Available online at www.sciencedirect.com

SCIENCE DIRECT®

Vision Research 46 (2006) 2749–2756

Vision Research

www.elsevier.com/locate/visres

Vertical-size disparities are temporally integrated for slant perception

Kazuho Fukuda [a,*], Hirohiko Kaneko [a], Kazumichi Matsumiya [b]

[a] *Imaging Science and Engineering Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Kanagawa 226-8503, Japan*
[b] *Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan*

Received 1 November 2005; received in revised form 27 January 2006

Abstract

We investigated temporal properties of vertical-size and horizontal-size disparity processing for slant perception. Subjects indicated perceived slants for a stereoscopic stimulus in which the two magnitudes of vertical-size or horizontal-size disparities were oscillated stepwise with various frequencies (from 0.2 to 10 Hz). For the stimulus with vertical-size disparity oscillation, two slants corresponding to the two magnitudes of disparity were perceived for low-frequency conditions, whereas only a static mean slant of the two slants was perceived for high frequencies (5 and 10 Hz). For the stimulus with horizontal-size disparity oscillation, two slants were perceived for all the temporal frequency conditions. These results indicate that temporal properties of vertical- and horizontal-size disparity processing are clearly different and vertical-size disparities are temporally integrated over a period of around 500 ms for slant perception.

Keywords: Vertical disparity; Slant perception; Induced effect; Temporal property; Temporal integration

1. Introduction

When observing a stereoscopic image presented on a front-parallel plane with vertical magnification of a half image for one eye relative to the other, you perceive a surface slanted about the vertical axis. This effect is called "the induced effect" (Ogle, 1938, 1964) and is interesting because the perception produced by this disparity pattern, vertical-size disparity, cannot be predicted from the geometry of the situation. When observing a stereoscopic image with horizontal-size disparity, you also perceive a surface slanted about the vertical axis. This effect is called "the geometric effect" (Ogle, 1938, 1964) because it is predictable from the geometry of the situation.

The value of vertical-size disparity depends on the coordinate system to define disparity. For example, in the Helmholtz's coordinate system, vertical-size disparity produced by a vertical line on a front-parallel plane is zero regardless of the eccentricity (Erkelens & van Ee, 1998) but in the Fick coordinate system, that is zero at straight ahead but changes as a function of the eccentricity (Gillam & Lawergren, 1983). Manipulating the vertical-size of stereoscopic images presented on a front-parallel screen has a direct relation to the vertical-size disparity defined in the Helmholtz coordinate system.

Although vertical-size and horizontal-size disparities both produce the perception of a slanted surface, there are several differences between the properties of these disparity processes for slant perception. One difference is that the range of vertical-size disparity that produces perceived slant is smaller than that of horizontal-size disparity. The linear relation between the magnitude of perceived slant and that of horizontal-size disparity is evident over a wide range of size disparities, but the linear relation between the magnitude of perceived slant and that of vertical-size disparity is limited up to about 3% of the size-disparity (Banks & Backus, 1998; Ogle, 1938). Another important difference is in spatial properties, as explained below. These differences engender the idea that the induced and geometric effects are based on different mechanisms.

* Corresponding author. Fax: +81 45 924 5293.
E-mail address: fukuda@isl.titech.ac.jp (K. Fukuda).

0042-6989/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2006.02.016

It has been reported that vertical disparities are spatially pooled for the perception of surface slant, but horizontal disparities are not. More precisely, the magnitude of perceived slant from vertical disparity depends on the integrated or averaged value of the disparities over a global area, but that from horizontal disparity fundamentally depends on the magnitude of the disparity at each local area (Adams, Frisby, Buckley, & Garding, 1996; Kaneko & Howard, 1996, 1997; Stenton, Frisby, & Mayhew, 1984). This difference in disparity processing is consistent with some empirical observations. For example, horizontal-size disparity produces a slant perception regardless of the stimulus size, whereas vertical-size disparity produces a small magnitude of slant perception for small stimuli (Backus, Banks, van Ee, & Crowell, 1999; Kaneko & Howard, 1996; Rogers & Bradshaw, 1993). In addition, the magnitude of perceived slant from horizontal-size disparity is either independent of or only slightly increased by a surrounding stimulus having zero disparity, whereas that from vertical-size disparity is reduced severely when presented with the surrounding stimulus (Kaneko & Howard, 1996; van Ee & Erkelens, 1995).

Regarding temporal properties of horizontal-size and vertical-size disparities, clear differences in them have not been shown, but only few studies have investigated this issue (Allison, Howard, Rogers, & Bridge, 1998; van Ee & Erkelens, 1996a, 1998). For example, Allison et al. (1998) presented stimuli with the horizontal-size or vertical-size disparity oscillating at up to 1.8 Hz, and measured changes in perceived slant. Their results showed no difference between the temporal properties of these disparity processes.

