Exp Brain Res (1982) 45: 179–188

Experimental Brain Research

Temporal Properties of the Visual Detectability of Moving Spatial White Noise*

A. J. van Doorn and J. J. Koenderink

Dept. of Medical and Physiological Physics, Physics Laboratory, State University Utrecht, Princetonplein 5, NL–3584 CC Utrecht, The Netherlands

Summary. We obtained movement detection thresholds for two-dimensional random speck-patterns ("Julesz" patterns) homogeneously moving over the whole target field (5.21 × 5.31 degrees of visual angle). We alternated between two uncorrelated but otherwise similar patterns, one moving with velocity $\vec{v}_1$, the other with velocity $\vec{v}_2$, such that each pattern was on for T ms. We masked this pattern (signal) with spatio-temporal white noise ("snow"). The total r.m.s. contrast was kept constant, whereas the ratio of the r.m.s. contrasts of signal and noise was varied. The square of this ratio was designated SNR.

At low SNR values the pattern was not perceptually different from the snow alone. At high SNR values the subject detected spatio-temporal correlation (e.g., movement). In these experiments we determined the threshold SNR values as a measure of the detectability of spatio-temporal correlation as a function of the parameters T, $\vec{v}_1$ and $\vec{v}_2$.

When $\vec{v}_1$ and $\vec{v}_2$ were sufficiently dissimilar one of three percepts occurred: for very large T the alternation could be followed, for very small T two transparent, simultaneously moving sheets of noise-pattern with different velocities could be seen. For intermediate T-values no systematic movement at all could be observed. At these T-values the threshold SNR was maximal. This "critical" T-value decreased with increasing velocity.

We found that it was possible to have more than one percept of uniform smooth movement at a single location in the visual field if these movements had velocity vectors with an angular difference of at least 30 deg or if their magnitudes differed by at least a factor of 4.

* Supported in part by the Netherlands Organization for the Advancement of Pure Research (Z.W.O.)

Offprint requests to: Dr. A.J. van Doorn (address see above)

Key words: Vision – Psychophysics – Movement perception

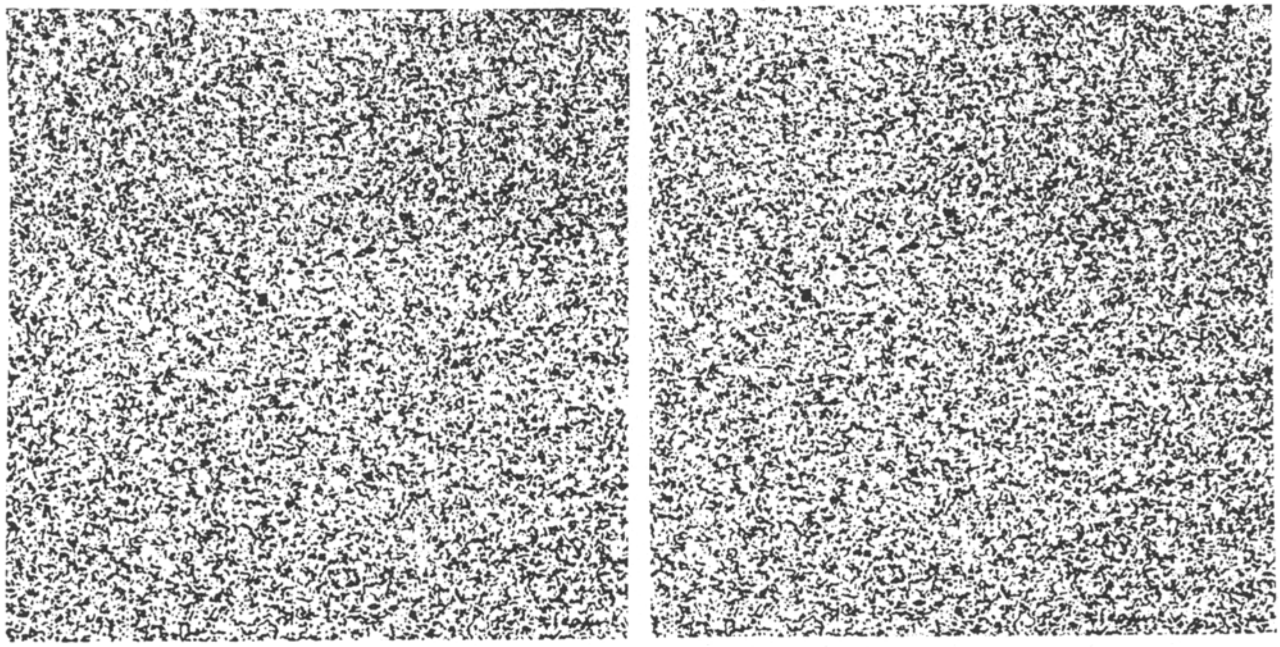
Introduction

The visual system of man and many animals is very sensitive to spatial patterns moving with respect to the retina, even to the extent that stabilized images have proved to be insufficient to sustain vision. Thus, movement with respect to the retina is a necessary condition for the sustained vision of spatial detail. Quantitative studies on visual detection of movement have a relatively long history in psychophysics.

