



## Rapid communication

## Motion in depth based on inter-ocular velocity differences

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**Abstract**

Two different binocular cues are known for detecting motion in depth. One is disparity change in time and the other is inter-ocular velocity difference. In contrast to the well known fact of the use of the disparity cues, no evidence of contribution of inter-ocular velocity differences for detecting motion in depth has been reported. We demonstrate that motion in depth can be seen based solely on inter-ocular velocity differences using binocularly uncorrelated random-dot kinematograms. This indicates that the visual system uses monocular velocity signals for processing motion in depth in addition to disparity change in time. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords:* Motion in depth; Inter-ocular velocity difference; Disparity

**1. Introduction**

Several experiments have confirmed that the human visual system has mechanism(s) that specialize in detecting motion in depth (Beverley & Regan, 1973; Regan & Beverley, 1973a; Hong & Regan, 1989; Regan, 1991). For example, detection threshold of motion in depth is elevated by selective adaptation of motion in depth stimuli, which produces little threshold change for detecting static disparity (Beverley & Regan, 1973). This implies that there are independent mechanisms for detecting static depth and motion in depth. Binocularly, there are two possible mechanisms for motion in depth (Regan, 1993; Cumming & Parker, 1994). One is that based on disparity change in time and the other is that based on inter-ocular velocity differences. In the former case, disparity is detected first, and then its change over time is calculated (Fig. 1A). In the latter case, monocular velocities are calculated first, and then compared (Fig. 1B). Since motion in depth can be seen in dynamic random-dot stereograms, where no coherent monocular motion exists, disparity change in time is used to see

motion in depth (Julesz, 1971; Norcia & Tyler, 1984). In contrast, little contribution of inter-ocular velocity differences to motion in depth has been reported (Nagata, 1982; Cumming & Parker, 1994).

It is surprising that there is little evidence for the use of monocular velocity information for perceiving motion in depth. Since detecting disparity is likely to be a slow process (Regan & Beverley, 1973b), there should be a benefit of the use of monocular motion signals, which is processed much faster. If there is only mechanism to use disparity change in time, poor temporal resolution for motion in depth will be expected. Although the mechanism for motion in depth perception may be a slow process in comparison with those for monocular lateral motion detection (Tyler, 1971), it is still possible to have better temporal resolution than the mechanism for disparity detection.

A different aspect of the use of velocity signals is for evaluating speed and direction of motion in depth (Cumming, 1994; Harris & Watamaniuk, 1995). Indeed, importance of monocular motion signal has been suggested for speed discrimination of motion in depth (Harris & Watamaniuk, 1995), although their conclusion might be valid in limited conditions (Portfors-Yeomans & Regan, 1996).

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As far as detection of motion in depth is concerned, no critical role of the inter-ocular velocity differences has been reported. We demonstrate that motion in depth can be seen based solely on inter-ocular velocity differences if proper conditions are used. To isolate the velocity cue from the disparity cue, we used binocularly uncorrelated random-dot kinematograms. There was no correlation between the left and right images, and

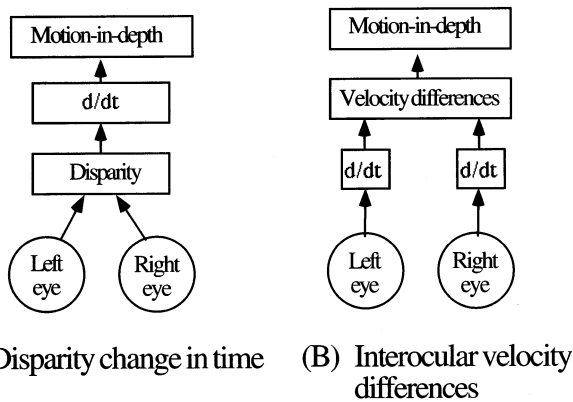


Fig. 1. Two possible mechanisms for motion in depth (modified from Cumming & Parker, 1994). (A) Disparities are detected first, and the disparity change in time is calculated ( $d/dt$  indicates the detecting velocity). No monocular velocity signal is required for this mechanism. (B) Velocities in each retina are calculated first, and then velocities of the left and right retinæ are compared. No disparity signal is required for this mechanism.