The present study also investigated temporal properties of vertical-size and horizontal-size disparities processes for slant perception because we thought that some differences of these properties would be apparent at a higher temporal frequency than that in the experiment of Allison et al. (1998). The differences in temporal properties were expected by the idea that the processes for horizontal-size and vertical-size disparities are based on different mechanisms. Moreover, in our unpublished preliminary experiment, subjects took a longer duration to perceive a slant for vertical-size disparity than for horizontal-size disparity. The methods we used here were similar to those used in the Allison's experiment, but the maximum frequency of disparity oscillations was extended up to 10 Hz. In Experiment 1 of this study, we measured the magnitude of slant perception produced by the stimulus with vertical-size or horizontal-size disparity oscillating stepwise at various frequencies. Thereby, we compared the temporal properties between these disparities. We analyzed the results in terms of temporal integration for disparities, which is analogous to the spatial integration found in vertical disparity processing (Adams et al., 1996; Kaneko & Howard, 1996, 1997; Stenton et al., 1984).

2. Experiment 1

2.1. Methods

2.1.1. Stimuli

Stimuli consisted of 2000 randomly positioned white dots on a black background with a circular shape that was 40 deg in diameter. Random dot stereogram with circular shape has relatively weak perspective cues for slant perception (Banks & Backus, 1998). Maximum luminance of each dot was 41 cd/m^2 at the center. Sub-pixel interpolation was employed to reduce the aliasing effects from the finite pixel size. Each dot had a Gaussian luminance distribution; the standard deviation of the distribution was 6.25 min of arc.

Vertical-size or horizontal-size disparity of the stimulus was manipulated over time. The images for right eye and left eye were, respectively, expanded and shrank along a direction with a same percentage relative to the original image in order to keep the average stimulus size approximately constant. The magnitude of size disparity was the sum of the percentage of size changes in both eyes' images, and the sign was positive when the image for right eye was larger than that for left eye. For example, when the magnitude of size disparity was +8%, the right and left eye images were expanded and shrank 4% relative to the original image, respectively. In Experiment 1, the magnitude of size disparity alternated stepwise between +2% and +8% (or −2% and −8%) at the same duty ratio. Each dot's position shifted according to the expansion and shrinkage of the images, but each dot's shape did not change.

2.1.2. Apparatus

Visual stimuli were generated by a computer (Macintosh Power Mac G4; Apple Computer Inc.) and presented stereoscopically using a Wheatstone stereoscope. The stereoscope consisted of two sets of a CRT monitor (GDM-520F; Sony Corp.) and a mirror, one for each eye. The decay times of the phosphors on the CRT were 0.59 ms (red), 0.08 ms (green), and 0.12 ms (blue), from the peak luminance to 10% of the peak. We confirmed that subjects did not perceive any color due to the delay of the decay of red phosphor. It took 1 ms or less for the luminance of a white dot to decay from the peak to 1% of the peak, which was sufficiently fast for the present experiment. The display area was 40×30 cm and comprised 1280×1024 pixels. Subjects perceived a fused stimulus 40 cm straight ahead at eye level. A head and chin rest was used to fix the position of the head and therefore the positions of the eyes. The stereoscope was placed in a darkened room so that the subjects could see only the stimuli on the display.

Subjects used an unseen manual paddle to indicate perceived slant about the vertical axis of the stimulus. The paddle was placed 40 cm ahead of the subject the same distance as the stimulus. The response, the angle of the manual paddle, was measured using a potentiometer attached to the axis of the paddle, and recorded using a computer through an AD converter.

2.1.3. Procedure

Subjects were instructed to indicate the maximum and minimum perceived slants for each presentation of the stimulus. This method was sufficient to measure the amplitude and absolute magnitude of the perceived slant, and to know whether the subjects perceived two separate slants or one static slant for the disparity oscillation. The time of observation was unlimited. Each session consisted of 20 or 24 conditions (two disparity types; vertical-size or horizontal-size disparity, five or six temporal frequencies; 0.2, 0.5, 1.0, 2.0, 5.0 or 10 Hz, and sign of disparity value; positive or negative). The stimulus with temporal frequency of 10 Hz was presented to two subjects. Each condition was presented randomly in a session. Each session was repeated four times for each subject. Four subjects participated in this experiment. They had normal or corrected-to-normal visual acuity and perceived the stereoscopic slant, as reported in previous studies (e.g., Ogle, 1938), for both the static stimuli with vertical-size disparity and that with horizontal-size disparity presented for 100 ms, which is short enough to avoid eye movements (van Ee & Richards, 2002).