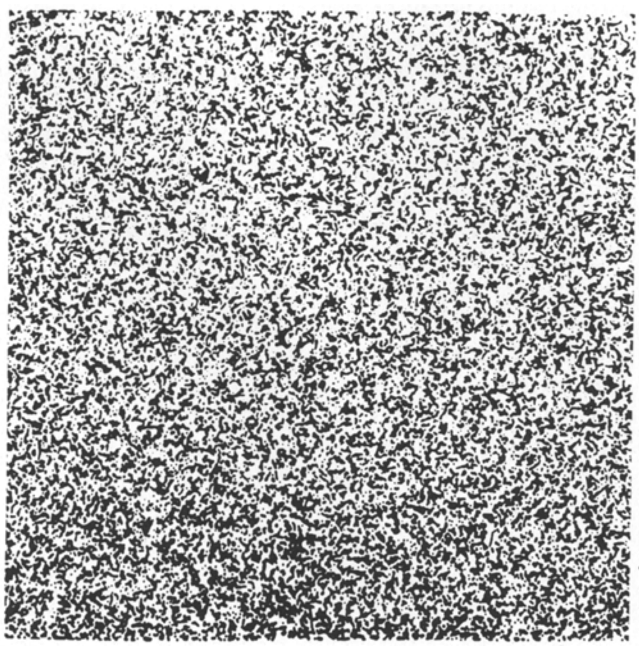
Up to now most data on movement perception refer to specific moving stimuli: certain figures, either localized (e.g., points) or non-localized (gratings). In general, these stimuli share a common property, i.e., if one considers two momentary spatial configurations a finite time difference apart it is possible to observe a well-defined displacement. This introduces a problem: in this way it is possible to detect movement by way of successive estimations of position, much like seeing the movement of the hour hand of a watch. It is generally agreed that the movement of the second hand is seen in a different way, i.e., this movement is detected "directly". We were interested in this second way of detecting movement. Thus, we could not use stimulus patterns with clearly-marked local features. We used homogeneously moving random speck-patterns (such as were introduced by Julesz (1971) in the study of stereopsis) over the entire target field.

If two single frames are presented to the subject, the subject is not able to detect the shift; in fact he is not even able to detect whether the patterns are identical but displaced or totally uncorrelated patterns (Fig. 1).

0014-4819/82/0045/0179/$ 2.00



a b



c

Fig. 1. a and **b** are completely correlated Julesz patterns except for a small strip. The pattern in **c** is completely uncorrelated with the patterns in **a** and **b.** Note that the fact that **a** is correlated with **b,** and not with **c,** is not perceived spontaneously but only after intently scrutinizing the patterns. When **a** and **b** form part of a regular sequence the correlation is at once apparent and a smooth flow is perceived

If a series of successive frames are presented in quick succession (in our case 10 ms per frame) a smooth uniform movement over the whole target field is immediately perceived. Thus, movement percept is a result of the detection of *spatio-temporal* correlation, because the shift in successive frames is in general not apparent when the frames are not presented in quick succession.

In quantitative studies of human movement perception two general ways are open to assign numbers to the detection performance: One either determines the extreme conditions of velocity for which a percept of movement occurs or degrades the stimulus in some reproducible manner. The first possibility has often been used, but is apt to yield rather incomplete data, i.e., with this method it is not possible to quantify the detection performance for intermediate velocities. This limitation is similar to the study of flicker by means of the critical flicker frequency only. The other manner is more suitable to yield comprehensive results. Most previous studies have used contrast as a variable. Obviously the impression of movement vanishes if the contrast is too low. However, there is the problem that we are not specifically interested in the detection of contrast but in the detection of movement. And several studies have indicated that the detection thresholds for pattern and movement detection differ (van Nes et al. 1967).

To avoid problems with the interpretation of results with respect to detection of spatio-temporal contrast and spatio-temporal correlation we used patterns with a constant supra-threshold r.m.s. contrast of the compound stimulus, i.e., the superposition of signal and noise. We degraded the spatio-temporal correlation (at constant r.m.s. contrast) in the following manner: the stimulus consisted of a superposition of two sequences of Julesz-patterns. In one sequence each pattern was shifted by a fixed amount for every new frame (the signal). In the other sequence all frames were completely uncorrelated (noise; this sequence alone looks like "snow"). The ratio of the r.m.s. contrasts of signal and noise was used as a variable that determined the amount of available spatio-temporal correlation. We called the square of this ratio the signal-to-noise ratio (SNR).

We determined the threshold SNR for several values of parameters that described either the spatio-temporal configuration of the stimulus or the velocities present in the signal.

Concerning the temporal behavior of movement perception, Clarke (1977) described a phenomenon caused by the interaction of moving patterns. When he alternated the direction of movement of a visual noise stimulus he obtained different kinds of appearance of the stimulus depending on the rate of alternation. For high alternation rates the oppositely directed movements of the alternated noise patterns were simultaneously visible at any location of the target field. With our equipment we found a similar phenomenon. We interpreted the results in terms of a simple and very general mechanism for the detection of spatio-temporal correlation. Our experimental results allowed us to estimate the temporal parameters of such mechanisms.