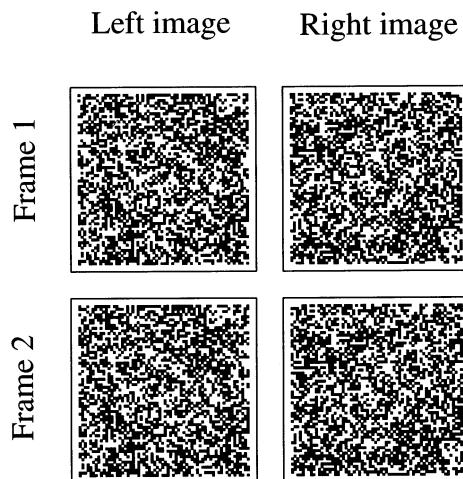


Fig. 2. A schematic view of the stimulus in Experiment 1. Two frames of random-dot patterns (50% light and 50% dark dots) were presented to each eye. There was no correlation between the left and right images (fusing the images provide an unstable surface), while 100% correlation between frames 1 and 2 for each eye (binocularly uncorrelated random-dot kinematogram). The dots in frame 1 were displaced by either 4, 8 or 16 dots to make frame 2. The dots in the upper half displaced leftward and those in the lower half displaced rightward (or vice versa). White frames (black in the figure) of  $4.6^\circ \times 4.6^\circ$  were always visible and used for fusion with observers voluntary fixating the center of the frame. The lower pixel resolution is used in the figure for the clarity.

therefore, little influence of the binocular disparity cue was expected to be available for depth processing. The result showed that direction of motion in depth can be identified in this stimulus. Since motion in depth was found to be seen even without binocular overlaps of dots in Experiment 2, an explanation by randomly pairings of dots that may be used for the disparity change in time was ruled out. In Experiment 3, we showed that the direction of motion in depth can be identified in the condition, in which monocular lateral motion in either retina did not provide any clue. This indicates that binocular process is required to explain our data.

## 2. Experiment 1

### 2.1. Method

The stimulus was random-dot kinematograms (50% light and 50% dark dots) that binocularly uncorrelated. The kinematograms contained two frames for each eye and the displacement of the dots of the left image was in the opposite direction to that of the right image (Fig. 2). There was no correlation between the left and right images, and therefore, no binocular disparity cue was available for depth processing (fusing the images in Fig. 2 provide an unstable surface with lacy depth). In each random-dot kinematogram, the upper half of the pattern moved leftward and the lower half moved rightward or vice versa, creating relative motion between the halves. The replacements of the frames provided motion signals in opposite direction for the two retinæ in each half of the images. The observers indicated the direction of motion in depth of upper half of the stimulus (moved forward or away) and the percentages of correct responses were recorded for different contrast levels of the stimulus by the method of constant stimuli. Four observers with normal vision, one author and three observers naive to the purpose of the experiment, participated in the experiment. The observers had at least two training sessions. Feedback signals were given after the responses both in training and experimental sessions.

The dots in frame 1 were displaced by 4, 8 or 16 dots (1 dot = 1 min) to make frame 2 and coherent motion was seen by their replacement when presented monocularly. White square frames ( $4.6^\circ \times 4.6^\circ$ ) were presented throughout a trial to help to fuse the images with observers voluntary fixating the center of the display. Frame 1 was presented for 480 ms and then replaced by frame 2, which was also presented for 480 ms. No ISI was interposed between the frames except for the refreshing of the display. Images for the two eyes were presented on two monochromatic monitors (Nanao Flex scan 6500) controlled by a computer (Apple Power