2.1.4. Predictions

We expect three types of results assuming three types of disparity processing for slant perception (Fig. 1). First, subjects might perceive two slants corresponding to the disparities presented in the stimulus regardless of temporal frequency of the disparity oscillation if disparities are processed immediately (Fig. 1A). Second, they might perceive a static and intermediate slant for the stimulus with high temporal frequency if disparities are integrated within a long duration (Fig. 1B). Third, if oscillating disparities with high temporal frequency are uninformative for slant perception, subjects might perceive a frontal plane from the other slant cues (Fig. 1C).

2.2. Results

We averaged the results for the positive and negative disparity conditions with the sign of the slant inverted because they showed the same tendency. An offset of slant responses was subtracted from each measured angle before the averaging. The offset was estimated with the stimulus having zero disparity for each subject, and was 3.2 deg or less. The sign of the perceived slant for horizontal-size disparity was positive when the direction of the slant corresponded to the theoretical direction, and was negative in the case of slant reversals (Gillam, 1968). For example, the sign was positive when a left-near slant was perceived for the stimulus with positive horizontal-size disparity (right eye's image is larger). For vertical disparity, the sign was defined as positive when a right-near slant was perceived for the stimulus with positive vertical-size disparity because the direction of perceived slant in the induced effect is known to be opposite that in the geometric effect when the signs of size disparity are identical (Ogle, 1938, 1964).

Fig. 2 shows perceived slants for horizontal-size or vertical-size disparity oscillation with various temporal frequencies. The results for the two types of size disparity differ markedly. For stimuli with horizontal-size disparity oscillation, the difference between two measurements of perceived slants (maximum and minimum slants) remained constant as the temporal frequency increased to 10 Hz. The subjects perceived two alternating slants, each corresponding to one magnitude of disparity presented in the stimulus for all temporal frequency conditions. For stimuli with vertical-size disparity oscillation, the difference between the two measurements also remained up to about 1 Hz, but then decreased and finally converged at high frequencies. The magnitude of the perceived slant at high frequencies was about the same as the mean of the extreme slants perceived for the stimuli with lower frequencies. These results for stimuli with vertical-size disparity indicate that the subjects perceived two alternating slants produced by each of two alternating disparities in the lower frequency conditions and that they perceived only one static slant depending on the averaged disparity in the higher frequency

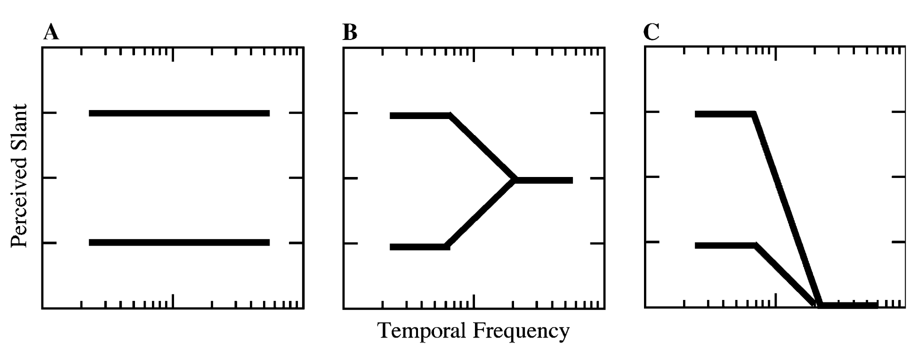

Fig. 1. Three kinds of prediction for the result of Experiment 1. (A–C) Predicted results for Experiment 1 based on three assumptions concerning disparity processing; (A) disparities are processed immediately for slant perception, (B) they are temporally integrated over a long period, and (C) they are uninformative when oscillating with high temporal frequency. The abscissa and the ordinate, respectively, indicate temporal frequency and perceived slant.

