TR－A－0140

Spatiotemporal properties of motion perception for random-check contrast modulations

Shin'ya Nishida

1992. 3.30

（1992. 3.17 受付）

ATR視聴覚機構研究所

〒619-02 京都府相楽郡精華町光台2-2 ☎07749-5-1411

ATR Auditory and Visual Perception Research Laboratories

2-2, Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-02 Japan

Telephone: +81-7749-5-1411
Facsimile: +81-7749-5-1408

Spatiotemporal properties of motion perception for random-check contrast modulations

Shin'ya Nishida

Vision Department

ATR Auditory and Visual Perception Research Laboratories,

Hikaridai 2-2, Seika-cho, Soraku-gun, Kyoto 619-02, Japan

Abstract ---- To clarify the mechanism of detecting the motion of contrast modulations, the spatiotemporal properties of direction discrimination for contrast motion were examined. The stimulus was a microbalanced random stimulus (Chubb & Sperling, 1988, *Journal of the Optical Society of America, A5,* 1986-2007), termed RWK (random window kinematogram), a shifting random checkerboard pattern in which each check was either a patch of random dots (uncorrelated between frames) or a patch of uniform gray having the mean luminance of the random dots. The effect of ED (exposure duration) on RWK discrimination could be described as SOA (stimulus onset asynchrony) dependency when the EDs of the first and second frames were the same, but the performance was better than predicted from SOA when the first ED was short while the second was long. RWK could be seen at longer inter-stimulus intervals than RDK (random dot kinematogram) having similar stimulus parameters (e.g., check size, effective contrast). Incoherent motion (e.g., reversed phi) could be seen for RWK. The D_{max} (maximum displacement limit) for RWK was comparable to that of RDK, but it increased in proportion to the check size, while the D_{max} for RDK did not. These results suggest that, like the luminance motion mechanism, the contrast motion mechanism extracts motion locally, and its motion extraction stage can be modeled as a correlation-type detector. Also, the spatial ranges of the contrast motion detectors are comparable to those of the luminance motion detectors, but their temporal range is larger. The preprocessing of the contrast motion detector may be different from that assumed in the model proposed by Chubb & Sperling.

Key Words ---- Motion perception, Contrast motion, Exposure duration, SOA, ISI, Displacement

Acknowledgements ---- The author is grateful to Takao Sato of NTT Basic Research Laboratories for his helpful comments on a draft of this manuscript, and to Eiji Yodogawa and Keiichi Ueno of Auditory and Visual Perception Research Laboratories for providing the opportunity to conduct this study.

CONTENTS

1. INTRODUCTION ... 4

2. METHODS ... 7
    2.1. Stimuli and apparatus ... 7
    2.2. Procedure ... 8
    2.3. Subjects ... 8

3. RESULTS ... 9
    3.1. Equiluminance setting ... 9
    3.2. Check size ... 11
    3.3. ED and SOA ... 14
    3.4. ISI ... 17
    3.5. Reversed phi ... 22
    3.6. Displacement ... 22

4. DISCUSSION ... 26
    4.1. Incoherent motion ... 26
    4.2. SOA and ED ... 27
    4.3. ISI ... 27
    4.4. Check size ... 29
    4.5. Displacement ... 29
    4.6. Displacement - check size interaction ... 30
    4.7. Summary of discussion ... 32

FOOTNOTES ... 33

REFERENCES ... 34

1. *INTRODUCTION*

The visual system involves a mechanism which derives motion from correlations of luminance value across space and time (e.g., Nakayama, 1985). Most current models assume that the luminance correlations are extracted by comparison of the outputs of two filters that have spatially and temporally offset receptive fields (Adelson & Bergen, 1985; Baker & Braddick, 1985; Reichardt, 1961; van Santen & Sperling, 1984, 1985; Watson & Ahumada, 1985). It is also known that a luminance motion detector is tuned to a narrow range of spatial frequency (Anderson & Burr, 1985, 1989; Pantle, Lehmkuhle & Caudill, 1978; van Santen & Sperling, 1984).

Some kinds of motion perception cannot be explained in terms of the activation of the luminance motion mechanism (Anstis, 1980; Badcock & Derrington, 1985; Georgeson & Shackleton, 1989; Julesz, 1971; Ramachandran, Rao & Vidyasager, 1973; Sperling, 1976). The movement of contrast modulations is a typical example. Badcock and Derrington (1985, 1989) showed that displacement detection for contrast modulations was mediated by a mechanism other than a luminance motion detector. Chubb & Sperling (1988) proved that some contrast motion displays that give a coherent motion impression are theoretically invisible to the luminance motion mechanism (microbalanced random stimuli). It is reasonable to assume that the visual system involves a contrast motion mechanism as well as the luminance motion mechanism (1).

Previous studies have shown that contrast motion has some properties which are similar to those obtained for luminance motion. For a drifting sinusoidal grating, the minimum aperture width for direction perception is nearly the same for the two types of motion (Cavanagh & Mather, 1989). Velocity discrimination for contrast motion depends on contrast and velocity in a way similar to luminance motion (Turano & Pantle, 1989). Plaid motion perception (Cavanagh & Mather, 1989), motion transparency (Cavanagh & Mather, 1989), and kinetic depth effects (Prazdny, 1986; but also see, Dosher, Landy & Sperling, 1989; Landy, Dosher, Sperling & Perkins, 1991) occur with contrast motion as well as luminance motion. On the other hand, unlike luminance motion, contrast motion is perceived with difficulty for stimuli consisting of small elements (Cavanagh & Mather, 1989; Landy et al., 1991) and for stimuli presented in the periphery (Dosher et al., 1989; Turano & Pantle, 1989). Contrast motion is almost ineffective in inducing motion after-effect (Derrington &

Badcock, 1985; but also see Mather, 1991; von Grünau, 1986). Region segregation is difficult from the velocity difference given by contrast motions (Cavanagh & Mather, 1989).

Chubb & Sperling (1988) proposed a mechanism which can detect the motion of contrast modulations. The input is first bandpass-filtered spatiotemporally, then full-wave rectified. This operation transforms contrast modulations into intensity modulations. The motion in the transformed image is derived by comparison of the outputs of two filters that have spatially and temporally offset receptive fields. The filters are tuned to a narrow range of spatial frequency in the transformed image. That is, the mechanism following rectification is identical to a luminance motion detector. Similarly, Cavanagh and Mather (1989) proposed that all kinds of non-luminance motion mechanism have same motion extraction stage as the luminance motion detector.

Previous findings on contrast motion perception shed some light on the underlying mechanism, but are insufficient to prove, or disprove, the model of the contrast motion detector. This is because most of these findings relate to processing stages in the contrast motion system later than the motion detection stage. To elucidate the detection mechanism, it is necessary to investigate the effects of spatiotemporal parameters which supposedly tap the motion detection stage, such as exposure duration (ED), stimulus-onset asynchrony (SOA), inter-stimulus interval (ISI), and displacement. There are few studies on how these basic parameters affect the perception of contrast motion. The present study systematically examines the effects of these parameters.

To clarify the differences in the underlying mechanism, the results for contrast motion were compared with those for luminance motion. In the comparison, it is important to make the stimuli for the two types of motion as similar as possible. Otherwise, the discrepancy in the results may be ascribed to the stimulus difference, rather than the mechanism difference (Cavanagh & Mather, 1989).

The random dot kinematogram [RDK; Figure 1(A)] is one of the stimuli most frequently used for investigation of the luminance motion mechanism (e.g., Baker & Braddick, 1985; Braddick, 1974). The contrast motion display employed in the present study [Figure 1(B)] had a similar spatial configuration to that of RDK. A frame of the stimulus was a random checkerboard pattern in which each check was either a patch of random dots or a patch of uniform gray. The luminance of the gray checks