Material and Methods

The stimulus was generated on a CRT display (HP, model 1317-A, P4 phosphor, 470 μs decay time to 1% intensity). The display contained 250 × 255 points. Each point subtended 1.25 min of arc. Every 10 ms a new frame could be written line for line. We presented the subject with moving two-dimensional white noise (Julesz pattern). In such a pattern, each point was randomly assigned a light or dark value with probability 0.5 as follows: successive frames contained identical Julesz patterns displaced over a certain small visual angle. At the border where new pattern was coming in, the image was completed with uncorrelated noise. A velocity value of 1.25 min per 10 ms (i.e., 2.08 deg of visual angle per second) was obtained when every 10 ms the pattern was displaced just one point on the display. Higher values of the velocity were realized by a displacement of the pattern by more than one point. Smaller values of the velocity were realized by writing identical patterns for a number of successive frames and then displacing the pattern over 1.25 min of arc. Because the magnitudes of the horizontal and vertical components of the velocity could be adjusted separately the direction of movement could be varied, too. With present electronic devices significantly better methods of generating these stimuli were not available.

In principle, the movement generated with this method was not continuous. In fact the stimulus consisted of stroboscopically displayed moving spatial noise patterns[1]. Nevertheless, the perception was always that of uniform smooth movement.

A single frame consisted of 250 × 255 dots that were light or dark with probability 50%. Thus, the screen consisted of many small patches with luminance either I_1 or I_2. The mean luminance of the screen was $\frac{1}{2}(I_1+I_2)$, whereas the r.m.s. contrast was:

$$\frac{(\overline{I^2} - (\bar{I})^2)^{1/2}}{\bar{I}} = \frac{I_1 - I_2}{I_1 + I_2}.$$

The noise pattern ("snow") was generated in the same way as the signal. The only difference was that every new frame was completely uncorrelated with the previous one. The r.m.s. contrast of the noise was defined in the same manner.

The r.m.s. contrast of the superposition of signal and noise was

$$C = \sqrt{(\text{r.m.s. contrast}_{\text{signal}})^2 + (\text{r.m.s. contrast}_{\text{noise}})^2}$$

because for uncorrelated patterns variances add. The value of C was 35% in all experiments.

The signal-to-noise ratio (SNR) was defined as

$$\text{SNR} = \frac{(\text{r.m.s. contrast}_{\text{signal}})^2}{(\text{r.m.s. contrast}_{\text{noise}})^2}$$

This was the parameter that was varied by the subjects in our experiments. The SNR could be varied in steps of 0.2 dB from 10^{-5} up to $4 \cdot 10^2$. The parameter variations were all obtained by (digital) electronic means.

The subject viewed the display with both eyes and natural pupils. He used a head and chin rest. The total target field measured 5.21 × 5.31 deg of visual angle. Mean luminance was 180 cd/m^2. The surround was dark. A black fixation spot (diameter: 4 min of arc) was presented in the center of the field. The distance from subject to screen was 2.75 m. The subjects (the

1 With such a stimulus the observer can have a percept of so-called α-stripes described by us in a previous paper (Koenderink and van Doorn 1980). The subject occasionally perceived a stationary grating pattern of which the bars were perpendicular to the direction of the moving noise. Apart from these so-called α-stripes, smooth optimal movement was seen. Adler and Grüsser (1979) reported the same phenomenon. It seems unlikely that this occasionally visible stationary irregular grating pattern influences our movement threshold measurements. Near the threshold SNRs the α-stripes were not detectable

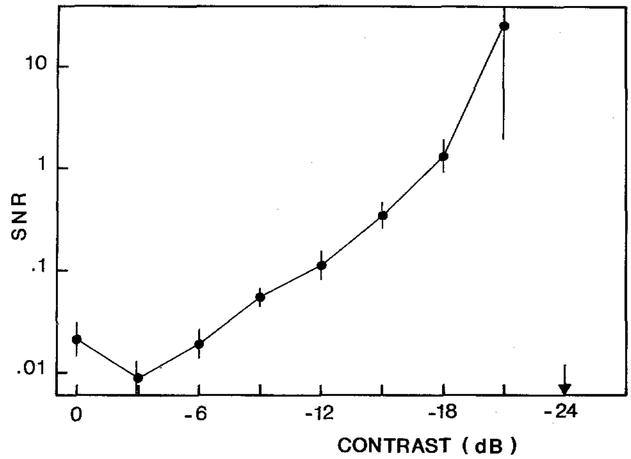


Fig. 2. The threshold SNR as a function of the r.m.s. contrast of the stimulus. v = 2.08 deg · s^{-1}. For this experiment T = 1,000 ms

authors) were normal trichromats (AD, female, 32 years, –2D myopic at both eyes; JK, male, 37 years, without correction).

The experimental procedure was as follows: The stimulus was periodical with period 2T ms. In one half-period (T ms, T a multiple of 10 ms) one Julesz pattern moved uniformly with velocity $\vec{v}_1$, the next half-period another (uncorrelated with the first) Julesz pattern moved uniformly with velocity $\vec{v}_2$. The threshold SNR was determined as a function of T, $\vec{v}_1$ and $\vec{v}_2$.

The subject fixated the center of the field and took his own time to reach the threshold. Starting with maximal SNR he lowered the SNR until the stimulus looked completely snow-like, then he raised the SNR until the signal appeared again, etc. This he repeated 16 times. The mean value of all upper and lower settings was taken as the threshold SNR.