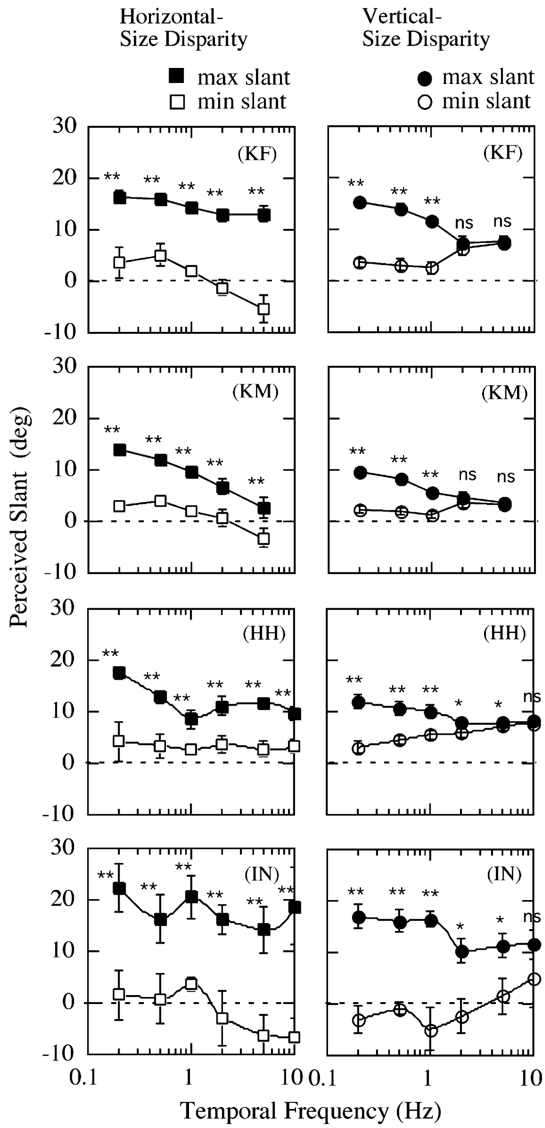

Fig. 2. Perceived slants for the stimulus with vertical-size or horizontal-size disparity oscillating in time (Section 2.2). The left and right panels, respectively, show individual results for horizontal-size and vertical-size disparity. The abscissa indicates the temporal frequency of disparity oscillation and the ordinate indicates perceived slants. Solid and open symbols, respectively, represent the perceived maximum and minimum slants indicated with the manual paddle for each condition. Shapes of the symbols, square and circle, respectively, indicate the results of horizontal-size and vertical-size disparities. Error bars indicate the standard errors of the means. Asterisks and the mark of ns indicate the significance levels regarding the differences between the two measurements of perceived slants (maximum and minimum slants) at each temporal frequency tested by Tukey's WSD post hoc test (* $P < 0.05$, ** $P < 0.01$, ns $P > 0.05$). In the case of the horizontal-size disparity condition for subject IN, these marks indicate main effect of the two slants by a two-way ANOVA because it showed no interaction.

condition. These results for vertical-size disparity are explainable by assuming that vertical-size disparities are temporally integrated over a longer period than are horizontal-size disparities.

We performed two-way ANOVAs separately for each subject to examine the effects of temporal frequencies and the two measurements (maximum and minimum slants) on the magnitudes of perceived slant. For horizontal-size disparity conditions, the main effects of the two measurements were significant for all subjects ($P < 0.01$), and those of temporal frequencies were significant for two subjects ($P < 0.01$ for KF and KM, $P > 0.05$ for HH and IN). The interactions between them were significant except for subject IN ($P > 0.05$ for IN, $P < 0.01$ for the others). For each temporal frequency condition, the differences between the two measurements were tested by Tukey's WSD post hoc test, and were significant for all of the conditions (** $P < 0.01$). For the vertical-size disparity condition, the main effects of the two measurements were significant for all subjects ($P < 0.01$), but the effects of temporal frequencies were significant only for subject KM ($P < 0.05$ for KM, $P > 0.05$ for the others). The interactions between them were significant for all subjects ($P < 0.01$). Tukey's post hoc test showed that the differences between the two measurements were significant at low frequencies (** $P < 0.01$, * $P < 0.05$), but were not significant at the highest temporal frequency (ns $P > 0.05$) for all subjects.

2.2.1. Binocular mismatching

Unintended disparity detections could also explain the present results, the perception of a static slant at high frequencies, for vertical-size disparity oscillation. First, there might be binocular mismatching across frames. Second, there might be monocular averaging of a dot position across frames before binocular matching. In these cases, the temporal changes of disparity magnitude would become smaller than that in the case of expected binocular matching. However, the same argument would apply to horizontal disparities. The present results for horizontal-size disparity oscillation, the perception of slant oscillation even at high frequencies, deny these possibilities of unintended disparity detections mentioned above. In addition, we redid the Experiment 1 using a dynamic random dot stereogram; the dot arrangement was refreshed whenever the magnitude of disparity changed to avoid the unintended disparity detections. The result (Fig. 3) showed the same tendency to that of Experiment 1 (Fig. 2) in which the dot arrangement was stable, and ensured our claim that the results in Experiment 1 were due to a temporal integration of vertical-size disparities over a longer period than are horizontal-size disparities.

