OPTICAL REVIEW Vol. 11, No. 4 (2004) 258–264

The Effect of Exposure Duration on Stereopsis and Its Dependency on Spatial Frequency

Seungbae LEE, Satoshi SHIOIRI[1] and Hirohisa YAGUCHI[1]

Graduate School of Science and Technology, Chiba University, 1-33 Yayoicho, Inage-ku, Chiba, 263-8522 Japan
[1]*Department of Information and Image Sciences, Chiba University, 1-33 Yayoicho, Inage-ku, Chiba, 263-8522 Japan*

(Received October 16, 2003; Revised February 9, 2004; Accepted February 27, 2004)

To investigate the effect of exposure duration on stereopsis and its spatial frequency dependency, we measured disparity threshold for the depth discrimination varying stimulus exposure duration between 0.05 and 2 s for three spatial frequencies (0.23, 0.94 and 3.75 c/deg). The results showed that disparity threshold decreased with increase in exposure duration up to a certain duration, beyond which it was approximately constant (the duration is called critical duration). The critical duration was about 150 ms for gratings with low and middle spatial frequencies (0.23 and 0.94 c/deg) while the duration was about 750 ms for gratings with high spatial frequency (3.75 c/deg). This suggests that temporal integration property varies dependently on stimulus spatial frequency. We also attempted to relate the spatial frequency dependency of the temporal integration property to the differences in temporal frequency tuning to different spatial frequency stimuli.

Key words: exposure duration, disparity threshold, stereo acuity, spatial frequency, tuning channel and stereopsis

1. Introduction

Depth can be seen in simple stereograms exposed for only 1 ms. This, however, does not indicate that the disparity sensitive mechanism can process the stimulus presented very briefly just as the one presented with long duration. The stereo acuity is very low with such a brief presentation and increases with exposure duration.[1,2] It is important to know how the stereo acuity varies with the presentation duration to understand the temporal property of stereopsis and to predict human performance of depth perception for dynamic stimulation.

Several studies have investigated the effect of exposure duration on stereo acuity and revealed the relationship between the stereo acuity and exposure duration (we refer this temporal integration property here).[1–8] For example, Ogle and Weil[3] reported that stereo acuity improved with exposure duration, from 40 sec arc at 6 ms exposure duration to 10 sec arc at 1 s exposure duration. They formulated the relationship as $\eta = kt^a$, where η was stereo acuity, t was exposure duration, k was the stereo acuity at 1 s and a was an exponent, which is about -0.3 according to their estimation. A similar relationship was found later with random dot stereograms in humans[4] and monkeys[5] although the exponent was about -1 rather than -0.3. These findings clearly revealed that stereo acuity improves with the increase in stimulus exposure duration (or declines with shortening of duration).

However, increase in exposure duration at long duration causes little or no improvement of stereo acuity. Stereo acuity increases with exposure duration until a certain duration, but it becomes approximately constant beyond the duration (the duration is called critical duration). This is similar to the effect of duration on light detection threshold. As for light detection, the effect of duration should be determined by how the mechanism that is responsible to the disparity detection integrates signals temporally. In this sense, critical duration, with which we can estimate the integration time, is another important factor of temporal integration property in addition to the exponent factor. Several estimates of critical duration for stereopsis have been reported. Watt reported that stereo acuity for a line target improves as exposure duration increases up to 1 s.[6] Beverley and Regan measured the effect of the stimulus exposure duration on the detection of impulse disparity change in dynamic random-dot stereograms and found critical exposure duration of about 100 ms.[7] Both studies showed the existence of critical duration although the values were very different.