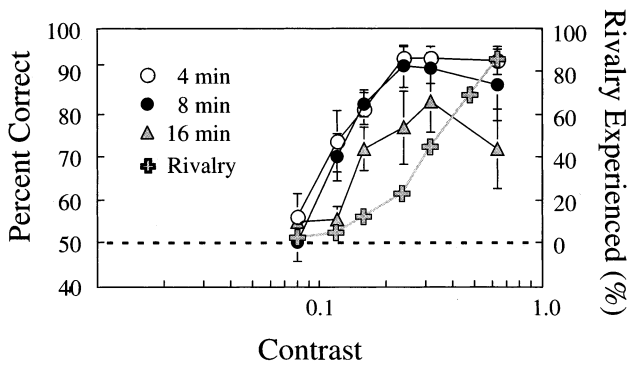


Fig. 3. The average percentages of correct responses (the left side axis) of four observers as a function of contrast. Different symbols represent different displacement sizes. The line of 50% indicates the chance level of performance. The error bars indicate standard errors of the mean across observers. The crosses and right-side axis indicate the average percentages of rivalry experienced by three of the observers. The results with 4 min displacement are shown, since the data with the other displacement sizes are very similar.

Macintosh 7100). The refresh rate was 67 Hz with average luminance of  $46 \text{ cd m}^{-2}$ . The observers viewed the monitors through mirrors arranged to fuse the images at a distance of 160 cm. Each random-dot field consisted of  $256 \times 256$  pixels which corresponds to  $4.3^\circ \times 4.3^\circ$  in visual angle.

Pilot observations revealed that the stimulus provided the sensation of motion in depth for the appropriate contrast levels, but with sensation of lateral motion. The observers reported that they saw lateral motion of the dots in many trials with or without motion in depth. The appearance of the display was that some clusters of dots moved in one direction and the other clusters moved in the opposite direction, creating a mosaic like mixture of opposite motions. This is similar to the depth perception with binocular rivalry in the stereogram with orthogonal lines (Kaufman, 1974). The lateral motion seen likely influenced the trajectory of motion in depth in some amount. The perceived direction was shifted to either left or right from the line of sight in some trials. The observers were instructed to neglect the lateral motion since it did not have useful information for discriminating between forward and away motions. Although it would be useful when s/he knew which eye the motion signal came from, the knowledge were not likely to be obtained by our observers (see Sections 4 and 5).

## 2.2. Results and discussion

Fig. 3 shows that the average percentages of correct responses of four observers as a function of contrast. Different symbols represent different displacement sizes. Contrast is Michelson contrast:  $(L_1 - L_d)/(L_1 + L_d)$ , where  $L_1$  is luminance of the light dots and the  $L_d$  is that of dark dots. Each datum point was based on 60

judgments for each of four observers. The line of 50% indicates the chance level of performance. The error bars indicate standard errors of the mean across observers.

The performance was clearly higher than chance level for contrasts of 0.2 or higher for all displacement sizes. Since no coherent disparity cue was provided in the stimuli, the result suggests that motion in depth can be seen based solely on inter-ocular velocity differences.

An alternative interpretation of the result is that randomly paired dots in the binocularly uncorrelated random-dot kinematograms provided a disparity signal that changed in time. Although there was no correlation between the left and right images, a certain number of dots could be paired with randomly varying disparity. Since only an unstable surface was seen when the stimulus was stationary, these randomly paired dots were not used for coherent static depth perception. However, they may have been used to detect disparity change in time when the dots moved. We conducted Experiment 2 to investigate this possible effect of the randomly pairing of dots.

## 3. Experiment 2

### 3.1. Method

To avoid randomly pairing of dots in binocularly uncorrelated random-dot patterns, we replaced parts of the random-dot display in each eye with uniform gray horizontal bands that alternated in vertical position in the left and right images (Fig. 4). Each image consisted of a square-wave horizontal grating of random-dot bands with gray bands. Since the bands with dots occupied alternate positions in the left and right images, there was no overlap with appropriate binocular fusion. To control vertical vergence eye movements, we used nonius lines for brief presentation duration. Horizontal and vertical nonius lines were presented with a bull's eye before each trial and the observer pressed a key to start a trial when the nonius lines appeared collinear. Each frame was presented for 60 ms. This stimulation should prevent the direct overlap of dots of the left and right images. The band size varied between 8 and 20 min and the contrast of the dots was fixed to 0.32.

Pilot observations showed that the stimulus with vertical displacements provided the sensation of motion in depth, although the sensation was somewhat weaker than that in the original stimulus. The observer reported that they saw lateral motion as in Experiment 1.