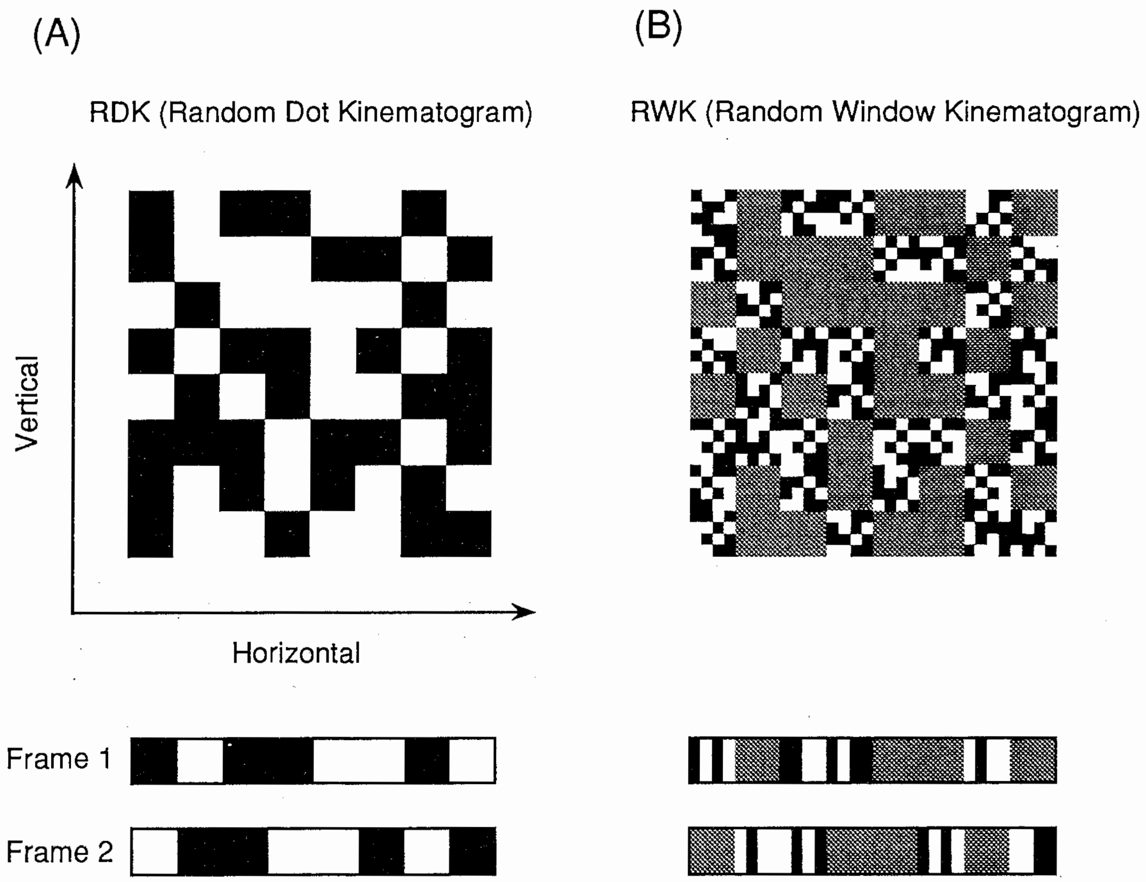


Figure 1. The stimuli employed. (A) RDK (random dot kinematogram). (B) RWK (random window kinematogram). Upper figures show spatial configurations. Lower figures show temporal sequences. See text for further explanation.

was set at the mean luminance of the random-dot checks. Between frames, the checkerboard pattern was shifted to either the right or left by a given displacement. The random dots were uncorrelated between frames. Since the stimulus simulates a view of randomly distributed windows shifting in front of dynamic random dots, it was termed a random window kinematogram (RWK). A similar stimulus was employed by Cavanagh and Mather (1989) to investigate region segregation by contrast motion. RWK is a microbalanced random stimulus (Chubb & Sperling, 1988), so its motion is visible to a contrast motion detector, but theoretically invisible to any kind of luminance motion detector.

The results for RWK were compared with those for RDK of the same spatiotemporal parameters. When needed, the effective contrasts of the two types of stimuli were equated. It is thus expected that the similarities and differences between the results for the two types of stimuli will reflect the properties of the contrast motion detector compared to those of the luminance motion detector.

2. *METHOD*

2.1. Stimuli and apparatus

The stimulus consisted of a two-frame sequence of 256 x 256 pixel images. Each pixel subtended 1 x 1 min with the viewing distance employed. Unless otherwise noted, the two frames were presented for the same duration. The stimuli were displayed at the center of a 19 x 15 deg uniform white field whose luminance was equal to the mean luminance of the stimulus. During ISI, only the uniform field was presented.

A sequence of RWK was made from three 512 x 512 pixel source images, one for the window checkerboard pattern and two for the random-dot pattern. Each check (dot) had one of two values with a probability of 50%. The size of a dot in the random-dot pattern was 1 x 1 pixel. For the first frame, the window and background patterns were sampled from two of the three source images, and combined appropriately to produce an RWK image on the display. The positions of the sampling windows were determined randomly. For the second frame, the position of the sampling window for the window pattern was displaced by the required number of pixels. If the sampling window crossed the edge of the source image, it wrapped around to the opposite side. The random-dot pattern was sampled from a source image different from that for the first frame. A sequence of RDK was made in a similar way, except that it was made from one checkerboard image.

The contrast of the stimulus was defined as $(L_{max}-L_{min})/(L_{max}+L_{min})$, where L_{max} (L_{min}) is the maximum (minimum) luminance in the stimulus. The RWK contrast was controlled by changing the luminance of the random dots, keeping the gray checks as they were. Thus, while the carrier contrast was varied, the modulation contrast was always 100%.

The stimulus was presented on a non-interlace raster-scan CRT (Sony GDM-1952) controlled by a workstation (Masscomp 6600). The refresh rate was 66.7 Hz, with 15 msec for a refresh. In this paper, the durations for ED and ISI are nominally described in multiplies of 15 msec. The maximum monitor contrast was 100% for high contrast stimuli, and compressed to 10% for low contrast stimuli. In either case, 256 intensity levels were available for each pixel. In a dimly-lit room, the subject binocularly viewed the display, with the chin rest set at the viewing distance of 104 cm.

2.2. *Procedure*

The subject started a trial by pressing a button. The fixation cross, located at the center of the stimulus, disappeared 495 msec after the button press, followed by a 195 msec interval of uniform field. Then, a stimulus sequence was presented. The subject's task was to report the direction of perceived motion by pressing one of two buttons. A block consisted of 50 to 130 trials, 10 trials for each stimulus parameter value. The shift direction and the parameter value were altered pseudo-randomly between trials. A session consisted of 5 to 10 blocks, lasting about half an hour. The source images were regenerated between blocks. The percentage of correct responses for each value of the stimulus parameter was calculated from at least 100 judgements.

2.3. *Subjects*

Two subjects participated in all the experiments. One, the author S.N. (male), was myopic with acuity corrected by contact lenses. The other subject, N.O. (female), had normal vision and some prior experience in psychophysical experiments, but was naive regarding the purpose of this study.

3. *RESULTS*

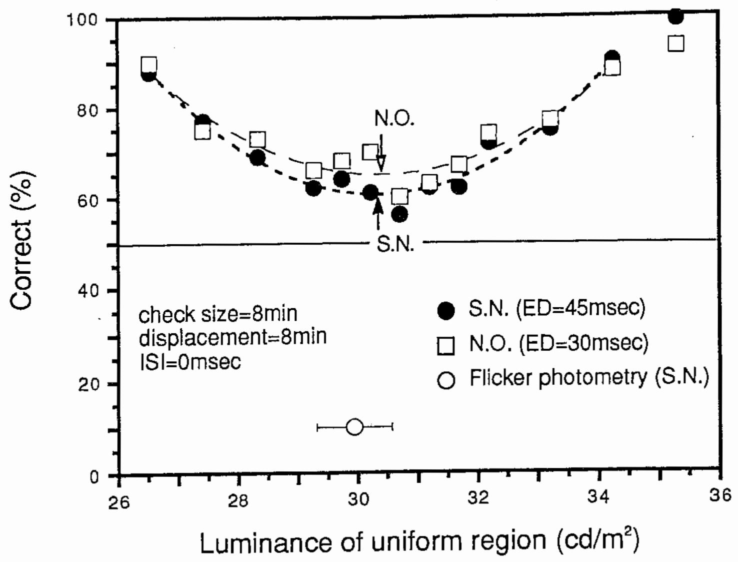
3.1. Equiluminance setting

A minimum motion technique was employed to equate the luminance of gray checks and the mean luminance of random-dot checks. Direction discrimination performance for RWK was measured while varying the luminance of the gray checks, and the gray checks whose luminance gave the worst performance were regarded as equiluminant to the random-dot checks. The rationale of this technique is that the contribution of the luminance motion mechanism should be minimum at the equiluminant point. Since this technique could not be employed under the condition where the contrast motion mechanism effectively detected the movement of RWK, a short ED and a small check size were employed (see below).

Figure 2(A) shows the percentage of correct responses of direction discrimination as a function of gray check luminance. The check size was 8 min, and the displacement was equal to the check size. The contrast was 100%. One frame was presented for 45 msec (S.N.) or 30 msec (N.O.) with no ISI. In the figure, the direction discrimination performance shows a U-shaped function against the gray check luminance. To determine the peak luminance value, a quadratic function was fitted to the data by the least square method. The data showing values larger than 90% were neglected in the fitting. The fit was fairly good for both subjects ($r > 0.94$). The arrow indicates the luminance of the estimated peak point. The luminance of the datum point nearest to the peak was used as the luminance of the gray checks in the following experiments (30.2 cd/m^2 for both subjects).

The U-shaped function in Figure 2(A) reflects the contribution of the luminance motion mechanism to RWK discrimination as a function of residual luminance contrast. In Figure 2(B), the luminance contrast dependency of the RWK perception (curves) is compared with that of the RDK perception (symbols). The data for RDK were collected in a manner similar to the RWK data, except that the random-dot checks in RWK were replaced by the uniform 30.2 cd/m^2 gray checks. While perfect discrimination for RDK requires a luminance contrast of less than 2%, perfect discrimination of RWK requires residual luminance contrast of about 8%. Thus, the contribution of the luminance motion mechanism to RWK discrimination is by far smaller than expected from RDK discrimination. This is probably because the luminance motion signals

(A)



(B)

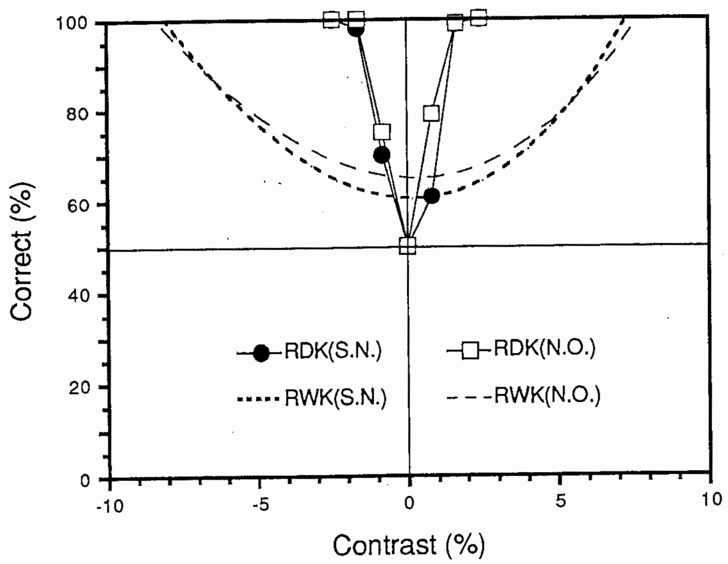


Figure 2. (A) Percentage of correct responses of direction discrimination for RWK as a function of the luminance of uniform gray checks (filled circles and open squares). The contrast of random-dot checks were 100%. Smooth curves are the best fitting quadratic functions, whose peaks are indicated by arrows. It is expected that random-dot checks and gray checks became equiluminant at the peak luminance. The open circle represents the equiluminant point estimated by flicker photometry for subject S.N. The error bar shows ±1SD. (B) The percentage of correct responses of direction discrimination for RDK as a function of contrast. Curves are functions fitted to the RWK data. Stimulus parameters are the same for RDK and RWK.

indicating correct direction are masked by the signals elicited by the dynamic random dots, indicating random directions. Because of the small contribution of the luminance motion mechanism to the perception for near-equiluminant RWK, a small error in equiluminance setting affects the results only slightly.