Stereo acuity as functions of exposure duration from experiments in the literature show the variability of the results as summarized in Fig. 1.[9] Both the slope, or the exponent of Ogle and Weil's formula, and the critical duration appears to differ from experiment to experiment, or even from condition to condition. One possible cause of the variation is the differences in spatial frequency contents of stimuli. Watt suggested that the improvement of stereo acuity for the line stimulus as a function of duration could be explained in term of changes of the spatial scale of analysis from coarse to fine over a period of presentation time.[6] That

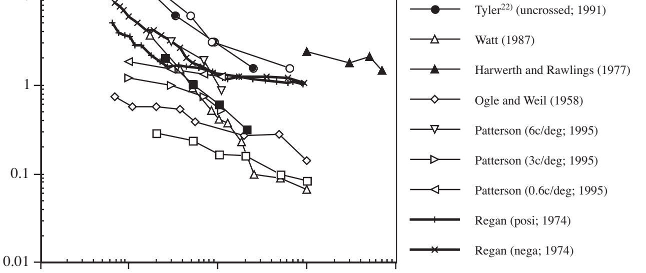


Fig. 1. Stereo acuity as functions of exposure duration of previous studies.

is, the spatial frequency channel in operation changes with presentation duration. A channel sensitive to low spatial frequencies (and thus to large disparities) perhaps works at short durations and a channel sensitive to high spatial frequencies (and thus to small disparities) perhaps works at long durations. Consequently, disparity threshold decreases with presentation duration. This is consistent with the studies of spatial frequency channels for stereopsis.[10–12] These studies suggested the existence of more than one spatial frequency channels for stereopsis. If these channels with different spatial frequency tunings have also different temporal frequency tunings, the temporal integration property should vary with spatial frequency. Indeed, Patterson[8] found different effect of exposure duration for stimuli with different spatial frequencies. Decreasing exposure duration impaired performance in grating patterns at a high spatial frequency, whereas it affected performance less at low spatial frequencies. However, temporal integration properties cannot be estimated fully from their results because they used only limited range of presentation durations (between 10 and 110 ms).

In this study, we investigated the spatial frequency dependency of the effect of exposure duration for stereo acuity and then attempted to predict the results with temporal frequency characteristics of the sensitivity to stimuli with different spatial frequencies. We first measured disparity threshold for the depth discrimination varying stimulus presentation duration between 0.05 and 2 s. Stimuli were luminance gratings with variable spatial frequencies (0.23, 0.94 and 3.75 c/deg) and contrasts (1 and 0.05). We next examined whether the different temporal frequency characteristics for different spatial frequency stimuli predict the experimental results.

2. Experiments

Stimulus display consisted with four squares filled with sinusoidal gratings arranged in a 2 × 2 array with gaps to separate them (Fig. 2). The size of each square was 4.3 deg × 4.3 deg (128 × 128 pixels) and gap size was 0.3 deg (10 pixels) in visual angle. Phases of stimulus gratings were varied to provide disparity between the squares with square edges unchanged. 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 (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.[11] 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 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.

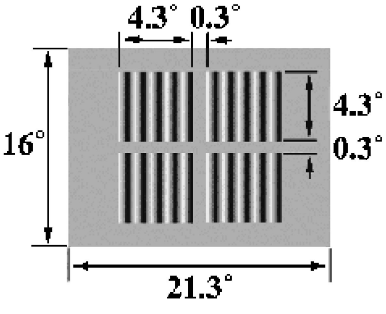


Fig. 2. The monocular image of experimental stimulus.