2.2.2. Estimation of the integration period

We estimated the period over which vertical-size disparities are integrated for slant perception, based on a simple convolution integral of the disparity, which is formulated as the following equation.

$$S(t_0) = \int_{t_0}^{t_0 - T} [k \times D(t)]\, dt. \qquad (1)$$

This equation shows perceived slant $S(t_0)$ at time t_0. Therein, t and t_0 indicate time, k is a coefficient to

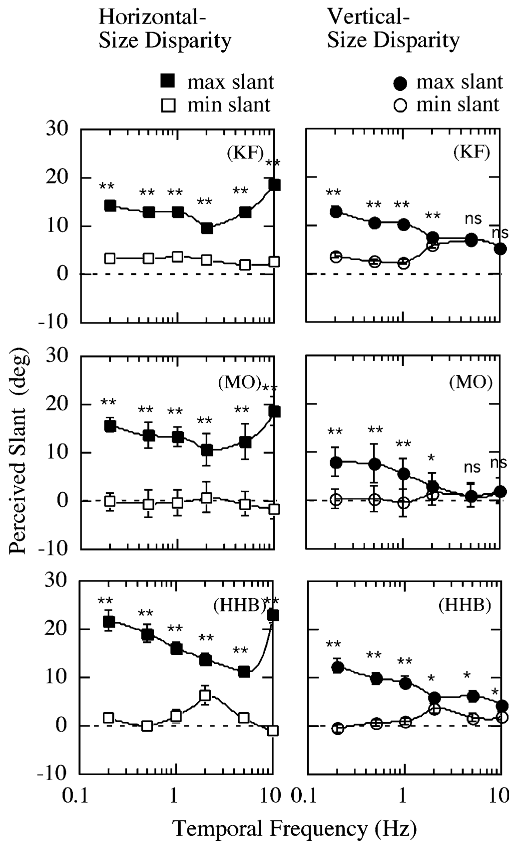

Fig. 3. Perceived slants for the dynamic random dot stimulus with disparity oscillation in time. Conventions of this figure are the same as those for Fig. 2. In this experiment, the dot arrangement was refreshed whenever the magnitude of disparity changed. MO and HHB were new subjects having corrected normal or corrected-to-normal visual acuity, and were confirmed to perceive stereoscopic slants.

transform disparity into perceived slant, T is the period of integration, $D(t)$ is the magnitude of disparity presented at time t, being represented by the following equation for the stimulus in Experiment 1 when the two magnitudes of vertical-size disparity is represented by D_a and D_b.

$$D(t) = \begin{cases} D_a\left(t_0 - \frac{n}{f} < t \leqslant t_0 - \frac{n-\frac{1}{2}}{f}\right) \\ D_b\left(t_0 - \frac{n-\frac{1}{2}}{f} < t \leqslant t_0 - \frac{n-1}{f}\right) \end{cases}. \quad (2)$$

Therein, f represents the frequency of disparity oscillation, and n shows arbitrary natural number. For the stimulus arrangement in Experiment 1, $S(t_0)$ is maximal when D_a and D_b, respectively, are 2% and 8%, and is minimal when D_a and D_b, respectively, are 8% and 2%. In our estimation, the value of $[k \times D(t)]$ was replaced with each mean of the extreme slants perceived for the stimuli with lower frequencies up to 1.0 Hz in Experiment 1. Specifically $[k \times 2\%]$ was the mean of the minimum slants perceived at conditions of 0.2, 0.5, and 1.0 Hz, and $[k \times 8\%]$ was the mean of the maximum slants perceived at those conditions. We calculated the maximum and minimum values of $S(t_0)$ as a function of frequency for various T using this formula, and compared those values with the Experimental data (Figs. 2 and 3). Then we determined the optimal T, which minimizes the mean square error between the theoretical and experimental results. Estimated periods of integration for each subject and the mean data are around 500 ms, as shown in Table 1.

Table 1
Integration periods of vertical-size disparity for each subject estimated using the experimental data in Fig. 2 for the static random dot stereogram (RDS) and that in Fig. 3 for the dynamic random dot stereogram (DRDS)

Stimuli	Subject	Integration period (ms)
RDS	KF	554
	KM	581
	HH	627
	IN	287
DRDS	KF	537
	MO	573
	HHB	541

3. Experiment 2

3.1. Purpose

We attributed the result of Experiment 1 to the mechanism of temporal integration for vertical disparities, but the result was explainable by the mechanism of spatial integration for the disparities (Adams et al., 1996; Kaneko & Howard, 1996; Stenton et al., 1984). In Experiment 1, each of the two different magnitudes of size disparity has presented with blanks one after the other. If the blanks were interpolated, the two magnitudes of disparity would be registered continuously, and spatial integration of the disparities should produce a perception of a static slant corresponding to the averaged magnitudes. In this experiment, we manipulated the duty ratio of the disparity oscillation in order to confirm which explanation, temporal or spatial integration, adequate for the result in Experiment 1. Temporal integration predicts that the perceived slant is dependent on the duty ration, whereas spatial integration predicts that the slant is independent of the duty ratio because two magnitudes of disparity were spatially equivalent.