The equiluminant point was estimated by flicker photometry as well as by the minimal motion technique. A random-dot field (256 x 256 min square, 100% contrast) was alternatively presented with a uniform gray field at a temporal frequency of 16.7 Hz. The subject adjusted the luminance of the gray field to where he perceived minimum flicker. The open circle in Figure 2(A) represents the estimated luminance averaged over 20 judgements by the subject S.N. Little difference is found between the equiluminant points estimated by the two techniques. Since the flicker photometry took much less time than the minimum motion technique, the equiluminant points of low contrast RWKs were set by flicker photometry. The procedure was similar to that described above, except that the maximum luminance of the random-dot field was varied.

3.2. *Check size*

Previous studies have suggested difficulty of contrast motion perception for stimuli consisting of small elements (Cavanagh & Mather, 1989; Landy et al., 1991). To select appropriate check sizes for the following experiments, the effect of check size on the RWK perception was first examined.

Figure 3 shows the percentage of correct responses of direction perception for RWK as a function of check size. The contrast was 100%, ED was 60 msec, and ISI was 0. The displacement was the same as the check size. At the check size of 2 min, the discrimination performance is at the chance level (50%). It gradually increases as check size increases, and reaches more than 90% at the size of 12 to 16 min.

In Figure 3, the effect of check size seems to saturate at larger sizes. However, this is a ceiling effect. In Figure 4, the percentage of correct responses of RWK discrimination is plotted as a function of contrast (open symbols). The check size was either 8, 16 or 32 min. The other stimulus parameters are the same as for the data in Figure 3. For any check size, the discrimination performance is an increasing function of the contrast. As check size increases from 8 min to 32 min, the function shifts towards lower contrast. In other words, at a given contrast, the performance is higher for

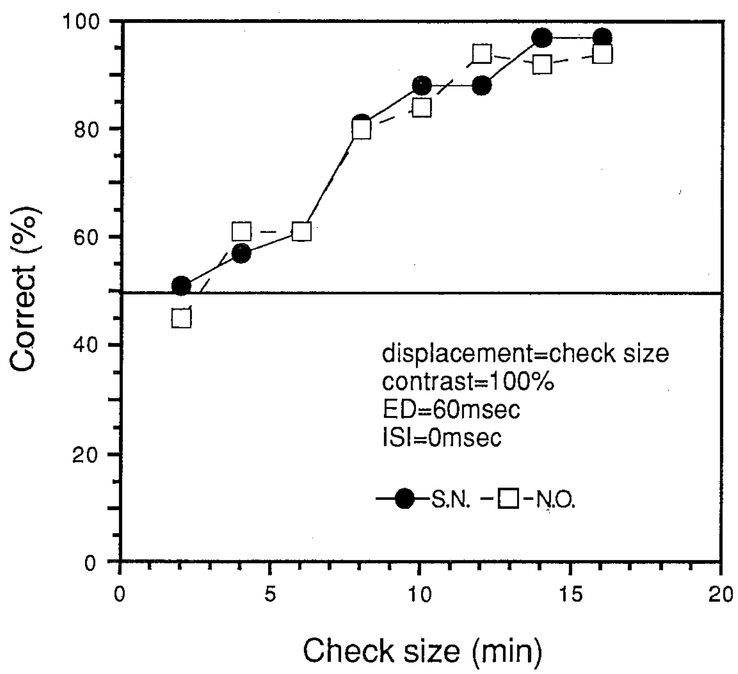


Figure 3. Percentage of correct responses of direction discrimination for RWK as a function of check size.

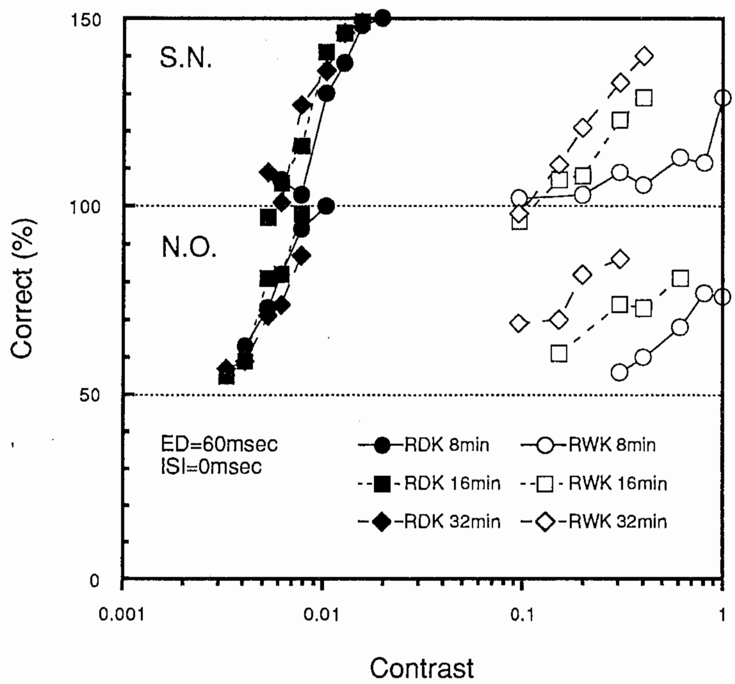


Figure 4. Contrast dependency of direction discrimination performance of RDK and RWK for three check sizes. While the data for N.O. are on the true scale, the data for S.N. are shifted upwards by 50%.

larger check size. Thus, the discrimination for RWK improves with check size, at least up to 32 min.

The filled symbols in Figure 4 represent the percentage of correct responses of direction perception of RDK for check sizes of 8, 16 and 32 min. Unlike the functions for RWK, the three functions for RDK roughly coincide. This suggests that the effect of check size is much smaller on luminance motion detection than on contrast motion detection.

Figure 4 also shows differences in contrast dependency between RWK and RDK. First, RWK discrimination requires much higher contrast than RDK discrimination, which suggests that the contrast motion mechanism has a higher contrast threshold than the luminance motion mechanism (Dosher et al., 1989; Sperling, 1989). Second, the slope of the function against log contrast is gentler for RWK than for RDK. This is probably because the contrast increase of RWK strengthens not only contrast motion signals, but also random-direction luminance motion signals elicited by the dynamic random dots.

3.3. ED and SOA

Next the effects of temporal parameters on the direction discrimination of RWK were examined. The effects of ED and SOA are described in this section, and the effect of ISI is described in the next section.

Figure 5 shows the percentage of correct responses for RWK discrimination as a function of the ED of a frame. The check size was either 8, 16 or 32 min, and the displacement was the same as the check size. The contrast was 100%, and ISI was 0. The discrimination performance rises with increase in ED from 15 to about 60 msec, and levels off for longer EDs. As the check size increases, performance rises more steeply.

Baker and Braddick (1985), who systematically investigated the temporal properties of direction discrimination for RDK, demonstrated an interaction between the effects of ED and ISI such that SOA (ED of the first frame + ISI) characterizes the lower temporal limit for discrimination. To test whether there is a similar interaction for RWK discrimination, ED was kept at the shortest value (15 msec), and ISI was varied. Figure 6 shows the result as a function of SOA, together with the function obtained with varying ED (replotted from Figure 5). The check size was 16 min for S.N., and 32 min for N.O. Although the discrimination performance obtained with varying ISI is slightly lower than obtained with varying ED, both