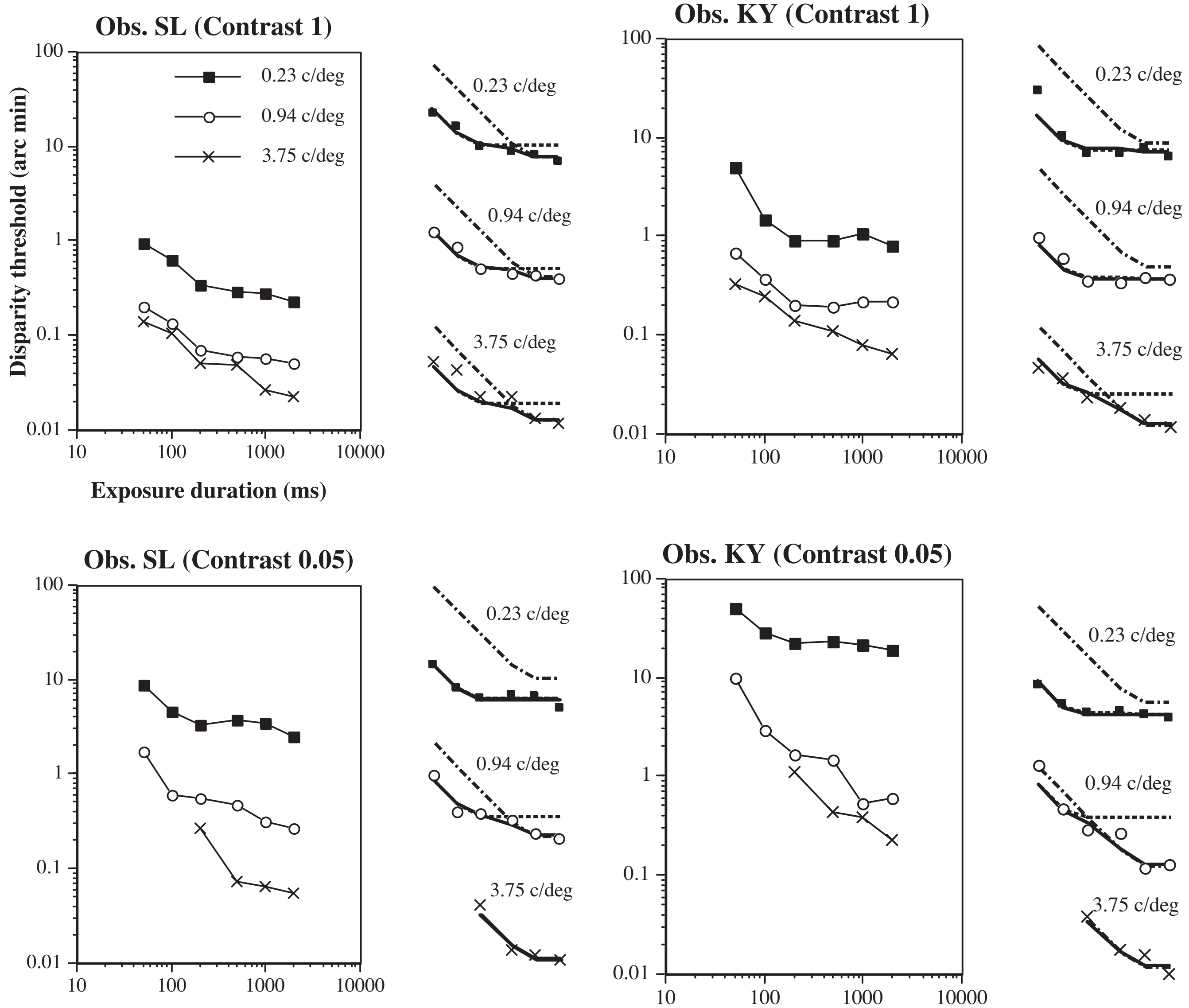
2.1 *Apparatus*

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 it was 0.5 cd/m^2 when viewed through the closed shutter. This light through the closed shutter changes the retinal disparity. Since our stimuli were sinusoidal gratings, the effect of the light from the closed shutter was easily estimated by adding two sinusoidal gratings, which was also a sinusoidal grating. Knowing the phase and amplitude of the grating through the closed shutter provided the net amplitude and phase on the retinal grating. The amount of the shift varied with disparity given (7.7% at maximum in the present measurements) and we used the values after compensation of the effect hereafter. Viewing distance was 82 cm, with which 1 pixel of the display corresponded to 2 arc min. 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, was used. Threshold disparity for depth detection was measured by a staircase procedure. A 2-up-1-down staircase procedure controlled stimulus disparity, 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. Observers received no feedback concerning the validity of their response.