3.2. Methods

We set Experiment 2 to test predictions from the spatial and temporal integration mechanisms to explain the present results by manipulating the duty ratio of disparity oscillation. The other settings were the same as those of Experiment 1. The temporal oscillation of disparity was kept constant at 5 Hz, for which all subjects reported perceiving one static slant in preliminary observations. The magnitudes of the alternating size disparity were 2% and 6%. The duty ratio of disparity oscillation was defined as the percentage of the duration of 6% vertical-size disparity within one period of disparity oscillation (Fig. 4), and was 0, 16, 25, 33, 42, 50, 58, 67, 75, 83, or 100% (42% and 58% only for subjects HH and IN). Subjects adjusted the slant of the manual paddle

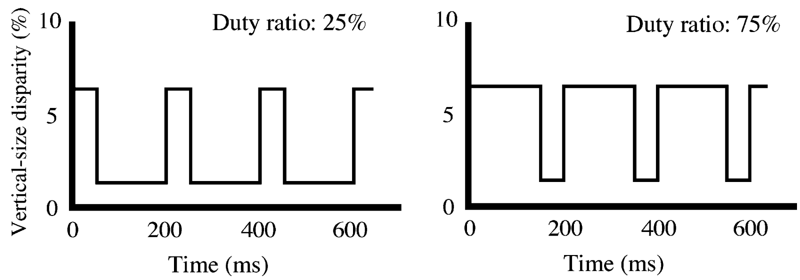

Fig. 4. Schematic representation of disparity oscillation in Experiment 2. Two magnitudes (2% and 6%) of vertical size disparity alternated with 5 Hz. The duty ratio, defined as the percentage of the duration of 6% vertical-size disparity within one period (200 ms), was the variable.

to the slant they perceived. Five subjects participated in this experiment. Four of them had also participated in Experiment 1. The other subject, HK, was confirmed to perceive stereoscopic slants as the other subjects did.

3.3. Results

Fig. 5 shows perceived slant as a function of the duty ratio. The signs of the perceived slant were determined as in Experiment 1. The solid line shows a linear regression to the data from 16% to 83% duty ratios. The dashed line shows the prediction based on the theory of temporal integration of vertical-size disparity.

The results show that the magnitude of the perceived slant is dependent on the duty ratio. The slope of the solid line is close to that of the dashed line. The difference between these slopes is 3% (SE/ST = 1.03) for the mean data among five subjects and that does not differ by as much as 40% for each subject. This effect of duty ratio on perceived slant is the temporal analog to previous observations in the spatial domain (Adams et al., 1996; Kaneko & Howard, 1996; Stenton et al., 1984) and supports the hypothesis of temporal integration, and cannot be explained using the notion of spatial integration.

4. General discussions

Most subjects perceived a static slant for the stimulus with vertical-size disparity oscillation of temporal frequencies higher than 1-5 Hz. Moreover, the magnitude of the