The SD of the means of successive upper and lower settings (except for the first and final setting) was also calculated. The same combination of T, $\vec{v}_1$ and $\vec{v}_2$ was repeated three times on different days. From those three mean threshold values the weighted mean (the final threshold value) was determined with its standard deviation.

The measurements were performed within 1 month. Repeatability was good, and both subjects showed the same threshold behavior.

For the interpretation of the results it was important to check that the threshold SNRs did not depend on C. If the thresholds were independent of C we could be sure that the subject detected movement on the basis of spatio-temporal correlation present in supra-threshold patterns (with respect to contrast). We have checked this in an experiment in which we determined threshold SNRs as a function of C. (Note that in all experiments reported in the remainder C was kept at a constant value.) Figure 2 displays a typical result. It can be seen that the threshold SNR was invariant against changes of C (within the experimental spread) for a range of supra-threshold contrast values of about 6 dB. The value for the contrast used in the remainder of this report corresponded to the 0 dB value in Fig. 2.

Results

Experiment 1

In this experiment, the magnitudes of the velocities $\vec{v}_1$ and $\vec{v}_2$ were equal, but the direction was periodically changed from right to left into left to right, etc. (Thus, $\vec{v}_1 = -\vec{v}_2$). The threshold SNR was determined as a function of the alternation period T, with the magnitude v (= $|\vec{v}_1| = |\vec{v}_2|$) as parameter. In Fig. 3 the results are gathered.

At suprathreshold values of the SNR three different percepts occurred dependent on the parameter values. First, for low alternation rates the subject could distinguish direction of movement and follow each reversal of direction. Thus, he perceived a back and forth movement. The threshold SNRs were

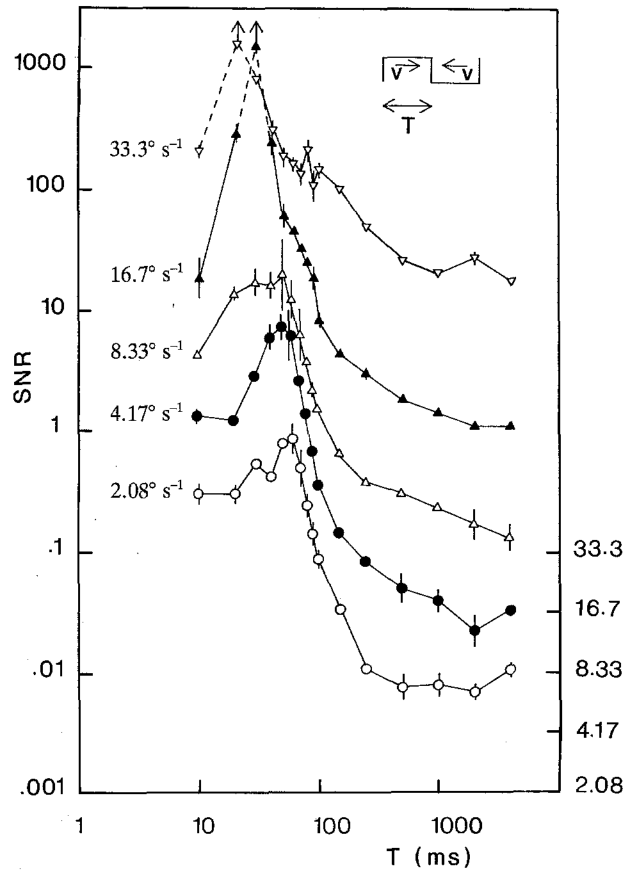


Fig. 3. The threshold SNR for the case that patterns moving with the same velocity in opposite directions are alternated. (Expt. 1: $\vec{v}_1 = -\vec{v}_2$). The inset at the top right of the figure schematically indicates the experimental condition. The numbers along the right side of the figure denote the values of the velocities used in the experiment (in deg · s^{-1}). For each velocity the height of the bottom of the SNR-scale (SNR = 0.001) is indicated with a mark along the vertical axis next to the value of that particular velocity. For v = 2.08 deg · s^{-1} this coincides with the bottom of the figure. This shift makes the curve more easily readable: they form a dense tangle if in the right position.
Subject AD. Total target extent 5.21 × 5.31 deg of visual angle. Mean luminance 180 cd/m^2. Dark surrounding. Vertical bars through the data points denote the standard deviation (SD) (only depicted when they exceed the size of the symbols)