Three spatial frequencies (0.23, 0.94 and 3.75 c/deg) and two stimulus contrasts (0.05 and 1) were used. The stimulus exposure duration varied between 0.05 and 2 s and gratings were stationary during the exposure. Two observers, the first author (SL) and a naive observer (KY), participated in the experiment. Both observers had corrected to normal visual



(a)

(b)

Fig. 3. Disparity threshold as a function of exposure duration for each spatial frequency stimulus. Solid lines in the right side figures show the approximation by a two-channel model with a two-line function. The dashed lines and one-dot-dashed lines show the two functions for each approximation (see text). Results with different spatial frequencies are plotted in the same panel for each contrast condition for observer SL (a) and for KY (b).

acuity, normal stereopsis and no history of any visual disorders. Each observer ran two sessions in each condition.

3. Results

Figure 3 shows disparity threshold as a function of exposure duration of the two observers, separately for different contrasts. Symbols represent the different spatial frequencies. The results showed that disparity threshold decreased with increase in exposure duration up to a certain duration, beyond which it was approximately constant or decreased only gradually (critical duration). Eye inspections tell the general tendency of the temporal integration property in each condition. For SL, the critical duration was shorter than 200 ms for low and middle spatial frequencies (0.23 and 0.94 c/deg) and it was longer than 700 ms for high spatial frequency (3.75 c/deg). The results of the other observer (KY) were similar except for the condition of the middle spatial frequency (0.94 c/deg) with low contrast (0.05). The critical duration in the condition of KY was rather similar to the one for the high spatial frequency stimulus (longer than 700 ms).

Close look of the data suggests that the situation is more complicated. The results in a couple of conditions (high frequency with contrast of 1 for SL and middle frequency with contrast of 0.05 for KY) are not consistent with the prediction with a single function. When exposure duration increased, disparity threshold became constant at about 200 ms once, and it decreased between 500 and 1,000 ms, beyond which it was constant again. Two functions with two different critical durations may be required to explain the results. Qualitative estimations of the results with a two-channel was made as described below.

A two-channel model assumes two channels with different temporal integrate properties obtained. First, we fit a two-line function to the data in high and low spatial frequencies with the contrast of 0.05. We assumed that the result in the high and low spatial frequency conditions reflected the temporal integration property of two channels with high and low spatial frequency tunings. The function consists of a line with slope of -1 and a line parallel to the x-axis. The intersection corresponds to the critical duration. Next, we used the two functions to predict results in the rest of conditions, assuming probability summation of the outputs of the two channels. To fit the two-line function at the first stage, a fixed slope of -1 was adopted. This is because conventional models of temporal integration predict the slope of -1 for shorter presentation durations. If stimulus energy is accumulated with time and threshold is determined by the total energy, threshold in terms of stimulus strength should be proportional with the inverse of presentation duration. Although this is not true when the summation is not perfect, we used -1 for simplicity. The use of the slope of -1 is not crucial in our analysis since estimations of critical duration showed similar difference among the conditions when the slope was varied as a fitting parameter. The reason why we used data in the low contrast conditions is because there is a better chance to have contribution of a single channel with the highest sensitivity in the condition to the threshold measurement.

After obtaining the two functions by a least square fitting, we predict the results in the other conditions also by a least square fitting with free parameters corresponding to the amounts of contributions of the two channels, assuming a probability summation as follows.

$$O(e_t) = ((S_1 \times C_1(e_t))^4 + (S_2 \times C_2(e_t))^4)^{1/4},$$

where, $O(e_t)$ is the output of the stereo system, $C_1(e_t)$ and $C_2(e_t)$ are the channel outputs, S_1 and S_2 are sensitivities of the channels in each condition that correspond to the amount of contribution of each channels, and e_t represents exposure duration. The threshold can be determined by setting a constant value of $O(e_t)$. Fitted functions predict the results well both in qualitatively and quantitatively as shown at the right side in each panel in Fig. 3.