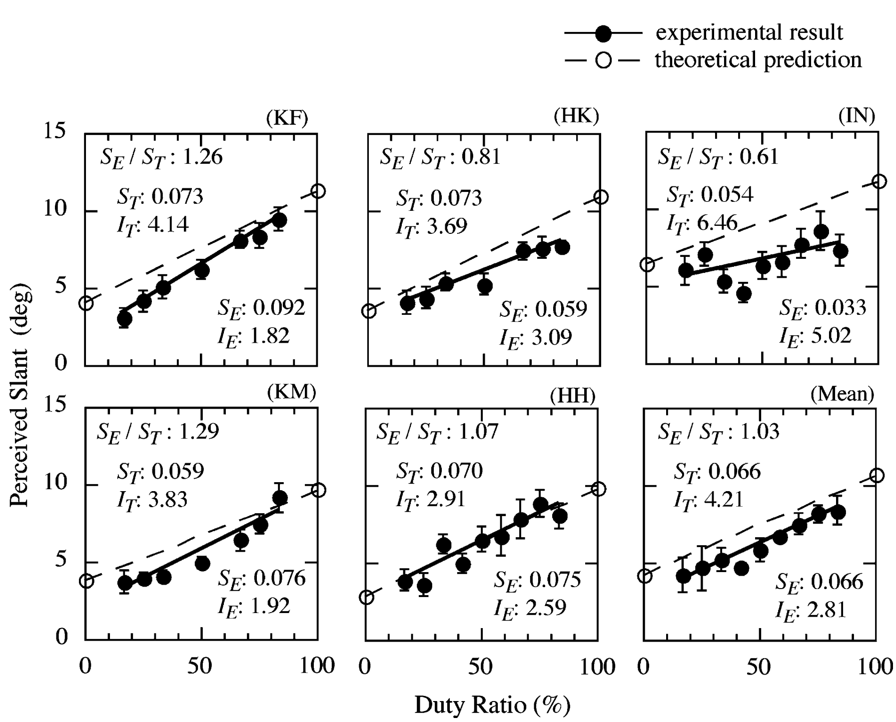

Fig. 5. Effect of the duty ratio of the vertical-size disparity oscillation on the perceived slant (Section 3.3) The upper and lower two (left and center) panels show individual results and the lower right panel shows averaged result across five subjects. The abscissa indicates the duty ratio of the vertical-size disparity oscillation and the ordinate indicates perceived slant. Error bars in the panels for respective subjects indicate the standard errors of the means, and that for the mean indicates the standard deviation. The solid line is a linear regression of data from 16% to 83% of the duty ratio. The dashed line connects two data for 0% and 100% of the duty ratio. S and I represent slopes and intercepts of the linear regressions for the experimental results (S_E, I_E, solid lines) and for the theoretical results (S_T, I_T, dashed lines).

static slant was almost equal to the mean of the maximum and minimum perceived slants for the stimuli with low frequencies (from 0.2 to 1.0 Hz). From these results and the integral model (formulae 1 and 2), we conclude that vertical-size disparities are temporally integrated over a period of around 500 ms for slant perception. A previous study (Allison et al., 1998) showed no difference between the temporal properties of vertical-size and horizontal-size disparities for slant perceptions up to 1.8 Hz of disparity oscillation, but our results demonstrate that a significant difference exists between those for stimuli when the oscillation rate is higher than 2 Hz of disparity oscillation.

For the stimulus with oscillating horizontal-size disparity, the subjects perceived two separate slants for all temporal frequency up to 10 Hz, the highest we tested. This result indicates that horizontal-size disparities are temporally integrated over a much shorter period. Some subjects perceived opposite slants to the geometrical prediction from the horizontal-size disparity. This type of slant reversal was reported in precedent studies (e.g., Allison et al., 1998; Gillam, 1968), and has been explained by cue conflict between disparity-cue and other depth cues (Gillam, 1968; Ryan & Gillam, 1994). Constant size and uniform and large density of dots in our stimulus might affect the slant reversal as conflicting cues to disparity. Otherwise, individual difference in whether slant reversal was perceived might correlate with the stereo capacity of the subject. We tested this possibility by a stereoanomaly test for both of crossed and uncrossed disparities (van Ee & Richards, 2002; van Ee, 2003). But, all of our subjects were classified into stereonormal. We cannot pursue this argument further because it is beyond the scope of this report, but this issue is worth investigating in greater detail.

Previous computational studies have suggested that vertical-size disparity would work as an eye-position signal because the magnitude of vertical-size disparity depends on the gaze direction for a given distance in a real scene (Backus et al., 1999; Erkelens & van Ee, 1998; Mayhew & Longuet-Higgins, 1982). Some psychophysical studies have shown that perceptual scaling effects produced by vertical-size disparity are generally consistent with predictions (e.g., Ogle, 1938; Rogers & Bradshaw, 1993). Regarding the effect of vertical-size disparity on perceived eccentricity, Berends, van Ee, and Erkelens (2002) demonstrated that the adaptation to vertical-size disparity affected the straight-ahead perception, whereas Banks, Backus, and Banks (2002) showed that vertical-size disparity did not affect the perception of eccentricity.

We presume that the mechanism of temporal integration of vertical-size disparity over a certain period (around 500 ms) is efficient for extracting a stable signal of eye position because it can reduce the temporal noise in the signal. In real situation, a temporal alternation of vertical-size disparity on a fixed retinal area necessarily accompanies eye (or head-and-eye) rotations (Mayhew & Longuet-Higgins, 1982; van Ee & Erkelens, 1996b), so that its frequency is limited to a few times per second because of the frequency of saccadic eye movement (Yarbus, 1967). Therefore, the integrated or mean value of vertical-size disparities over the period of around 500 ms would be a suitable measure of eye position signal, but more studies are needed to confirm this relationship between eye movement and the integration mechanism of vertical-size disparity. Spatial integration of vertical-size disparities within a certain area, which has been shown in previous studies (Adams et al., 1996; Kaneko & Howard, 1996, 1997; Stenton et al., 1984), is also efficient for extracting a stable signal of eye position or eccentric gaze direction of an object.