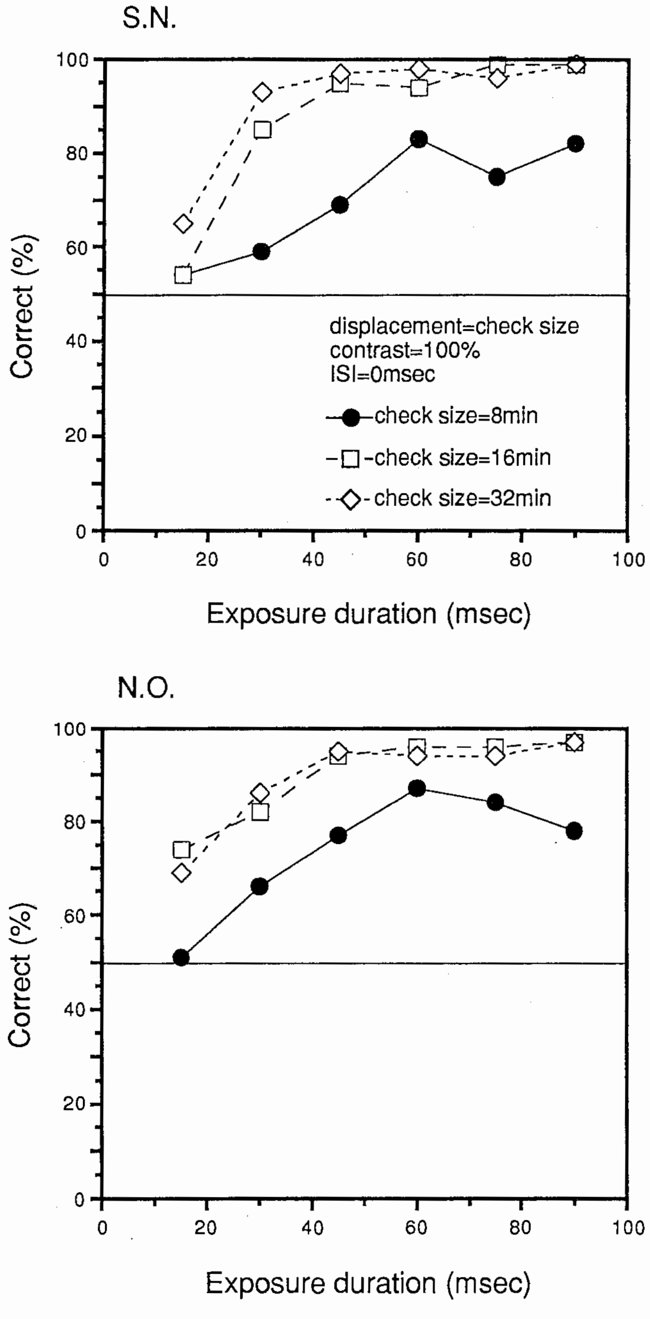
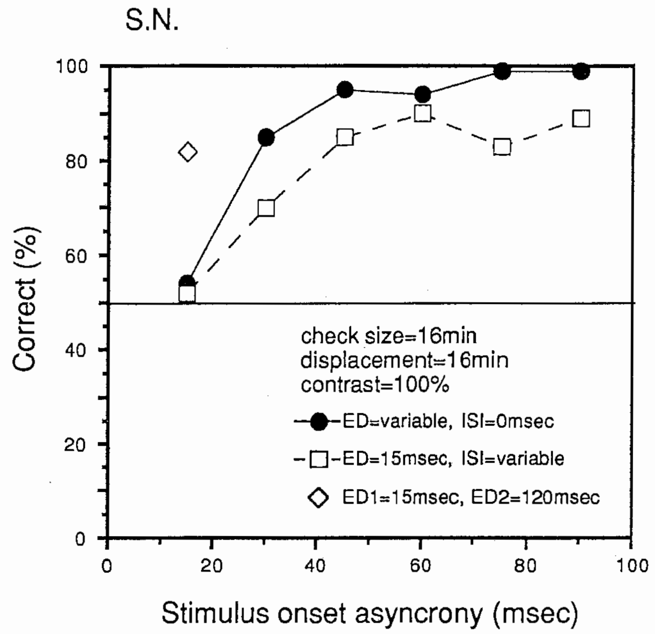


Figure 5. Percentage of correct responses of direction discrimination for RWK as a function of exposure duration.



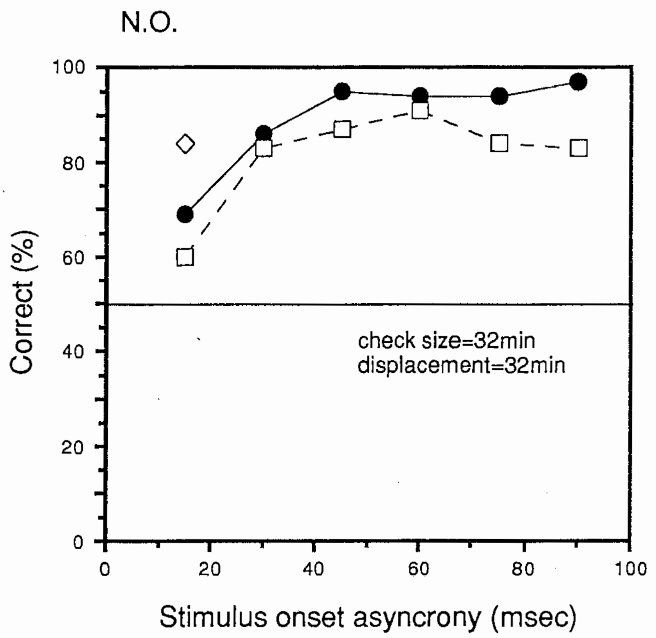


Figure 6. Percentage of correct responses of direction discrimination for RWK as a function of SOA.

functions show similar tendencies against SOA. The results suggest that the interaction between the effects of ED and ISI on the lower temporal limit for RWK discrimination is similar to that found for RDK discrimination.

As for RDK discrimination, the lowest temporal limit is determined by SOA only when the EDs of the first and second frames are the same. Even when SOA is kept very short, the direction discrimination performance increases with increasing ED of the second frame (Baker & Braddick, 1985). This is also the case for the direction perception for RWK. The discrimination performance obtained when ED was 15 msec for the first frame, and 120 msec for the second (open diamond in Figure 6) is much better than when the EDs of both frames were 15 msec, even though the SOAs were the same (15 msec) for both cases.

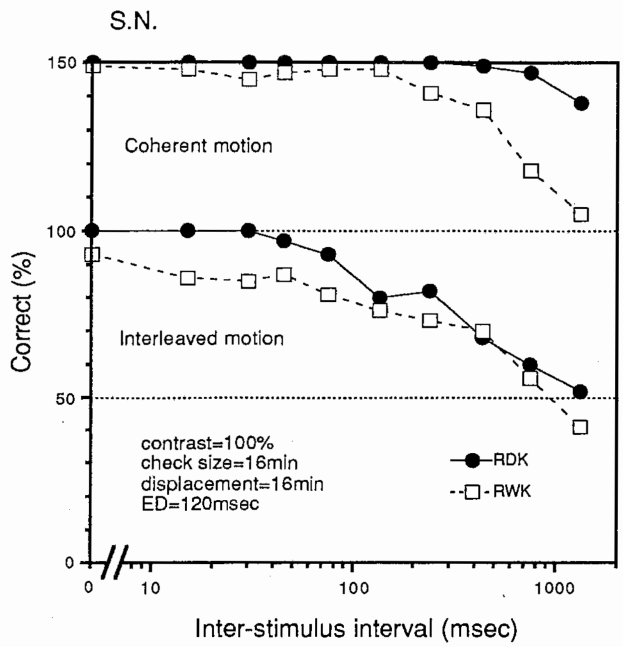
These results suggest that the effects of ED and SOA on the contrast motion mechanism are qualitatively similar to those on the luminance motion mechanism.

3.4. ISI

Previous studies have shown that the contribution of the non-luminance motion mechanism relative to that of the luminance motion mechanism gradually increases with ISI (Boulton & Baker, 1991; Georgeson & Harris, 1990), suggesting that the contrast motion mechanism may operate over a larger range of ISI than the luminance motion mechanism. This conjecture was examined in the following experiments by directly comparing the ISI dependencies of the direction discrimination for RDK and RWK.

First, the percentage of correct responses for discrimination of RDK and RWK was measured as a function of ISI, with their contrasts set at 100%. The check size and the displacement were both 16 min. ED was 120 msec, long enough to avoid the contribution of the ED effects described in the previous section. The results are shown in the upper portion of Figure 7 (coherent motion). As ISI increases, the discrimination performance for RDK gradually decreases. The function for RWK shows a similar ISI dependency. For all ISIs employed here, the performance for RWK is nearly equal to or slightly lower than that for RDK.

There is an individual difference such that discrimination for the larger ISIs is better for S.N. than for N.O. Note here that in the results for



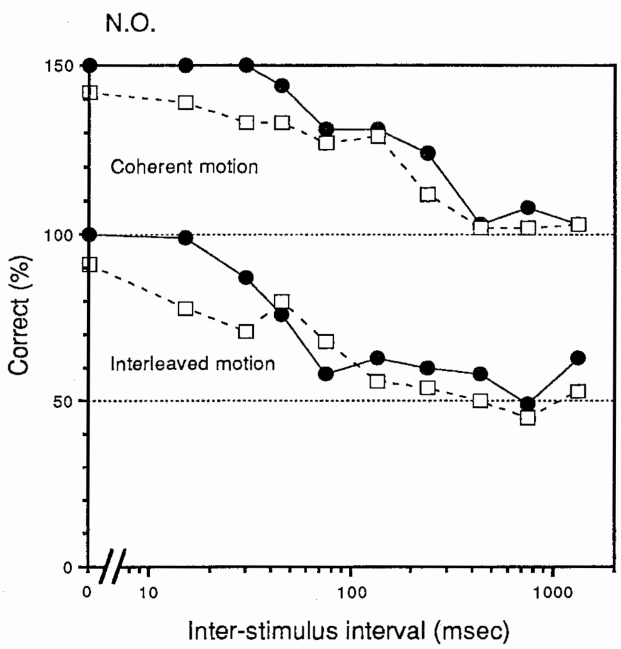
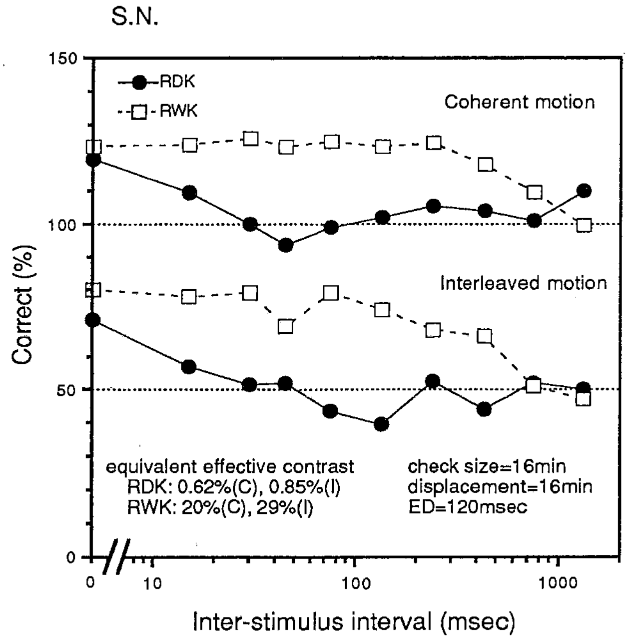


Figure 7. Percentage of correct responses of direction discrimination for RDK and RWK as a function of ISI. The data for coherent motion are shifted upwards by 50%, while the data for interleaved motion are on the true scale.