We used dynamic random dot stereograms to stimulate the disparity detection mechanism in addition to

the binocularly uncorrelated stimulus. Even without direct overlap of dots, it might still be possible for the disparity mechanism to integrate the randomly corresponding dots inside its fusional or summation area. The results for the stimulus with disparity cue should reveal the integration limit of the mechanism. This

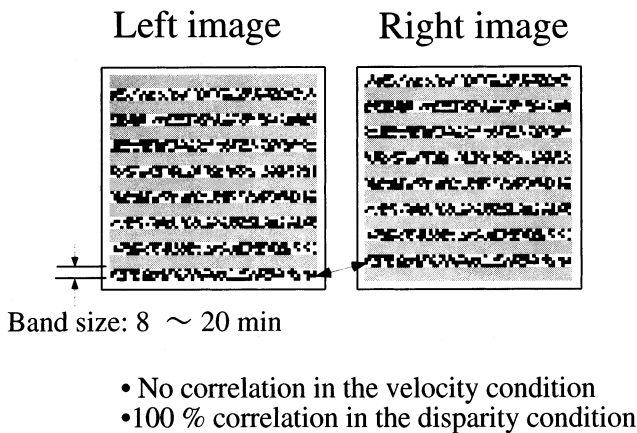


Fig. 4. Stimulus without binocular overlaps of dots. To remove the possible random pairing of dots, bands of dots were replaced by a uniform gray alternately in the left and right images so that there was no overlap of dots when the displays were appropriately fused. In the velocity condition, the stimulus was made from the same random-dot patterns as in the original condition. In the disparity condition, binocularly correlated but temporally uncorrelated random-dot patterns (dynamic random-dot stereograms) were used to provide the disparity cues, but with vertical disparity equal to the band size (dots in the right image shifted upward). The two images may be fused by disparity detecting mechanism if the vertical disparity is inside the fusional area. The displacement size (or disparity) was fixed at 4 min. Actual contrast of the dots was much less than shown (0.32).

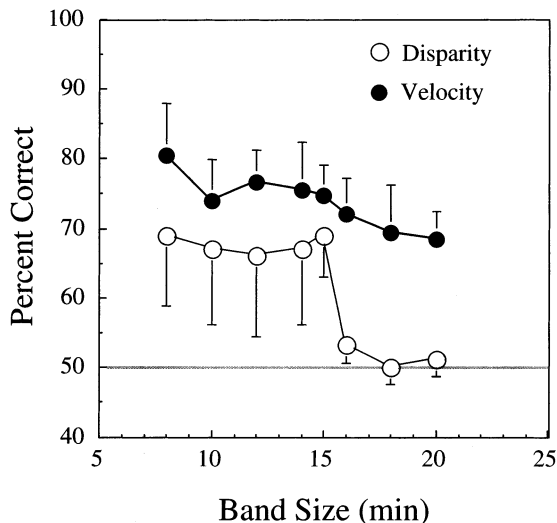


Fig. 5. The average percentages of correct responses of four observers as a function of band size. ● represent the velocity condition and ○ represent the disparity condition. Each datum point is based on 100 judgments for each observer. The line of 50% indicates the chance level of performance. The error bars indicate standard errors of mean across observers.

stimulus was similar to that for inter-ocular velocity differences. The critical difference was that the dots in the left and right images were correlated whereas the dots in the two sequential frames were not correlated (binocularly correlated and temporally uncorrelated patterns). The arrow in Fig. 4 indicates the corresponding bands in the images. Because of the gray band to remove the direct overlap of dots, a vertical disparity with the same as the band size was introduced to the corresponding dots in this stimulus. We call this the disparity condition, and the one with inter-ocular velocity differences, the velocity condition. Fixed size of 4 min was used both for the displacement in the velocity condition and the size of disparity change in the disparity condition. Four observers (one from the original experiment, the author, and three new observers) participated in the experiment. The observers had at least two training sessions. Feedback signals were given in the practice and experimental sessions.