The estimated critical duration for the high and low spatial frequency stimuli was 140 and 742 ms for SL and 125 and 746 ms for KY. The two line functions approximate the results well, and the model predicted the results for the other four conditions similarly well. Importantly, the model predicts the two-stage reduction of sensitivity for high frequency with contrast of 1 for SL and middle frequency with contrast of 0.05 for KY. These results indicate that the two-channel model successfully predicts the temporal integration properties in different spatial frequency and contrast conditions. The present analysis showed that the critical duration or temporal integration time was longer for higher spatial frequency stimuli. This suggests that the stereo mechanism sensitive to higher spatial frequencies is sensitive to lower temporal frequencies since lower temporal frequency tuning should provide longer temporal integration. In the next section, we examine whether the temporal frequency tuning function of disparity detection for high and low spatial frequency stimuli can predict the temporal integration properties obtained in the experiment.

4. Prediction from Temporal Frequency Characteristics

We attempted to explain the different spatial frequency dependency of temporal integration property (i.e., threshold change with exposure duration), assuming two underlying mechanisms with different temporal frequency tunings. Several studies have reported that change in stimulus spatial frequency varies temporal frequency tunings for detecting binocular depth.[8,12] This suggests that temporal integration property is also expected to vary with spatial frequency. For a linear system, temporal frequency characteristics predict outputs to arbitrarily chosen inputs. Although the visual system is not linear,[13] frequency analysis often predicts the experimental results at least at threshold.[14] In this section, we simulated temporal integration properties for different spatial frequency stimuli, assuming two channels with different temporal frequency tunings.

The present analysis used temporal frequency characteristics of observer SL, which were measured in a experiment previously reported with the same method and apparatus as in the present experiment.[15] In the experiment, temporal frequencies were varied by drifting gratings with a fixed exposure duration (1 sec) and a fixed contrast (0.05), and stereo acuity was measured as in the present experiment. Figure 4 shows the temporal frequency dependency of disparity threshold for spatial frequencies of 0.23 and 3.75 c/deg. We assumed that these functions represented temporal frequency tunings of the assumed two channels for stereopsis. Although we do not think this use of temporal frequency characteristics measured for 0.23 and 3.75 c/deg is the best for our purpose, we chose this method as first approximation, following the successful use of temporal

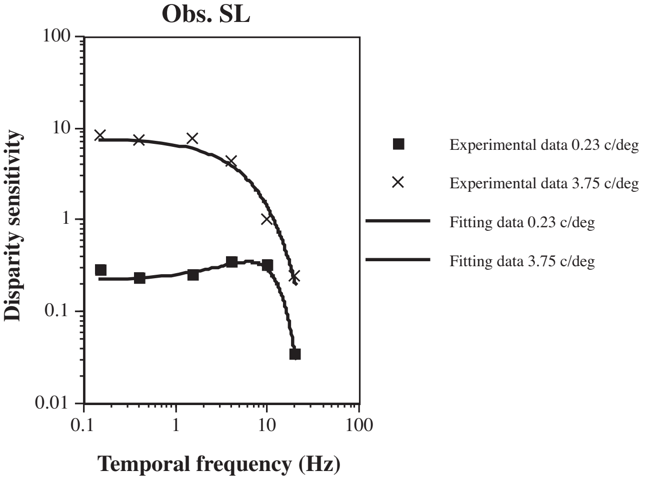


Fig. 4. Disparity threshold as a function of temporal frequencies for two spatial frequencies with a contrast of 0.05. (S. Lee, S. Shioiri and H. Yaguchi: Opt. Rev. **10** (2003) 120.)

integration properties of 0.23 and 3.75 c/deg with contrast of 0.05 for predicting the other conditions. For the use in the analysis, a Gaussian function approximated the temporal frequency function, F_{f_x}, for a given spatial frequency of f_x, as follows.

$$F_{f_x}(f_t) = \exp\left(-\frac{(f_t - \mu_{f_x})^2}{2{\sigma_{f_x}}^2}\right),$$

where f_t is temporal frequency, μ_{f_x} is the temporal frequency with the highest stereo acuity (minimum disparity threshold) and σ_{f_x} is the bandwidth of frequency tuning. Solid curves in Fig. 4 indicates the Gaussian functions approximated the results by a least square method.