Backus et al. (1999) investigated the effects of vertical disparity and eccentricity (eye position) on the perceived slant of a stereoscopically defined surface. Although the eccentricities indicated by the vertical-size disparities and that of the stimulus itself (straight ahead) were conflicting in our experiments, the contribution of eccentricity (eye position) to slant perception should be invalidated or reduced because our stimuli were sufficiently large to extract the validity of vertical disparity. Backus et al. (1999) reported that perceived slant was quite consistent with slant estimation by horizontal-size disparity and vertical-size disparity for large stimuli, but it was consistent with that by horizontal-size disparity and eccentricity for small stimuli. The temporal property of vertical-size disparity processing found in the present study could be different for small size of stimulus and further experiments using small stimulus presented at various eccentricities should be required for fully understanding the mechanism for slant perception in natural scene.

5. Conclusion

Measuring slant perception for stimuli with vertical-size and horizontal-size disparity oscillation, we found a difference in temporal properties in the processing of the two types of disparity. Vertical-size disparities are temporally integrated over longer intervals than horizontal-size disparities, and the integration period of vertical-size disparities is around 500 ms. This temporal property of vertical-size disparity processing can reduce noise in the eye position signal extracted from vertical-size disparities presented within a fixation in normal viewing.

References

Adams, W., Frisby, J. P., Buckley, D. B, & Garding, J. (1996). Pooling of vertical disparities by the human visual system. *Perception, 25*, 165–176.

Allison, R. S., Howard, I. P., Rogers, B. J., & Bridge, H. (1998). Temporal aspects of slant and inclination perception. *Perception, 27*, 1287–1304.

Backus, B. T, Banks, M. S., van Ee, R., & Crowell, J. A. (1999). Horizontal and vertical disparity, eye position, and stereoscopic slant perception. *Vision Research, 39*, 1143–1170.

Banks, M. S., & Backus, B. T. (1998). Extra-retinal and perspective cues cause the small range of the induced effect. *Vision Research, 38*, 187–194.

Banks, M. S., Backus, B. T., & Banks, R. S. (2002). Is vertical disparity used to determine azimuth? *Vision Research, 42*, 801–807.

Berends, E. M., van Ee, R., & Erkelens, C. J. (2002). Vertical disparity can alter perceived direction. *Vision Research, 31*, 1323–1333.

Erkelens, C. J., & van Ee, R. (1998). A computational model of depth perception based on headcentric disparity. *Vision Research, 38*, 2999–3018.

Gillam, B. J. (1968). Perception of slant when perspective and stereopsis conflict: Experiments with aniseikonic lenses. *Journal of Experimental Psychology, 78*(2), 299–305.

Gillam, B., & Lawergren, B. (1983). The induced effect, vertical disparity, and stereoscopic theory. *Perception & Psychophysics, 44*, 477–488.

Kaneko, H., & Howard, I. P. (1996). Relative size disparities and the perception of surface slant. *Vision Research, 36*, 1919–1930.

Kaneko, H., & Howard, I. P. (1997). Spatial limitation of vertical-size disparity processing. *Vision Research, 37*, 2871–2878.

Mayhew, J. E. W., & Longuet-Higgins, H. C. (1982). A computational model of binocular depth perception. *Nature, 297*, 376–378.

Ogle, K. N. (1938). Induced size effect. I. A new phenomenon in binocular space-perception associated with the relative sizes of the images of the two eyes. *AMA Archives of Ophthalmology, 20*, 604–623.

Ogle, K. N. (1964). *Researches in binocular vision*. New York: Hafner.

Rogers, B. J., & Bradshaw, M. F. (1993). Vertical disparities differential perspective and binocular stereopsis. *Nature, 361*, 253–255.

Ryan, C., & Gillam, B. (1994). Cue conflict and stereoscopic surface slant about horizontal and vertical axes. *Perception, 23*, 645–658.

Stenton, S. P., Frisby, J. P., & Mayhew, J. E. W. (1984). Vertical disparity pooling and the induced effect. *Nature, 309*, 622–624.

van Ee, R. (2003). Correlation between stereoanomaly and perceived depth when disparity and motion interact in binocular matching. *Perception, 32*, 67–84.

van Ee, R., & Erkelens, C. J. (1995). Binocular perception of slant about oblique axes relative to a visual frame of reference. *Perception, 24*, 299–314.

van Ee, R., & Erkelens, C. J. (1996a). Temporal aspects of binocular slant perception. *Vision Research, 36*, 43–51.

van Ee, R., & Erkelens, C. J. (1996b). Stability of binocular depth perception with moving head and eyes. *Vision Research, 36*, 3827–3842.

van Ee, R., & Erkelens, C. J. (1998). Temporal aspects of stereoscopic slant estimation: An evaluation and extension of Howard and Kaneko's theory. *Vision Research, 38*, 3871–3882.

van Ee, R., & Richards, W. (2002). A planar and a volumetric test for stereoanomaly. *Perception, 31*, 51–64.

Yarbus, A. L. (1967). *Eye movements and vision; translated from Russian by Basil Haigh*. New York: Plenum Press.