spatial frequency characteristics of contrast sensitivity influence strongly on the spatial frequency characteristics of disparity threshold. However, it is necessary to know how disparity threshold is determined to estimate spatial frequency tunings of the contrast sensitivity from disparity threshold.

If disparity determined the threshold, we expect constant threshold across spatial frequency unless contrast is so low



(a) (b)

Fig. 2. Disparity threshold as a function of spatial frequency. Results with different temporal frequencies are plotted in the same panel for each contrast condition for observer SL (a) and for JK (b).

that contrast sensitivity influences disparity threshold. The dependency of disparity threshold on spatial frequency (Fig. 2) suggests that threshold is not determined by disparity. Figure 4 shows that the threshold in terms of phase disparity, the phase difference between the left and right gratings at threshold. Threshold is approximately constant across spatial frequencies except when contrasts are low or when temporal frequency is high. This suggests that threshold is determined by phase disparity. Under the assumption that the disparity threshold is determined by phase difference, the phase disparity threshold function in low contrast conditions is a rough estimate of spatial frequency tuning of contrast sensitivity is roughly estimated in. At low temporal frequencies, spatial frequency tuning shows a band-pass property with a peak sensitivity (lowest threshold) at around 2 c/deg whereas at high temporal frequencies, it shows a band-pass property with spatial frequency lower than 1 c/deg or a low-pass property. These

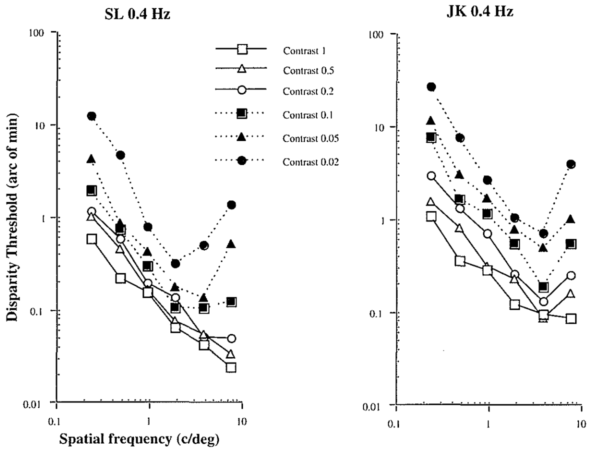
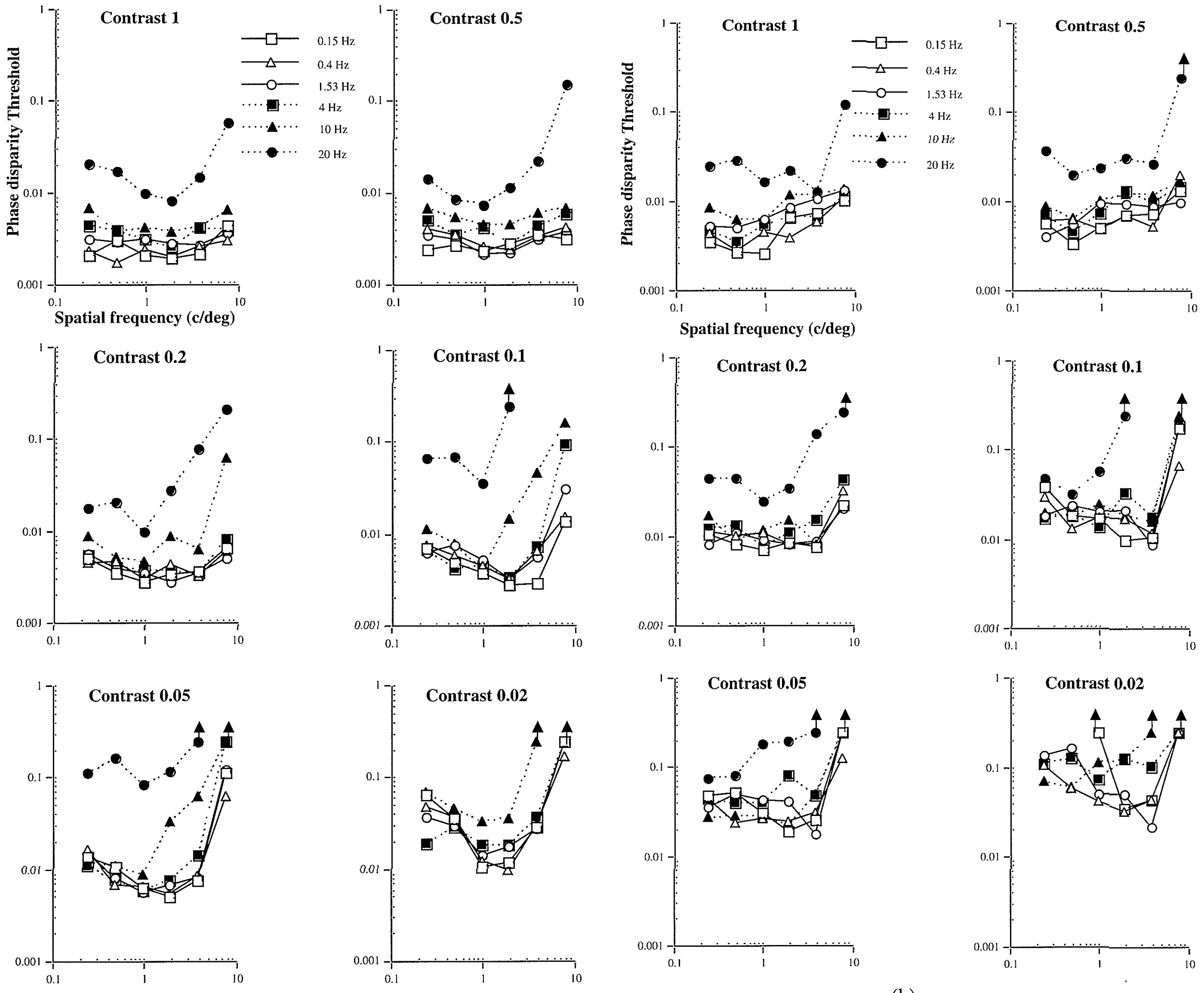


Fig. 3. Disparity threshold as a function of spatial frequency for the speed of 0.4 Hz. Different contrasts are plotted together in the same panel.



(a) (b)

Fig. 4. Phase disparity threshold as a function of spatial frequency for observer SL (a) and for JK (b).

results are consistent with the prediction that multiple mechanisms with different spatiotemporal frequency tunings contribute to stereopsis. Spatial frequency channels are likely to play a role for perceiving depth information. It is an issue of future investigation whether or not these multi-mechanisms are related to spatial frequency channels estimated for stereopsis by masking experiments.[6–8]

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