S.N. the performance for RDK is much better than the chance level even at ISI of more than 1000 msec. This suggests that a higher cognitive process which infers the shift direction from positional change of the pattern might contribute to the direction discrimination. To reduce the contribution of such a process, the experiment was replicated with an interleaved motion stimulus, where only elements in the rows of odd numbers (or even numbers) are shifted between the first and second frames. It is known for luminance motion that clear motion is seen in an interleaved motion display, but that the identity of the first and second patterns is hardly recognized (Sato, 1990,1991). The results obtained with the interleaved motion stimuli are shown in the lower portion of Figure 7. The discrimination performance for interleaved motion decreases with ISI more rapidly than for coherent motion. In the results for S.N., the performance for RDK decreases to the chance level at the longest ISI. Except for these points, the results for interleaved motion shows similar tendencies as those for coherent motion. The ISI dependencies for RDK and RWK are roughly the same.

The results shown in Figure 7 do not support the conjecture that the contrast motion mechanism operates over a larger range of ISI than the luminance motion mechanism. However, in this experiment, the contrasts of RDK and RWK were physically the same. Since the direction of RDK can be discriminated at a much lower contrast than required for RWK discrimination (Figure 4), the contrast condition was advantageous for RDK discrimination. Further, the RDK discrimination might be mediated by the contrast motion mechanism rather than the luminance motion mechanism, because the contrast motion mechanism prefers high contrast and large check size (Figures 3, 4). To equate the effective contrasts of RDK and RWK, the contrast dependency of direction discrimination for these stimuli was measured at zero ISI, and the contrast which gave 70 to 80% discrimination was estimated. The contrast of RDK given by this procedure is fairly low ($< 1\%$), so it is unlikely that the contrast motion mechanism contributes to the RDK discrimination.

The results obtained under equivalent effective contrast (Figure 8) shows a great difference in the ISI dependencies of RDK and RWK. The discrimination performance for RDK decreases rapidly with increasing ISI, down to the chance level at the ISI of roughly 30 msec. On the other hand, the performance for RWK remains nearly the same for a range of ISI (0 to 300 msec for S.N., 0 to 75 msec for N.O.), and then decreases to the chance



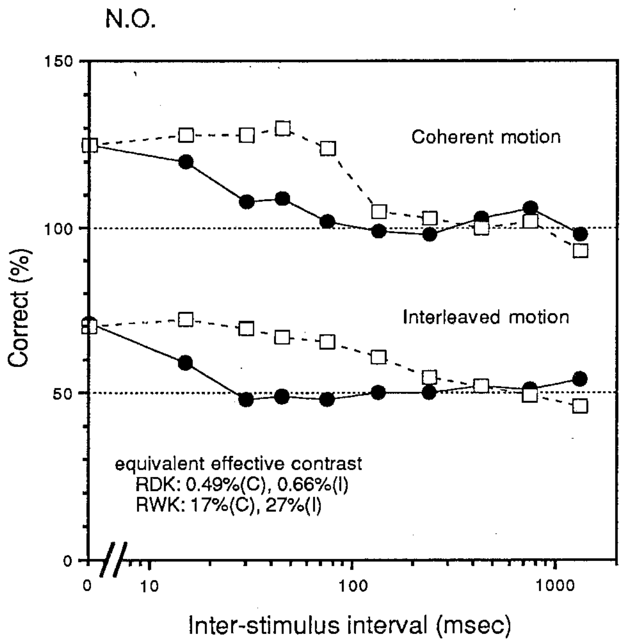


Figure 8. ISI dependencies of RDK and RWK discrimination performance obtained under equivalent effective contrast.

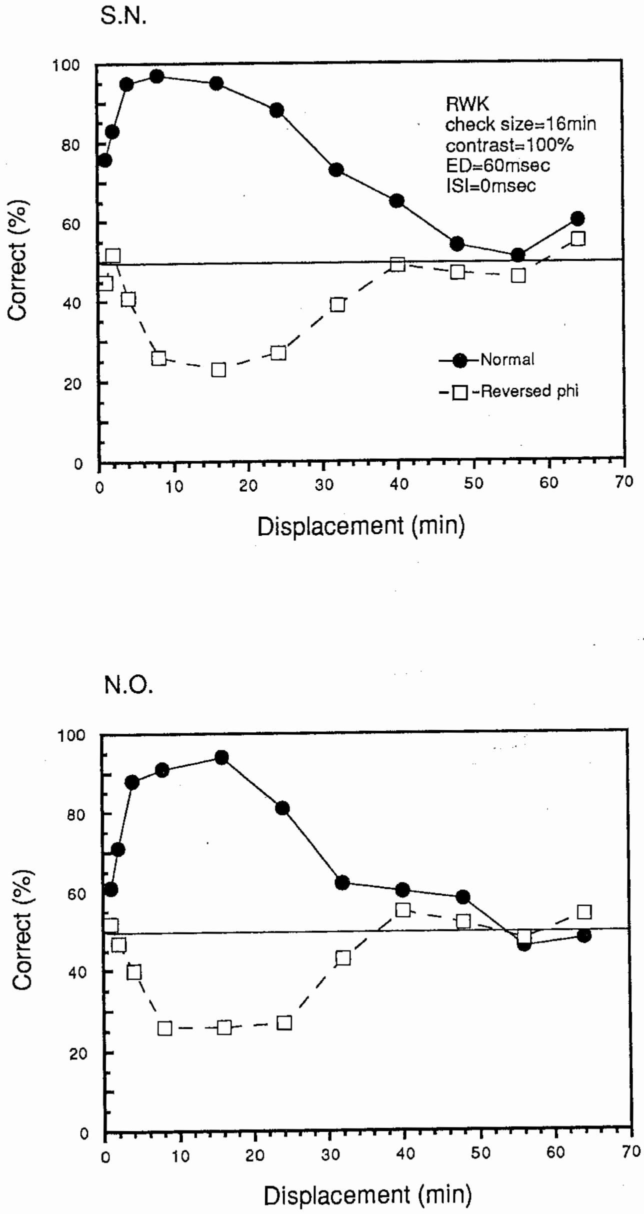


Figure 9. Percentage of correct responses of direction discrimination for RWK as a function of displacement. Filled circles represent the data obtained for normal coherent motion. Squares represent the data obtained when the random-dot checks and the gray checks were exchanged in the second frame, as in the reversed-phi display of luminance motion.

level with increasing ISI. Little difference is found between the results for the coherent and interleaved motion stimuli. These results suggest that the contrast motion mechanism operates over a greater range of ISI than the luminance motion mechanism.

3.5. Reversed phi

When the luminance contrasts of the first and second patterns are reversed, RDK is perceived to move in the direction opposite to the displacement (Anstis, 1970; Anstis & Rogers, 1975). To elucidate the mechanism for detecting contrast motion, it is of interest to see whether a similar phenomenon is obtained for RWK.

The window pattern was shifted between the first and second frames. At the same time, the random-dot checks were made uniform gray checks, and the gray checks were made random-dot checks. The discrimination performance for the pattern-reversed RWK is shown in Figure 9 as a function of displacement, together with the data for normal RWK. The check size was 16 min. ED was 60 msec, and ISI was 0. For a given range of displacement, the performance for the pattern-reversed RWK is significantly lower than the chance level, implying that motion in the reversed direction is perceived like a reversed-phi display of luminance motion. The displacement dependency for the pattern-reversed RWK is roughly symmetrical to that for the normal RWK, which implies that the reversed motion is mediated by the same mechanism as normal contrast motion.

3.6. Displacement

Displacement dependency, especially the maximum displacement limit (D_{max}), has been examined extensively for the perception of RDK (e.g., Braddick, 1974). Finally, the displacement dependencies for RDK and RWK were compared.