Prediction started with calculation of the output of each channel to stimuli with different exposure duration. We used the approximated temporal frequency tuning functions as filters and calculated the output of the filters to the stimulation in frequency domain. To estimate the total amount of the output to stimulation with each presentation duration, the output at each frequencies was summed between 0.25 Hz and 50 Hz. We set the highest frequency of 50 Hz because the filter outputs at frequencies higher than 50 Hz were virtually zero. We set the lowest frequency because we had no information for temporal frequency lower than that and we do not think temporal integration continues forever (including lower temporal frequency results the longer integration duration and integration continues forever if there is no low frequency cutoff).

Figure 5 shows the temporal integration properties calculated for two spatial frequencies of 0.23 and 3.75 c/deg with the low contrast. In both cases, disparity threshold decreases with a slope of about -1 with short exposure durations and the threshold approaches to a constant value with longer durations. Estimating critical durations with a two-line function as for experimental results (one with a slope of -1 and the other parallel to the x-axis) revealed that it was 87 and 1,187 ms for low and high spatial frequency stimuli. The model predicts different critical durations for two spatial frequency stimuli. Critical duration is shorter for low spatial frequency stimulus than for high spatial frequencies as experimental results showed. However, the value for low spatial frequency is too short and that for high spatial frequency is too long to explain the experimental results.