### 3.2. Results and discussion

The results showed that the direction of motion in depth can be identified even without direct binocular overlaps of dots in the velocity conditions (Fig. 5). Direct overlaps of left and right dots are not necessary for identifying the direction of motion in depth. This fact itself cannot be regarded as the evidence that motion in depth is perceived without disparity detection, since the performance was higher than chance level also in the disparity condition when band size was small. However, it is strong evidence for motion in depth perception without disparity detection that the percentage of correct responses is higher for the velocity condition than for the disparity condition. Only exception was that one observer showed better performance for the disparity condition with band sizes 14 min or smaller. The better performance in the velocity condition, in general, indicates that identification of motion direction in the velocity condition cannot be attributed to the disparity detection mechanism. The mechanism to detect signal of motion in depth from inter-ocular velocity differences is required to explain the results.

The difference in the dependency of the performance on the band size also suggests that different mechanisms contribute in the two conditions. In the disparity condition, performance was relatively constant with band sizes of 14 min or smaller and it decreased quickly to the chance level at larger band sizes. In the velocity condition, on the other hand, the performance gradually decreased with band size but never reached at the chance performance within the range of band sizes used. This suggests that the vertical fusional limit for disparity detection is about 15 ms whereas that for inter-ocular velocity comparison is larger.

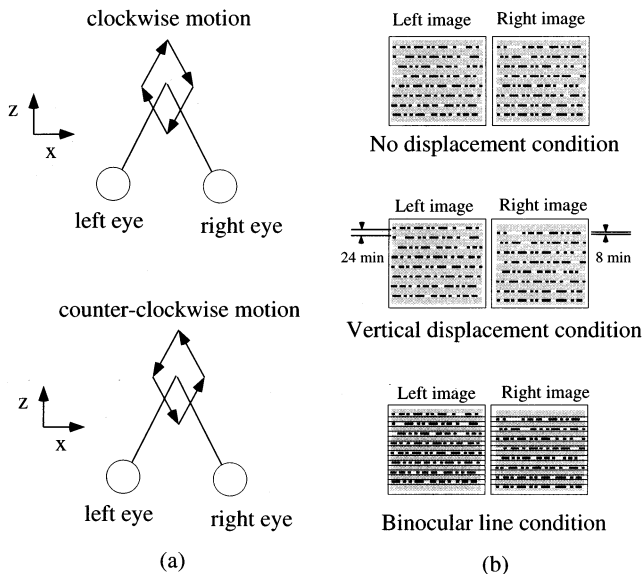


Fig. 6. (a) The schematic description of rotation in depth stimulus used in Experiment 3. The observer identified the direction of rotation in depth (clockwise or counter-clockwise). (b) The schematic views of the three stimuli used in Experiment 3. Actual contrast of the dots was much less than shown (0.32).

#### 4. Experiment 3

There is a potential methodological problem in the previous experiments. It was theoretically possible that the observer responded correctly if s/he was able to detect the motion direction on either retina with the knowledge of which eye the motion signal from. Although it is unlikely that there is information of 'eye-of-origin' that is consciously available in general, there are cues that may help to *guess* it in some conditions (Ono & Barbeito, 1985). Experiment 3 was conducted to examine whether monocular cues are responsible for identifying motion direction in depth in the binocularly uncorrelated kinematograms we used.

Since the observer reported that they saw motion in depth when they responded with confidence, monocular motion signal is not likely the source of the better performance than chance level. However, we conducted Experiment 3 to confirm that monocular motion cues were not critical to see motion in depth from inter-ocular velocity differences. We used stimulus for rotation in depth, which direction cannot be discriminated only with motion signal from either retina. Velocities of the left and right random dots were determined to simulate the rotation in depth (Regan & Beverley, 1973a). For one cycle of clockwise rotation (in the top view as in Fig. 6), the motion sequence of the left image may be rightward-stationary-leftward-stationary with that of the right image being stationary-leftward-stationary-rightward. For counter-clockwise rotation, the motion sequence of the left image may be stationary-rightward-

stationary-leftward with that of the right image being leftward-stationary-rightward-stationary. When the starting phase of the sequence is randomly varied from trial to trial, it is impossible to identify the direction of rotation only with signals from either retina. Binocular information is necessary.