Figure 10 shows the percentage of correct responses of direction discrimination for RDK and RWK as a function of displacement. The contrast was 100% for both stimuli, and the check size was either 8, 16 or 32 min. ED was 60 msec, and ISI was 0. For RDK, the discrimination performance first increases slightly, then decreases with increasing displacement. There is an interaction between the effects of displacement and check size such that D_{max} gradually increases with check size. These tendencies are consistent with those obtained in previous studies (e.g.,

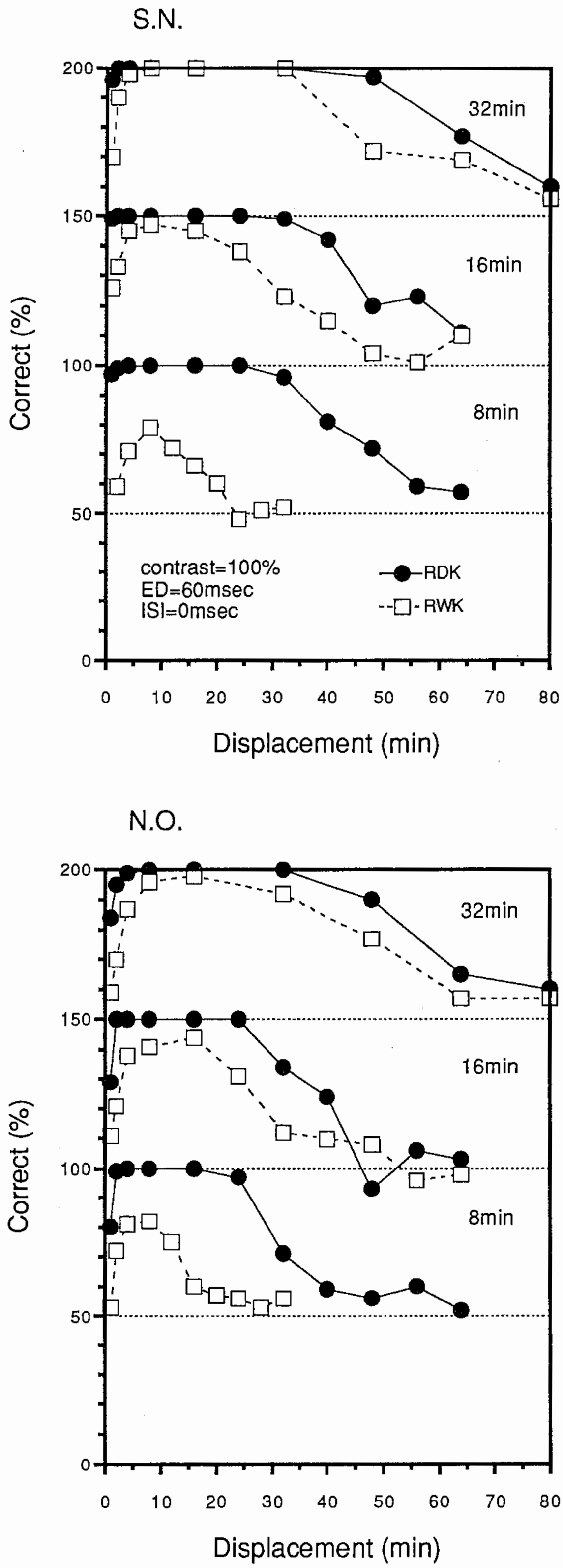


Figure 10. Percentage of correct responses of direction discrimination of RDK and RWK as a function of displacement. While the data obtained when the check size was 8 min are on the true scale, the data for 16 min and 32 min are shifted upwards by 50% and 100%, respectively.

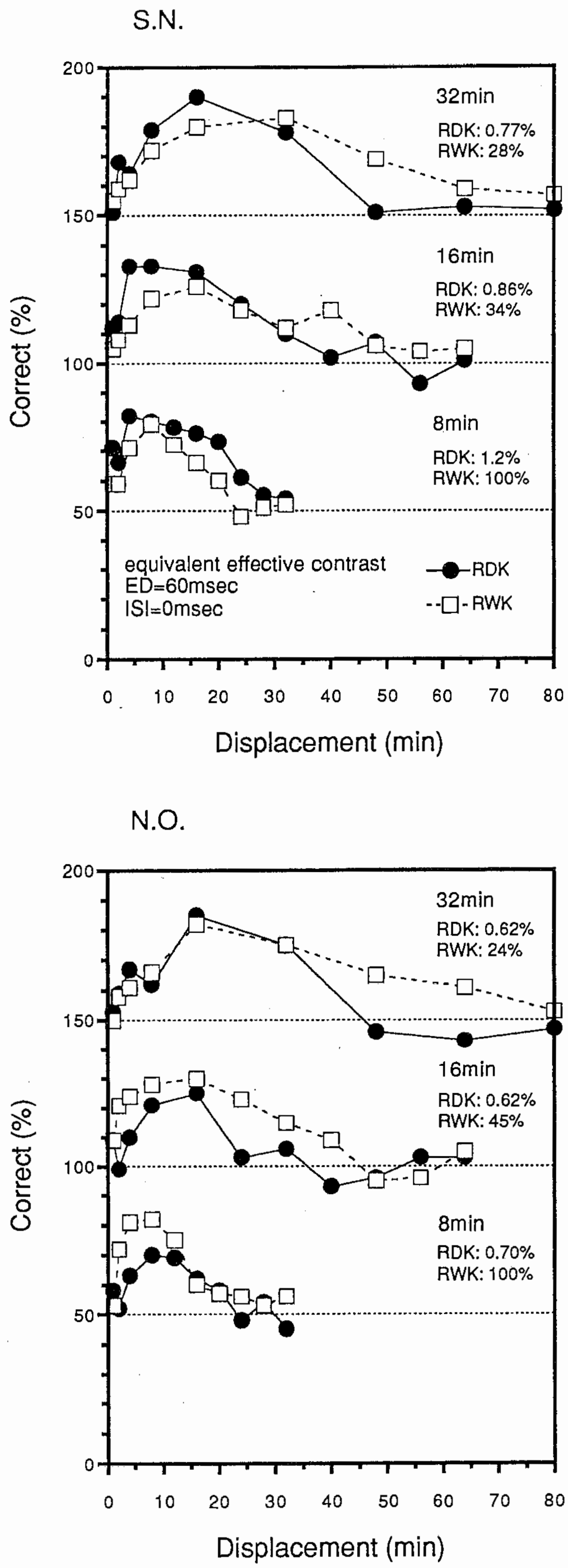


Figure 11. Displacement dependencies of RDK and RWK discrimination performance obtained under equivalent effective contrast.

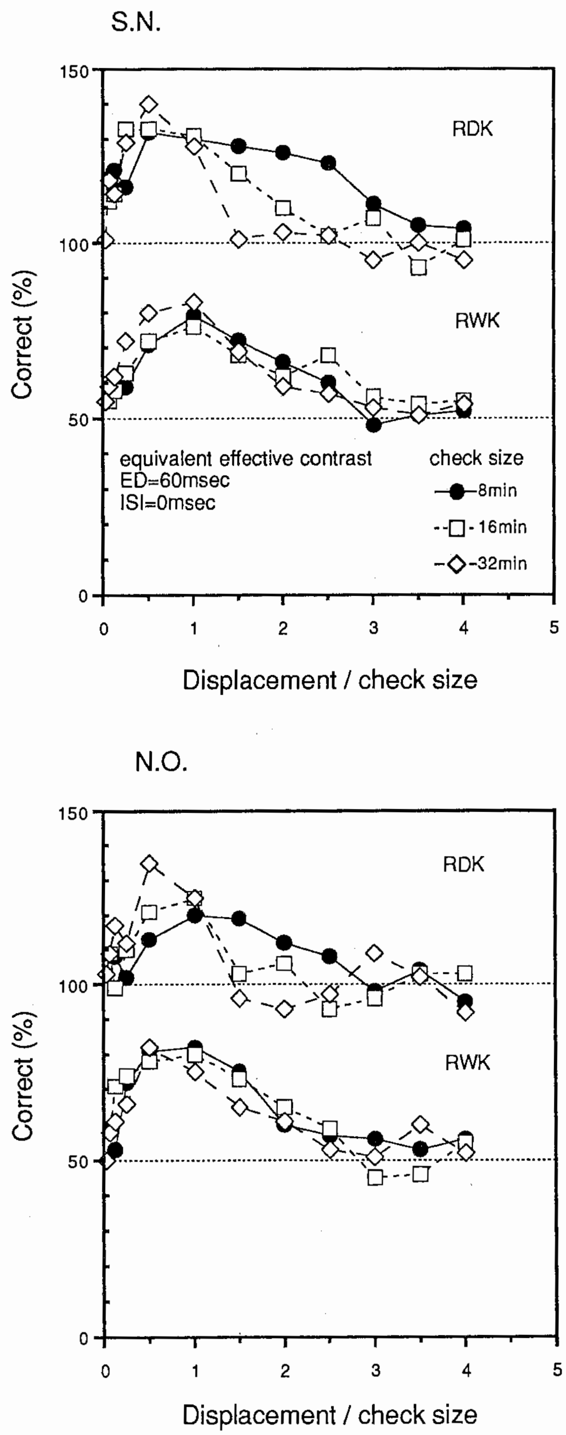


Figure 12. Percentage of correct responses of direction discrimination for RDK and RWK as a function of relative displacement (displacement / check size). The data obtained under equivalent effective contrast (Figure 11). While RWK data are on the true scale, RDK data are shifted upwards by 50%.

Cavanagh, Boeglin & Favreau, 1985; Lappin & Bell, 1976). For RWK, the effect of displacement and the interaction between the effects of displacement and check size are qualitatively similar to those obtained for RDK.

In Figure 10, the performance is better, so D_{max} is larger, for RDK than for RWK, especially when the check size is small. This tendency mainly results from a difference in the effective contrast of the stimuli. Figure 11 shows the results obtained under an equivalent effective contrast condition. Each stimulus employed the contrast for which the performance fell in the range of 70 to 80% with displacement equal to check size. Under this condition, the discrepancy in the displacement dependency is remarkably small between RDK and RWK. The D_{max} is not generally larger for RDK than RWK (or vice versa).