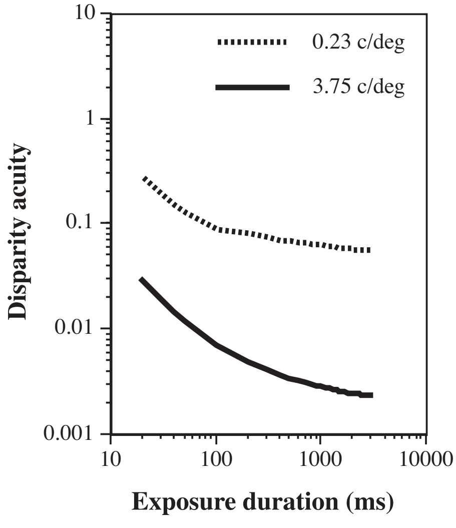


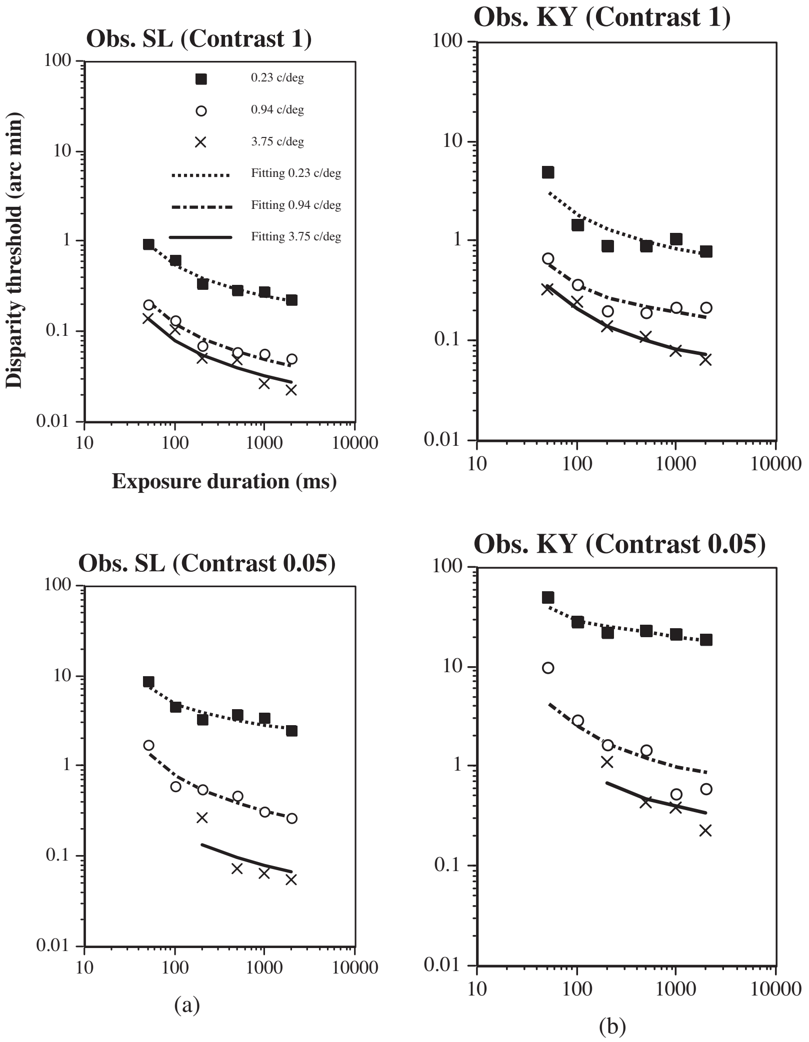
Fig. 5. Disparity threshold as a function of exposure duration obtained from the model simulation based on temporal frequency tunings shown in Fig. 3 for low and high spatial frequencies (0.23 and 3.75 c/deg).

We predicted the experimental results from the outputs of the two channels, assuming probability summation. The equation of probability summation same as that used for experimental results in the previous section was used and a least square method sought the sensitivity parameters, S_1 and S_2, for the best fit. Figure 6 shows the predictions for three spatial frequencies for the two observers. The temporal frequency tunings obtained from observer SL are also used for predicting the results of observer KY. The simulation predicts basic features of the temporal integration property in the experimental data. Although the model predicts general tendency that threshold decreases with exposure duration quickly at short durations and approached to a constant at long durations, the model cannot predict the two-stage reduction of threshold shown in the results (e.g., 3.75 c/deg with contrast 1 for SL). This indicates that the prediction is not satisfactory. Since we can predict results much better when we use temporal integration property obtained in the experiment (Fig. 3), the problem of the prediction is likely due to the unsuccessful prediction of temporal integration property from temporal frequency tuning functions. One possible problem of the prediction is that our simulation is in disparity scale. Contrast sensitivity may be a better measure to characterize temporal frequency tuning for general purpose, although the relationship between the contrast threshold and disparity threshold is required to predict disparity threshold.[16,17] Another problem might be caused by that we used the temporal frequency characteristics for 0.23 and 3.75 c/deg stimuli. More than one mechanisms may contribute threshold measurements for each of the stimuli. We expect that careful consideration of the temporal frequency tuning of each spatial frequency channel will results better prediction.

5. Discussion

We investigated the effect of stimulus exposure duration on stereo acuity, measuring disparity threshold. The results showed that the dependency of disparity threshold on exposure duration were different among different spatial frequency and contrast conditions. Threshold decreased (sensitivity increased) with increase in duration quickly at short durations and then became approximately constant, or decrease only gradually, beyond a certain duration. This was true for all spatial frequencies, while the critical duration estimated was about 150 ms for low spatial frequency stimuli and about 750 ms for high spatial frequency stimuli.

The difference in temporal integration property for different spatial frequency stimuli suggests that different underlying mechanisms with different temporal frequency tunings contribute to stereo acuity. The results suggest, furthermore, that a mechanism or channel sensitive to high spatial



(a)

(b)

Fig. 6. Comparison of the experimental results and the model simulation curves for observer SL (a) and for KY (b).

frequencies is sensitive to low temporal frequencies, and one sensitive to low spatial frequencies is sensitive to high temporal frequencies.[6] We showed that two channels with different temporal integration properties could predict the results well.