#### 4.1. Method

The spatial configuration of the stimulus was similar to that in Experiment 2 with a few differences (Fig. 6b). The band size was different for dots and gray bands. The gray band was 24 min and the dot band was 8 min with the dot size of  $8 \times 8$  min. The vertical displacement of the band was either zero or 16 min and we call them no displacement and vertical displacement conditions. In the vertical displacement condition, the effect of the vertical vergence was minimized by the large gray band (24 min) for the longer presentation duration. We also used a variation of the vertical displacement condition to prevent vertical vergence eye movement. In the condition, black horizontal lines were presented binocularly between the dot bands (binocular line condition). In the all three conditions, the dots in the upper and lower halves moved always in the opposite directions as in the previous experiments. The direction of rotation, however, was the same in both halves with a half cycle of phase difference. Stimulus presentation was one cycle of 780 msec and the 2D velocity of dots was 67 min/s when they moved.

Thirteen observers with normal or corrected-to-normal acuity participated in the experiment. Ten of the observers were naive and they had never experienced motion in depth stimulus of random-dot patterns before the experiment. Three of the observers were familiar to the stimuli and the general purpose of the experiment although they were not informed of the detail of the experimental conditions. One training session was given for each of the no and vertical displacement conditions. Three conditions were run in different sessions and each observer judged the direction of rotation 96 times in each condition. No feedback was given in this experiment.

#### 4.2. Results and discussion

The average percentage of correct responses across observers is 76.2% (ranging from 55.2 to 99.0%) in the no displacement condition, 67.7% (54.2–88.5%) in the vertical displacement condition, and 62.9% (52.1–95.8%) in the binocular line condition. Clearly, the direction of rotation in motion can be identified in all three conditions above the chance level. This confirms that any monocular lateral motion cue is not responsible to the observers' performance for detecting the direction of motion in depth. The average percentage of

correct responses for the three experienced observers is 72.9, 65.6 and 62.9% in the no displacement, vertical displacement, and the binocular line conditions. The results are similar to the average of all, suggesting little effect of training and the knowledge of the experiment. This also supports our conclusion since training and knowledge of the experiment should improve the complicated use of the monocular cues for identifying the direction of rotation in depth.

Interestingly, some observers reported that, in addition to the rotation in depth, they saw lateral motions of dots in the opposite directions in the adjacent bands when there was vertical displacement. A surface of a half of the display appeared to move in depth, while each band of dots appeared to move laterally independently from the motion in depth. The visual system seems to have accesses to monocular lateral motion and to motion in depth based on the monocular motion signals.

## 5. Discussion

### 5.1. Effect of binocular rivalry

We showed that the percentage of correct responses to identify the direction of motion in depth was clearly above chance for the binocularly uncorrelated random-dot kinematograms, when contrast was high. However, it never reached 100% even with the highest contrast used (Fig. 3). In fact, the performance was lowered slightly at higher contrast levels. One may think, therefore, that inter-ocular velocity difference is less important than disparity change in time. The limited performance in our experiments, however, could be due to the stimulus used. Since there was no correlation between the two retinal images, binocular rivalry may have impaired seeing motion in depth (or coherency over the random-dot field in general). If binocular rivalry impairs the detection of motion in depth, the effect is expected to be at contrasts higher than the threshold for binocular rivalry.

To examine the possible effect of binocular rivalry, we measured the frequencies of experiencing binocular rivalry in our stimulus, at various contrast levels. The crosses and right-side axis in Fig. 3 indicate the average percentages of rivalry experienced by three of the observers for the same stimulation as in Experiment 1. Observers reported whether they experienced instability of the stimulus field across space and/or time except for the displacement of the random-dots. The results of only 4 min displacement are shown in Fig. 3, since the data with the other displacement sizes are essentially the same. The result showed that the rivalry is experienced more at higher contrast levels, as previously reported (Lei, Tyler & Schor, 1992), and the experience

of rivalry exceeds 50% at a contrast of about 0.4. The percentage of correct responses for motion in depth peaks at a contrast slightly less than the threshold of binocular rivalry and reduces with the further increase of contrast levels. This suggests that binocular rivalry, indeed, impairs the detection of motion in depth. We, therefore, claim that contribution of inter-ocular velocity differences to motion in depth perception can be greater in everyday life than one might expect from our experimental results.