Although small, there is an interesting difference between the results for RDK and RWK in the interaction of the effects of displacement and check size. The difference is clearly seen when the results are plotted against displacement relative to check size (Figure 12). On this plot, the functions for RWK obtained for different check sizes nearly coincide. For all functions, the peaks of performance are at the displacement of 0.5 to 1.0 times the check size. On the other hand, the three functions for RDK show different dependencies on the relative displacement. As the check size increases from 8 to 32 min, the function shifts towards smaller relative displacement. In short, the performance for RWK can be characterized in terms of displacement relative to the check size, while that for RDK cannot.

4. *DISCUSSION*

The present study investigated the effects of various spatiotemporal parameters on the perception of contrast motion (RWK), and compared them with those obtained for luminance motion having a similar stimulus configuration (RDK). Since most of the parameters examined here supposedly tap the motion detection mechanism, the present results are discussed in terms of the contrast motion detector.

4.1. Incoherent motion

Like luminance motion, contrast motion was perceived for stimuli in which the pattern was not shifted coherently between frames. When only the elements in the odd or even rows were shifted, motion in the correct direction was perceived (interleaved motion; Figures 7,8). When the element patterns were reversed between frames, motion was perceived in the direction opposite to the displacement (reversed phi; Figure 9).

As the patterns of contrast modulations in these stimuli are not the same for the two frames, it is unlikely that the contrast motion mechanism calculates motion from global pattern matching. Since these incoherent motions can be derived from local correlations of contrast value across time and space, it is reasonable to suppose that a contrast motion detector operates on a local spatial area, as does a luminance motion detector.

4.2. SOA and ED

For short EDs, the performance for RWK increased with increasing ED (Figure 5). The effect of ED could be described as SOA dependency when the EDs of the frames were the same, but the performance was better than predicted from SOA when the first ED was short while the second was long. (Figure 6).

Baker and Braddick (1985) found exactly the same tendencies in direction discrimination for RDK. They argued that these properties reflect the dynamics of a spatiotemporal comparison (i.e., motion extraction) process of the luminance motion detector. The present results suggest that luminance and contrast motion detectors involve qualitatively similar motion extraction processes. Further, Baker and Braddick claimed that temporal properties as found in the present study are easily understood in terms of a correlation type of motion detection model (e.g., Reicherdt, 1961). Similarly, it could be argued from the present results that the motion extraction process of the contrast motion mechanism can be modeled as a correlation-type detector, as has been proposed by Chubb & Sperling (1988), and Cavanagh & Mather (1989).

4.3. ISI

On the other hand, the effects of ISI showed a quantitative difference between the motion extraction mechanisms for luminance and contrast motions. Under equivalent effective contrast, the discrimination performance decreased more gradually with ISI for RWK than for RDK (Figure 8). The results indicate that the contrast motion detector operates over a greater range of ISI than the luminance motion detector.

The maximum ISI for RDK discrimination shown in Figure 8 (less than 30 msec) was smaller than suggested by previous studies [about 100 msec (Baker & Braddick, 1985; Lappin & Bell, 1976)]. This underestimation is mainly due to the low contrasts employed in the present study. The maximum ISI value, however, was not an underestimation for the comparison with the RWK performance, since the effective contrast of RWK was supposedly as low as that of RDK.

The ISI dependency of direction discrimination for the high contrast RDK (Figure 7) was greatly different from that for the low contrast RDK (Figure 8), while being quite similar to the ISI dependency of RWK discrimination. Note here that the contrast motion detector prefers high stimulus contrast. Further, the check size employed here (16 min) was large enough to activate the contrast motion detector. It is likely that direction discrimination for the high contrast RDK was mediated by contrast motion detectors, at least for large ISIs.

The spatial frequency components were not the same for RDK and RWK; RWK contains more high frequency components than RDK. One might point out that the difference in the ISI dependencies of RWK and RDK can be ascribed to the difference in the spatial frequency content of the stimuli rather than to the mechanism difference. However, the difference in the spatial frequency content cannot account for the overall results of the present study. If one accepts that perception of the high contrast RDK is mediated by the same mechanism as that of RWK, it could be argued that the ISI dependencies for the low and high contrast RDKs reflect the temporal properties of the luminance and contrast motion mechanisms, respectively. The difference in ISI dependency cannot be ascribed to the difference in the spatial frequency content, since the stimuli differ from each other only in contrast.

Georgeson and Harris (1990) examined the effects of ISI on motion perception for the missing fundamental square-wave grating, successively shifting with displacements of a quarter cycle of the fundamental frequency. At ISIs shorter than 40 msec, motion was perceived in the reversed direction, presumably due to the activation of the luminance motion mechanism (Adelson, 1982; Adelson & Bergen, 1985), while at longer ISIs, motion was perceived in the correct direction. Their result suggests that the mechanism mediating correct direction operates over a greater range of ISI than the luminance motion mechanism. Interestingly, it could be shown that correct direction perception for the missing fundamental square-wave grating is not easily explained in terms of the rectification model proposed by Chubb & Sperling (1988). If it is mediated by the same mechanism as contrast motion, the model should be modified. The present results on the effects of ISI are not inconsistent with this possibility. Yet there remains the other possibility that the correct direction perception for the missing fundamental square-wave grating is mediated by a second-order mechanism of a different type, or by the attention-based feature-tracking process recently proposed by Cavanagh (1991).

4.4. Check size

The discrimination performance for RWK increased with check size, while the performance for RDK did not show such a tendency (Figures 3,4). Jamar and Koenderink (1985), who measured the contrast detection threshold of a sinusoidally-modulated white noise grating, showed that the detection threshold rises with the modulation frequency. Sutter, Chubb and Sperling (1991) reported similar results using two-dimensional stimuli. Their results suggest that the effect of check size on direction discrimination for RWK may take place at the level of contrast modulation detection.

Several studies have suggested that contrast modulation is extracted by examination of the outputs of low-level units which detect limited bands of luminance spatial frequencies (Badcock & Derrington, 1989; Chubb and Sperling, 1988; Henning, Hertz & Broadbent, 1975). For this kind of mechanism, low-frequency contrast modulations of random dots will be detected more efficiently than high-frequency modulations, because low-frequency modulations can be extracted from the outputs of bandpass units tuned to a wide range of luminance frequencies, while high-frequency modulations can be extracted only from outputs of units tuned to very high luminance frequencies. Therefore, it is reasonable to expect improvement in discrimination performance as check size increases. Of course there may remain other factors which also contribute to the effects of check size.

4.5. Displacement

When the contrast was 100% for RDK and RWK, the D_{max} values was larger for RDK than for RWK (Figure 10). However, when the effective contrast was the same for RDK and RWK, the D_{max} values for RDK and RWK were roughly the same (Figure 11). These results suggest that contrast motion detectors operate over spatial ranges comparable to those of luminance motion detectors when the spatial configurations and the effective contrasts of the stimuli are the same. In addition, this finding strongly supports the idea that the dichotomy of motion processes which regards the difference in D_{max} values as an important criterion (e.g., Braddick, 1974, 1980) is not valid (Cavanagh, 1991; Cavanagh & Mather, 1989).

4.6. Displacement - check size interaction

When the discrimination performance obtained under equivalent effective contrast was plotted as a function of relative displacement (displacement/check size), the functions for RWKs of different check sizes coincided, while the functions for RDK did not (Figure 12). This implies that the D_{max} for RWK increases in proportion to check size, while the D_{max} for RDK increases less than proportionally. The difference in the interaction between the effects of check size and displacement is one of the most interesting findings in the present study, since it suggests a qualitative difference between luminance and contrast motion mechanisms. Although previous studies have shown that the D_{max} for RDK increases linearly with the check size for sizes larger than 30 min (Cavanagh et al., 1985; Sato, 1990,1991), their finding may reflect a property of the contrast motion mechanism, because the stimuli they employed had high contrast and large check sizes.

Consider first the results for RDK. The visual system involves several types of luminance motion detectors, each tuned to a different range of spatial frequency (e.g., Adelson & Bergen, 1985). Since the contrasts of RDKs employed here (about 1%) was near the detection threshold, it is likely that the discrimination was mediated by a few detectors sensitive to the stimulus (2), and that the displacement dependencies roughly reflect their spatial scales. The spatial frequency spectrum of RDK is a lowpass function, a sinc function in 1D, whose scale in the frequency domain is inversely proportional to check size. If the sensitivity factor could be neglected, the scale of sensitive detectors might increase in proportion to check size. However, the contrast sensitivity of luminance motion detectors, as a whole, is a bandpass function against spatial frequency, whose peak lies at a fairly low spatial frequency (Kelly, 1979; Burr & Ross, 1982). Thus, the scale of sensitive detectors will come closer to the sensitivity peak, and it is reasonable that D_{max} increases with check size to an extent less than expected from proportional increase.

Consider next the D_{max} for RWK, which increased in proportion to the check size. If contrast motion is extracted by an algorithm similar to that for luminance motion (Chubb & Sperling, 1988; Cavanagh & Mather, 1989), it is natural to expect different types of contrast motion detectors, each tuned to a different range of spatial frequency of contrast modulation. Since the spatial frequency spectrum of RWK contrast modulation is the same as that of RDK luminance modulation, this model predicts a proportional increase in D_{max} for RWK with check size if the sensitivity of contrast motion detectors, as a whole, is independent of the spatial frequency of the contrast modulation. However, sensitivity to contrast modulation steadily decreases with spatial frequency (Jamar and Koenderink, 1985; Sutter et al., 1991). Thus, it is expected, as in the case for RDK, that D_{max} for RWK increases with check size to an extent less than expected from proportional increase. This is inconsistent with the present results.