The present results also showed that disparity and spatial frequency or sizes of stimulus are closely related. Disparity threshold was higher for lower spatial frequency stimulus (compare the three curves in each panel of Fig. 3), which is referred as the so-called size-disparity correlation.[18,19] This was true for long durations of both contrasts. This supports the notion that the channel sensitive to low spatial frequency is sensitive to large disparities and the one sensitive to high frequency is sensitive to small disparities (that is, channels with different spatiotemporal frequency tunings have different disparity tunings). Although the present results give no information of the number of channels, two channels for stereopsis have been estimated by masking experiments.[10,11] There are two reports of spatial frequency masking experiments, both of which suggest that the stereo mechanism have two spatial frequency channels. The peak sensitivities of the channels in the reports are either 1.5 and 3 c/deg or 3 and 5 c/deg, but it is not clear how these channels might relate to the two channels discussed here. Our attempt to predict temporal integration properties from temporal frequency tuning functions for low and high spatial frequency stimuli did not provide quantitatively satisfactory results. Further investigation of spatiotemporal property of channels for stereopsis is necessary to build a model for stereopsis that predicts human depth perception to any given retinal stimulation, including the effect of presentation duration.

References

1) N. M. S. Langlands: Trans. Opt. Soc. **28** (1926) 45.
2) N. M. S. Langlands: Med. Res. Counc. Spec. Rep. Ser., No. 133 (1929).
3) K. N. Ogle and M. P. Weil: Arch. Ophthal. **59** (1958) p. 4.
4) R. S. Harwerth and S. C. Rawlings: Am. J. Optom. & Physiol. Opt. **54** (1977) 452.
5) R. S. Harwerth and R. L. Boltz: Vision Res. **19** (1979) 985.
6) R. J. Watt: J. Opt. Soc. Am. A **4** (1987) 2006.
7) K. I. Beverly and D. Regan: Vision Res. **14** (1974) 357.
8) R. Patterson: Am. Acad. Optom. **67** (1990) 123.
9) S. Shioiri: *Handbook of Visual Information Process*, ed. The Vision Society of Japan (Asakura, Tokyo, 2000) Chap. 7. 2., p. 299 [in

Japanese].
10) Y. Yang and R. Blake: Vision Res. **31** (1991) 1177.
11) S. Shioiri, T. Hatori and H. Yaguchi: Opt. Rev. **1** (1994) 311.
12) S. Shioiri, A. Morinaga and H. Yaguchi: *Video and Display Technologies* (Springer, Berlin, 2002) p. 397.
13) e.g. S. Shioiri and P. Cavanagh: Percept. & Psychophys. **62** (2000) 1182.
14) e.g. S. Shioiri and P. Cavanagh: Vision Res. **30** (1990) 757.
15) S. Lee, S. Shioiri and H. Yaguchi: Opt. Rev. **10** (2003) 120.
16) S. Shioiri, H. Ono and T. Sato: J. Opt. Soc. Am. A Image Sci. Vis. **19** (2002) 1465.
17) S. Shioiri, S. Ito, K. Sakurai and T. Sato: J. Opt. Soc. Am. A, **19** (2002) 2169.
18) H. S. Smallman and D. I. A. MacLeod: J. Opt. Soc. Am. **11** (1994) 2169.
19) M. Minematsu, S. Shioiri and H. Yaguchi: Proc. 5th Int. Conf. High Technology, 1996, p. 411.
20) G. K. Shortness and J. Krauskopf: J. Opt. Soc. Am. **51** (1961) 555.
21) J. M. Forley and C. W. Tyler: Percept. & Psychophys. **20** (1976) 125.
22) C. W. Tyler: *Binocular Vision*, ed. D. Regan (MacMillan, Ontario, 1991) Vol. 9, Chap. 3, p. 38.