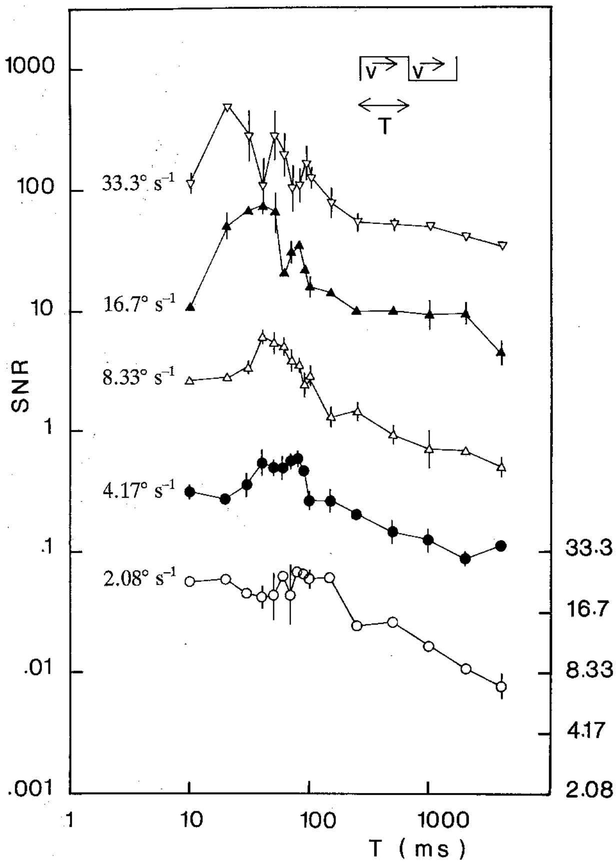


Fig. 4. The threshold SNR for the case that patterns moving with the same velocity in the same direction are alternated. (Expt. 2: $\vec{v}_1 = \vec{v}_2$). The inset at the top right of the figure schematically indicates the experimental condition. The numbers along the right side of the figure denote the values of the velocities used in the experiment (in deg $\cdot$ s^{-1}). For each velocity the height of the bottom of the SNR-scale is indicated with a mark along the vertical axis next to the value of that particular velocity. For v = 2.08 deg $\cdot$ s^{-1} this coincides with the bottom of the figure.
Subject AD. Total target extent 5.21 × 5.31 deg of visual angle. Mean luminance 180 cd/m^2. Dark surrounding. Vertical bars through the data points denote the standard deviation (only depicted when they exceed the size of the symbols)

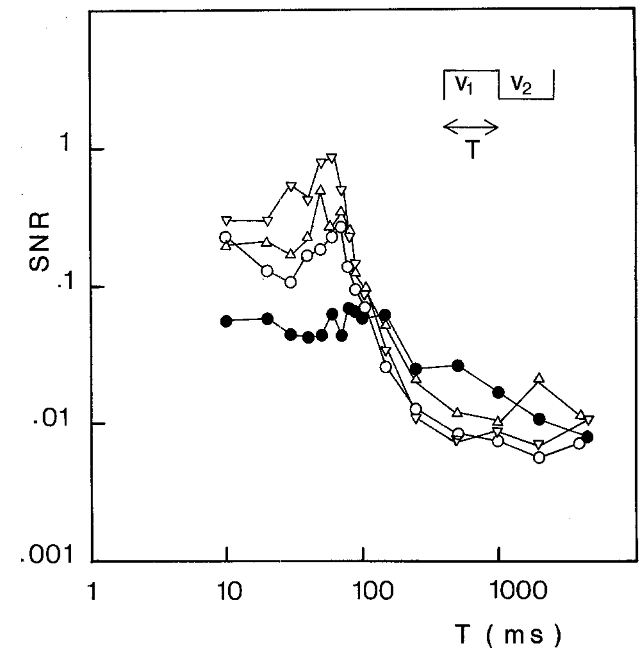


Fig. 5. The threshold SNR in the case that a Julesz pattern moving with velocity $\vec{v}_1$ is alternated with a Julesz pattern moving with velocity $\vec{v}_2$. The inset at the top right of the figure schematically indicates the experimental condition (Expts. 1–3).
○ $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and orthogonal directions. $|\vec{v}_1| = |\vec{v}_2| = 2.08°\ s^{-1}$
▽ $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and opposite directions. $|\vec{v}_1| = |\vec{v}_2| = 2.08°\ s^{-1}$
● $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and equal directions. $|\vec{v}_1| = |\vec{v}_2| = 2.08°\ s^{-1}$
△ $|\vec{v}_1| = 2.08°\ s^{-1}$, $|\vec{v}_2| = 0°\ s^{-1}$
Subject AD. Total target extent 5.21 × 5.31 deg of visual angle. Mean luminance 180 cd/m^2. Dark surrounding

relatively low (in Fig. 3 all threshold data at the right side of the maxima). Secondly, for high alternation rates the subject could not follow the alternation, instead he could see two patterns moving simultaneously over the entire field in opposite directions. The percept was that of two transparent moving sheets, the alternation frequency was in no way apparent (in Fig. 3 the threshold SNRs at the left side of the maxima). Thirdly, there was an intermediate range of alternation rates for which there was no percept of movement at all. In those cases the display looked like "snow". The subject did not perceive coherent movement over appreciable areas nor was the alternation apparent. It was at these alternation rates that the maxima in the threshold curves occurred (Fig. 3). The value of this *critical period* was seen to depend on the velocity v (Fig. 3).

Experiment 2

In this experiment, a Julesz pattern that moved uniformly with velocity $\vec{v}$ was alternated periodically with another Julesz pattern that moved uniformly with the same velocity $\vec{v}$ ($\vec{v}_1 = \vec{v}_2$). In this condition the perceptions of back and forth movement or transparent sheets did, of course, not occur. The intermediate region where the percept was "snow"-like did occur. The threshold SNRs are gathered in Fig. 4. In this case, as in Expt. 1, we found relatively high values of the threshold SNR in the region of intermediate alternation rates where the percept was snow-like.