The model of Chubb & Sperling (1988) involves spatiotemporal filtering before demodulation, which affects the contrast modulation available for the following motion extraction stage. However, it is hard to imagine that the effect of this stage gives rise to a proportional increase in D_{max} with check size.

There is a possibility that each of the contrast motion detectors may not be tuned to a narrow range of contrast spatial frequency. For example, the detector may have a Gaussian-like, rather than Gabor-like, receptive field. Although it might be possible to develop a model which can explain the present results on the basis of this possibility, such a model cannot help being too speculative from the knowledge currently available.

It has been suggested that some motion mechanisms extract motion after analysis and representation of features (Anstis, 1980; Georgeson & Shackleton, 1989; Georgeson & Harris, 1990). If one assumes that the motion in RWK is extracted after representation of edges and/or blobs of contrast modulations, it is not surprising for D_{max} to be limited by the number of false targets in the stimulus. The D_{max} would increase in proportion to check size, as found in the present study. This hypothesis is not inconsistent with the incoherent motion perception for RWK (interleaved motion, reversed phi), because even these kinds of motion can be derived from correlations of local features across time and space (Georgeson & Shackleton, 1989). A possible interpretation of the present results is that local features of contrast modulation are explicitly represented before motion extraction, giving rise to a proportional increase in D_{max}.

From the finding that the D_{max} for RWK increased in proportion to check size while D_{max} for RDK did not, it is possible to conclude that preprocessing of the contrast motion detector is different from, and probably more complex than, that assumed in the model of Chubb & Sperling (1988).

4.7. Summary of discussion

Like the luminance motion mechanism, the contrast motion mechanism extracts motion locally, and its motion extraction stage can be modeled as a correlation-type detector. These points are consistent with the model currently proposed (Cavanagh & Mather, 1989; Chubb & Sperling, 1988). The spatial ranges of the contrast motion detectors are comparable to those of the luminance motion detectors, but their temporal range is larger. Preprocessing before motion extraction is probably more complex than assumed in the rectification model of Chubb & Sperling (1988).

FOOTNOTES

(1) In this paper, the terms "luminance" and "contrast motion mechanisms" are used rather than "first-order" and "second-order mechanisms" (Cavanagh & Mather, 1989; Chubb & Sperling, 1989), because the latter terms may refer to mechanisms more general than those addressed in this paper. According to the definition by Cavanagh & Mather (1989), first-order includes a color motion mechanism, as well as luminance motion mechanism; second-order includes contrast motion mechanism, but also includes motion mechanisms for stimuli defined by difference in temporal frequency, motion, stereo disparity and so on. In my terminology, luminance (contrast) motion mechanism implies the mechanism for detection of motion of luminance (contrast) modulation. It is possible to suppose that the luminance motion mechanism detects color motion, and that the contrast motion mechanism detects some other types of second-order motion.

(2) For RDK of supra-threshold contrast, one might have to consider complex interaction among detectors tuned to different spatial frequencies (e.g., Cleary & Braddick, 1990).

REFERENCES

Adelson, E. H. (1982). Some new illusions and some old ones analyzed in terms of their Fourier components. *Investigative Ophthalmology & Visual Science (Suppl.), 22,* 144.

Adelson, E. H. & Bergen, J. R. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America, A2,* 284-299.

Anderson, S. J. & Burr, D. C. (1985). Spatial and temporal selectivity of the human motion detection system. *Vision Research, 25,* 1147-1154.

Anderson, S. J. & Burr, D. C. (1989). Receptive field properties of human motion detector units inferred from spatial frequency masking. *Vision Research, 29,* 1343-1358.

Anstis, S. M. (1970). Phi movement as a subtraction process. *Vision research, 10,* 1411-1430.

Anstis, S. M. (1980). The perception of apparent motion. *Philosophical Transactions of the Royal Society, London, B290,* 153-168.

Anstis, S. M. & Rogers, B. J. (1975). Illusory reversal of visual depth and movement during changes of contrast. *Vision Research, 15,* 957-961.

Badcock, D. R. & Derrington, A. M. (1985). Detecting the displacement of periodic patterns. *Vision Research, 25,* 1253-1258.

Badcock, D. R. & Derrington, A. M. (1989). Detecting the displacements of spatial beats: no role for distortion products. *Vision Research, 29,* 731-739.

Baker Jr, C. L. & Braddick, O. (1985). Temporal properties of the short-range process in apparent motion. *Perception, 14,* 181-192.

Braddick, O. J. (1974). A short-range process in apparent motion. *Vision Research, 14,* 519-527.

Braddick, O. J. (1980). Low-level and high-level processes in apparent motion. *Philosophical Transactions of the Royal Society, London, B290,* 137-151.

Boulton, J. C. & Baker Jr, C. L. (1991). Non-fourier mechanisms in apparent motion. *Investigative Ophthalmology & Visual Science (Suppl.), 32,* 893.

Burr, D. C. & Ross, J. (1982). Contrast sensitivity at high velocities. *Vision Research, 22,* 479-484.

Cavanagh, P. (1991). Short-range vs long-range motion: Not a valid distinction. *Spatial Vision, 5,* 303-309.

Cavanagh, P., Boeglin, J. & Favreau, O. E. (1985). Perception of motion in equiluminous kinematograms. *Perception, 14,* 151-162.

Cavanagh, P. & Mather, G. (1989). Motion: The long and short of it. *Spatial Vision, 4,* 103-129.

Chubb, C & Sperling, G. (1988). Drift-balanced random stimuli: a general basis for studying non-Fourier motion perception. *Journal of the Optical Society of America, A5,* 1986-2007.

Cleary, R. & Braddick, O. J. (1990). Masking of low frequency information in short-range apparent motion. *Vision Research, 30,* 317-327.

Derrington, A. M. & Badcock, D. R. (1985). Separate detectors for simple and complex grating patterns? *Vision Research, 25,* 1869-1878.

Dosher, B. A., Landy, M. S. & Sperling, G. (1989). Kinetic depth effect and optic flow – I. 3D shape from Fourier motion. *Vision Research, 29,* 1789-1813.

Georgeson, M. A. & Harris, M. G. (1990). The temporal range of motion sensing and motion perception. *Vision Research, 30,* 615-619.

Georgeson, M. A. & Shackleton, T. M. (1989). Monocular motion sensing, binocular motion perception. *Vision Research, 29,* 1511-1523.

Henning, G. B., Hertz, B. G. & Broadbent, D. E. (1975). Some experiments bearing on the hypothesis that the visual system analyses spatial patterns in independent bands of spatial frequency. *Vision Research, 15,* 887-897.

Jamar, J. H. T. & Koenderink, J. J. (1985). Contrast detection and detection of contrast modulation for noise gratings. *Vision Research, 25,* 511-521.

Julesz, B. (1971). *Foundations of cyclopian Perception.* University of Chicago Press, Chicago, IL.

Kelly, D. H. (1979). Motion and vision II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America, 69,* 1340-1349.

Landy, M. S., Dosher, B. A., Sperling, G. & Perkins, M. E. (1991). Kinetic depth effect and optic flow – II. First- and second-order motion. *Vision Research, 31,* 859-876.

Lappin, J. S. & Bell, H. H. (1976). The detection of coherence in moving random-dot patterns. *Vision Research, 16,* 161-168.

Mather, G. (1991). First-order and second-order visual processes in the perception of motion and tilt. *Vision Research, 31,* 161-167.

Nakayama, K. (1985). Biological image motion processing: a review. *Vision Research, 25,* 625-660.

Pantle, A., Lehmkuhle, S. & Caudill, M. (1978). On the capacity of directionally selective mechanisms to encode different dimensions of moving stimuli. *Perception, 7,* 261-267.

Prazdny, K. (1986). Three-dimensional structure from long-range apparent motion. *Perception, 15,* 619-625.

Ramachandran, V. S., Rao, V. M. & Vidyasager, T. R. (1973). Apparent motion with subjective contours. *Vision Research, 13,* 1399-1401.

Reicherdt, W. (1961). Autocorrelation, a principle for the evaluation of sensory information by the central nervous system. In Rosenblith, W. A. (Ed.) *Sensory communication.* Cambridge, Mass.: MIT Press and New York: Wiley.

Sato, T. (1990). Effects of dot-size and density on motion perception with random-dot kinematograms. *Perception,* 19, 329(A7).

Sato, T. (1991). Stimulus parameters underlying the short- and long-range difference. *Investigative Ophthalmology & Visual Science (Suppl.), 32,* 826.

Sperling, G. (1976). Movement perception in computer-driven visual displays. *Behavior Research Methods & Instrumentation, 8,* 144-151.

Sperling, G. (1989). Three stages and two systems of visual processing. *Spatial Vision, 4,* 183-207.

Sutter, A., Sperling, G. & Chubb, C. (1991). Further measurements of the spatial frequency selectivity of second-order texture mechanisms. *Investigative Ophthalmology & Visual Science (Suppl.), 32,* 1039.

Turano, K. & Pantle, A. (1989). On the mechanism that encodes the movement of contrast variations: velocity discrimination. *Vision Research, 29,* 207-221.

Van Santen, J. P. H. & Sperling, G. (1984). Temporal covariance model of human motion perception. *Journal of the Optical Society of America A, 1,* 451-473.

Van Santen, J. P. H. & Sperling, G. (1985). Elaborated Reichardt detectors. *Journal of the Optical Society of America A, 2,* 300-321.

Von Grünau, M. W. (1986). A motion aftereffect for long-range stroboscopic apparent motion. *Perception & Psychophysics, 40,* 31-38.

Watson, A. B. & Ahumada, A. J. Jr (1985). Model of human visual-motion sensing. *Journal of the Optical Society of America A, 2,* 322-342.