### 5.2. Relative versus uniform motion

One of the important features of motion in depth perception for the stimulus with both disparity and velocity cues is that motion in depth is not seen in the absence of a stationary reference or relative motion (Erkelens & Collewijn, 1985). We therefore expected poor performance of detection of motion in depth with uniform motion of binocularly uncorrelated images. To examine this, we measured performance of motion in depth detection with a uniform motion stimulus instead of a relative motion stimulus. In the uniform motion condition, all dots in the image for one eye moved in the same direction while in the opposite directions between the left and right images. Other details were the same as in Experiment 1.

The results showed chance levels of performance and no increase with contrast levels for the three displacement sizes of 4, 8 and 16 min. The average percentage of correct responses for two observers from Experiment 1 was less than 60% in all conditions. Importance of relative motion was shown also for motion in depth based on inter-ocular velocity differences. Note that the motion in the display was not completely absolute. White frames outside the random-dot fields were presented throughout a trial, but the result indicates that the frame at the periphery did not provide information strong enough to see motion in depth.

### 5.3. Monocular cues

Experiment 3 was conducted to examine whether the direction of motion in depth can be identified under the condition in which monocular information did not provide any clue for the direction of motion. Even in the condition, the observers responded the direction of motion in depth correctly better than chance level. This ruled out the possibility that our task was performed based on the percept of monocular motion.

Strictly speaking, however, perception of motion in depth is not necessary for performing the task even in the conditions of Experiment 3. Since the movements of dots of the two images have to be unique to each direction, motion sequences of both images with the knowledge of which is from which retina provide infor-

mation for the correct response. However, it was practically impossible to use the information for the presentation duration used and preliminary observation suggests that it would not be easier with longer duration. No observers, including three experienced observers, noticed the relationship of lateral motion in the retinae and motion in depth. In addition, the better performance in the no displacement condition than in the vertical displacement conditions also suggests that the observers did not respond based on the monocular lateral motion signals. Since lateral motion was seen clearer in the vertical displacement conditions, the use of lateral motion cues predicts the better performance in these conditions.

For the stimulus in Experiment 1, the results with uniform motion stimulus suggest that monocular lateral motion cues influenced little observers' performance. If the monocular motion signals were critical, the performance should be much better than chance for uniform motion stimuli since the monocular lateral motion was also seen in the uniform motion stimulus. However, the results showed that motion in depth was rarely seen with the uniform motion stimulus. The lower sensitivity for uniform motion comparing to that for relative motion in monocular conditions cannot account for the results. Uniform motion stimulus used was well above the threshold for monocular motion detection in the most of the conditions we tested.

#### 5.4. Comparison with previous studies

Our conclusion is supported by recent measurements of the perceived velocity (Howard, Allison & Howard, 1998) and our preliminary report of contrast threshold measurements for motion in depth (Shioiri, 1995). Both studies used binocularly uncorrelated random-dot kinematograms similar to that in the present experiments. The fact that these measurements could be made suggests that the inter-ocular velocity differences can be a cue for motion in depth, although it may not be a direct indication. On the other hand, our results apparently inconsistent with the reports that found no evidence of the contribution of inter-ocular velocity differences to motion in depth perception (Nagata, 1982; Cumming & Parker, 1994). The differences are perhaps due to the differences of the experimental conditions.