This experiment was of interest because the percept near the threshold SNR was always the same,

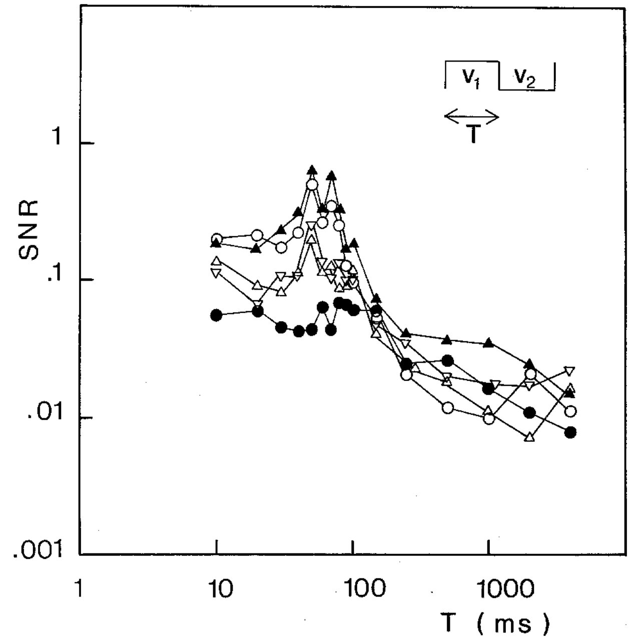


Fig. 6. The threshold SNR in the case that a Julesz pattern moving with velocity v_1 is alternated with a Julesz pattern moving with velocity v_2 in the same direction. v_1 is always the same, v_2 is varied. The inset at the top right of the figure schematically indicates the experimental condition.
○ $v_1 = 2.08° s^{-1}$, $v_2 = 0° s^{-1}$
● $v_1 = 2.08° s^{-1}$, $v_2 = 2.08° s^{-1}$
▽ $v_1 = 2.08° s^{-1}$, $v_2 = 4.17° s^{-1}$
△ $v_1 = 2.08° s^{-1}$, $v_2 = 8.33° s^{-1}$
▲ $v_1 = 2.08° s^{-1}$, $v_2 = 16.7° s^{-1}$
Subject AD. Total target extent 5.21 × 5.31 degrees of visual angle. Mean luminance 180 cd/m^2. Dark surrounding

a degraded uniformly moving Julesz pattern. Thus, we were sure that the subject's detection criterion was the same for all alternation rates.

It will be seen from Figs. 3 and 4 that the threshold SNRs for large values of T differed somewhat for the two conditions. We did not investigate the cause of this difference. Intuitively, we expect the direction reversal to be important here as it makes the patterns more conspicuous.

Experiment 3

In this experiment the directions of the velocity in successive periods were perpendicular to each other. The results of this experiment were completely analog to those of the first experiment. We measured about the same threshold curves, and again three possible percepts could be distinguished. In Fig. 5 some typical results obtained in the situations of Expts. 1, 2, and 3 are compared.

Experiment 4

In this experiment we alternated between two Julesz patterns moving uniformly in the same direction but with different magnitudes (Thus, $\vec{v}_1 = \alpha\vec{v}_2$ with $\alpha \geq 0$). In this case the introspective reports of the subject were similar to those in Expt. 2 when the magnitudes of $\vec{v}_1$ and $\vec{v}_2$ were not too different ($1/4 < \alpha < 4$). When the magnitudes of the velocities differed more, then transparency occurred at high alternation rates. The subject reported two uniformly moving patterns that moved simultaneously in the same direction with different velocities. There was again an intermediate range of alternation rates where the impression of movement was highly degraded. Some of the results are gathered in Fig. 6.

Experiment 5

In this experiment we alternated between two Julesz patterns moving uniformly with velocities of equal magnitude but different direction. We always used the highest alternation frequency (T = 10 ms). The angular difference of the velocities was varied and the task of the subject was to judge whether transparency occurred at an infinite value of the SNR (only signal, no noise). Irrespective of the magnitude of the velocities it was found that transparency occurred whenever the angular difference exceeded 30 deg.

Discussion

To be able to assess the capability of visual detection of uniformly moving Julesz patterns it is necessary to know the theoretical limit for the sensitivity of any system that is sensitive to movement. This theoretical limit is set by the statistical fluctuations of the pattern. The relevant variable is the spatio-temporal correlation. The value of this correlation is a sum of elementary contributions due to the correlation of the signal at one location at a certain time with the signal at another location at another time. The summation extends over all such pairs present in the field of view of the mechanism and in the time window used by the mechanism.

Let the amplitude of the signal with respect to the mean luminance be $\pm s$, that of the noise $\pm n$. Then the correlation of an elementary pair is s^2 or 0 according to whether the spatio-temporal separation of the pair agrees with the velocity of the signal or not.

Let there be N of such pairs in the field of view and time window of the mechanism for which the spatio-temporal separation agrees with the velocity. Then the total spatio-temporal correlation equals

$$N \cdot s^2.$$

The variance in the correlation is due to the noise. This is because we treat the ideal case of moving patterns "matched" to the correlator structure. In the non-ideal case the signal also gives rise to variance because the correlators also process unmatched stimulus pairs. The noise pattern does not contribute on the average to the correlation, but yields a variance equal to n^4 for each elementary pair. Thus the total variance is

$$N \cdot n^4.$$

The spatio-temporal correlation is significantly different from zero if the average value exceeds the standard deviation which is, of course, an extra assumption. However, it should suffice for an order of magnitude estimate, which is our aim; i.e., whenever:

$$N \cdot s^2 > \sqrt{N \cdot n^4}.$$

We have defined the SNR as s^2/n^2.
Thus, the theoretical limit is

$$\mathrm{SNR} > \sqrt{\frac{1}{N}}.$$

In two successive frames there are $(250-1) \times 255$ pairs that contribute. Thus, $N \approx 6.4 \times 10^4$, and we expect $\mathrm{SNR} \geq 10^{-2}$. If more than two successive frames are processed the theoretical limiting value can be much less than that. (The number of contributing pairs grows much faster than proportional to the number of frames.)

In Fig. 7 we have gathered the threshold SNRs for the lowest and highest alternation rates as a function of the velocity. It can be seen that the lowest threshold SNRs are close to 10^{-2}. Consequently, the visual system uses at least an amount of information such as is present in two successive frames, although it might be the case that more than two frames contribute to the detection threshold, but then much of the available information must be discarded. It is clear from Fig. 7 that the detection of movement is much less efficient (in the sense that the theoretical available information is less well utilized) at higher velocities.

Our finding that three different kinds of percept are possible, dependent on the rate of alternation, is comparable to the phenomenon described by Clarke (1977). At each velocity there is a "critical" period

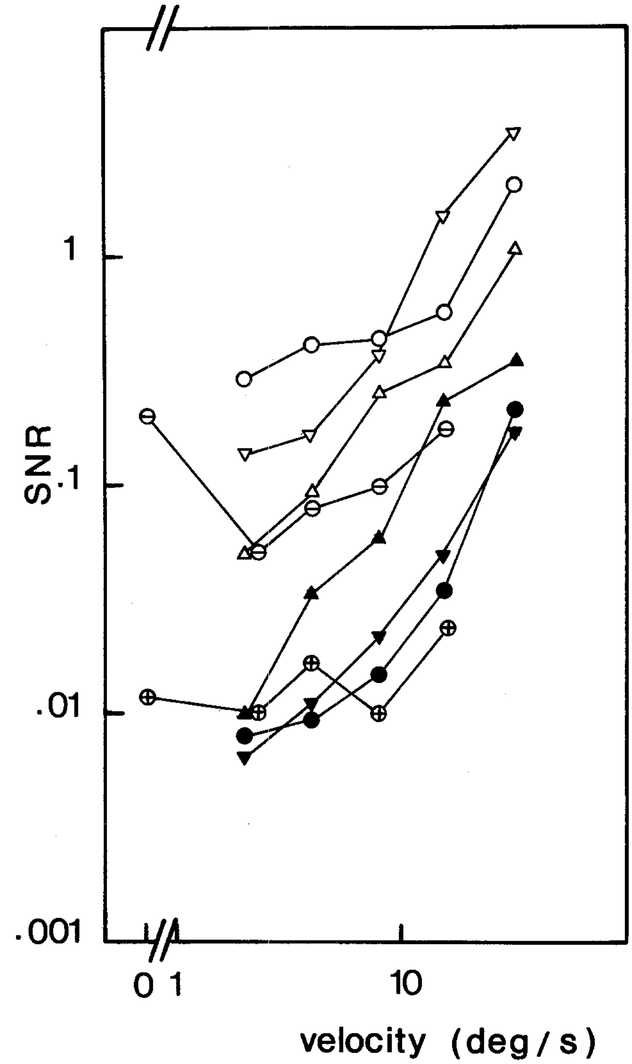


Fig. 7. The threshold SNR for very small alternation period (all data indicated by ⊖ and open symbols) and very large alternation period (all data indicated by ⊕ and filled symbols) as a function of the velocity (in deg · s^{-1}). Each period T a Julesz pattern moving with velocity $\vec{v}_1$ is alternated with a Julesz pattern moving with velocity $\vec{v}_2$.
○ ● $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and directions opposite to each other
△ ▲ $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and equal directions
▽ ▼ $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and orthogonal directions
⊖ ⊕ $\vec{v}_1$ fixed (2.08° · s^{-1}), in this case is $\vec{v}_2$ the parameter along the horizontal axis. $\vec{v}_1$ and $\vec{v}_2$ have equal directions.
Subject AD. Total target extent 5.21 × 5.31 deg of visual angle. Mean luminance 180 cd/m^2. Dark surrounding

for which no movement at all is perceived, and in that condition the threshold SNR always has a maximum value (see Figs. 3–6).

In Fig. 8 the values of this critical period for which the threshold SNR is maximal, are depicted as a function of the velocity for three different experimental conditions. In all three cases the critical period decreases with increasing velocity.