Cumming and Parker (1994) examined whether there are conditions in which motion in depth is perceived with temporally correlated random-dot stereograms but not with dynamic (temporally uncorrelated) random-dot stereograms. Their results can be summarized as that spatial and temporal properties for motion in depth are similar to the two types of stimuli. In other words, they found no contribution of temporal correlation, or monocular motion signals, to see motion in depth. This is not, however, inconsistent with our re-

sults. They did not use binocularly uncorrelated stimulus and it is possible that contributions of motion signals to motion in depth perception will be found in Cumming and Parker's stimulus, when the disparity cues are removed. On the other hand, the better performance in the velocity condition than in disparity condition in Experiment 2 might be inconsistent with Cumming and Parker's results. They did not find any condition where sensitivity is higher for stimulus with motion cue than that without it. In contrast, the results of Experiment 2 suggest that sensitivity is higher with motion cue in some conditions. There are three differences that are, we think, critical. First, Cumming and Parker measured disparity threshold, while we used a fixed size of disparity change (4 min). Their measurements, perhaps, assessed the mechanism that is sensitive to slow speed whereas ours assessed the mechanism sensitive to faster speed. Velocity sensitive mechanisms may dominate in the stimuli of faster motion.

Second, there was vertical disparity in our stimulus and that weakened the disparity signals. Although the vertical shift, perhaps, influenced also on the detection of velocity differences, the results of Experiment 2 suggest that the effect was smaller than that on the disparity detection. This could be a reason for the higher sensitivity in the velocity condition than in the disparity condition in Experiment 2. In this context, the difference of stimulus size may also contribute to produce the differences between the results of Cumming and Parker and ours. The results of Experiment 2 suggest that the spatial extent of the integration or fusional area of the disparity detection mechanism is smaller than that of the mechanism to compare the motion signals between the retinae. Motion cue may be more important for larger targets than disparity cue. Since the moving area in our display ( $4.3^\circ$ ) was larger than that in their display ( $1^\circ$  or  $1.2^\circ$ ), motion cue could have been more effective in our stimulus.

Third, our stimulus presentation was very short (60 ms for each frame), to which mechanisms for motion is likely more sensitive than that for disparity. The stimulus of Cumming and Parker, on the other hand, oscillated at temporal frequencies less than or equal to 4 Hz, since they found that 8 Hz was too high to see motion in depth. Our temporal condition might be equivalent to a temporal frequency between 4 and 8 Hz in their condition and motion cue may be more efficient than disparity cue at temporal frequency higher than 4 Hz. Indeed, an indication of better sensitivity for stimulus with monocular motion signals can be seen in their Fig. 3. The threshold is higher for the stimulus without motion cue at frequency lower than 2 Hz but it was similar at 4 Hz in the two conditions.

Nagata (1982) also reported no perceived motion in depth with binocularly uncorrelated stimulus. He prevented the binocular rivalry by presenting the left and

right images alternately in time and, therefore, there is little influence of binocular rivalry. There was, however, little relative motion signal in his stimulus and this could be the reason why the motion in depth was not seen.

### 5.5. Integration of velocities from two retinæ

There are two important issues related to the integration of velocity signals from two retinæ. First, to calculate the direction of motion in depth from the velocity differences, the regions on the retinæ to compare the velocity have to be determined. The simplest way might be to compare the velocities of corresponding retinal regions without considering the disparity information. This could detect motion in depth quickly, skipping the slow process of detecting disparity (Regan & Beverley, 1973b) and be useful to obtain speed information of moving objects in depth. A different view might be that the velocity signal is used with disparity signal (Harris & Watamaniuk, 1995; Morgan & Tyler, 1995; Harris, Mackee & Watamaniuk, 1997). Although our results indicate that there is a mechanism to detect motion in depth without disparity cues, the mechanism might still use the disparity cue when it is useful.

Second, all monocular motion signals may not be used for the integration. It has been shown that the sensitivity of motion in depth is not high for faster velocities in comparison with monocular lateral motion (Tyler, 1971). This suggests that only parts of motion signals processed monocularly are integrated for motion in depth perception. The observers' report in our experiments that they saw motion in depth with percepts of lateral motions is consistent with this notion. There may be parallel motion pathways for motion in depth and lateral motion.

## 6. Conclusion

We showed that motion in depth can be seen based solely on inter-ocular velocity differences using binocularly uncorrelated random-dot kinematograms. This indicates that the visual system uses monocular velocity signals for processing motion in depth, in addition to disparity change in time. The role of inter-ocular velocity differences may be to detect motion in depth of large objects moving fast.

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