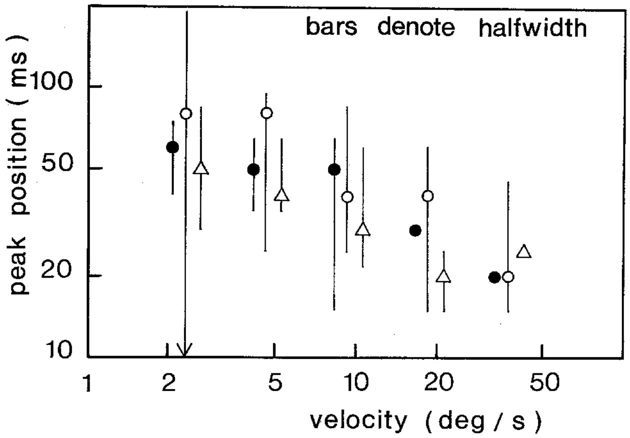


Fig. 8. The critical alternation period T* (in ms, T* is defined as that alternation period at which the threshold SNR curve reaches its maximum), as a function of the velocity (in deg · s^{-1}). The vertical bars through the data points indicate the halfwidth of the threshold SNR curves. Subject AD. Total target extent 5.21 × 5.31 deg of visual angle. Mean luminance 180 cd/m^2. Dark surrounding. Successive periods alternately contain Julesz patterns moving with velocity $\vec{v}_1$ and $\vec{v}_2$.
● $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and directions opposite to each other
○ $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and equal directions
△ $\vec{v}_1$ and $\vec{v}_2$ have equal magnitude and orthogonal directions.
If the threshold SNR curve does not drop to half its top value, this is indicated by an arrow

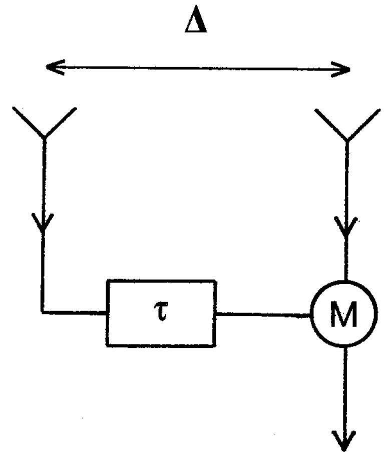


Fig. 9. A schematic representation of Reichardt's model. It is constituted of a pair of inputs, a distance Δ apart from each other. The signal from one input, with a delay indicated by τ, is multiplied with the signal from the other input

A least square fit in double logarithmic coordinates results in the following functional relation:

$$T^* = 89 \cdot v^{-0.40}$$

(T*: critical period in ms, v: velocity in deg · s^{-1})
The regression coefficient is –0.86.

In the threshold SNR curves we looked for those values of T at either side of the maximum for which the threshold SNR is half of the maximum value; the interval between these T values we called the halfwidth. The dependence of these halfwidths on the velocity is indicated by the vertical bars through the data points in Fig. 8.

Due to experimental scatter the halfwidths could not be determined very precisely. The relative halfwidth $\Delta T/T^*$ was not significantly different for the various velocities. Its value was rather large. (The halfwidth was about 0.4 log units.)

The relevance of the critical period can be interpreted in terms of a simple mechanistic model for the detection of spatio-temporal correlation. Elementary contributions to the correlation are due to retinal excitations at a distance Δ and at times differing by τ, where Δ and τ are related to the velocity of the pattern as follows:

$$v = \frac{\Delta}{\tau}.$$

Any mechanistic implementation of such a contribution must take the form of a system with two spatially separated inputs connected to a coincidence detector (e.g., a multiplier) by way of a direct link for one input and a delay for the other. Several possible implementations have been suggested (Schouten 1967; Barlow and Levick 1965; Reichardt 1961). Reichardt's model is perhaps the most general and certainly the most convenient for mathematical treatment. An adaptation of this model was proposed by Foster (1971a, b) to explain psychophysical contrast detection thresholds for spatio-temporal modulations.

In Fig. 9 a simplified version of Reichardt's model in which the leaky integrator is replaced with an ideal time delay, is schematically depicted. Let us now consider how this model would react to the stimuli of Expt. 1. If the alternation rate is very low ($T \gg \tau$) the model responds normally in one halfperiod and not at all in the other. If the alternation period is such that $T = \tau$, the model cannot react at all. The inputs of the multiplier can never be correlated in this case. If the alternation rate is higher ($T < \tau$) the model reacts again, although the average output will be lower than in the first case. Thus, the model is selectively insensitive to alternation rates with period $T = \tau$.

In conceivable physiologic systems you cannot expect to find anything as schematic as this model. An ideal delay element is improbable and its place would probably be taken by a leaky integrator (Reichardt 1961). Moreover, in any ensemble of an appreciable number of elementary correlators the temporal parameter (τ) is likely to be statistically distributed around some average value. All such effects have the consequence of smearing out the localized insensitivity of this simplified system.

If we interprete our measurements (Figs. 3–6) in these terms it seems that Reichardt's model is able to provide a likely explanation of the insensitivity peak. If this interpretation is correct, then Fig. 8 shows the dependence of the temporal parameter τ on the velocity of the stimuli.

The qualitative observation that patterns moving in the same direction with velocities that differ by a factor of 4 or more can be perceived simultaneously at the same position in the visual field, shows that the coding of velocity in the visual system differs essentially from, for instance, the speed indication in an automobile. This points to the fact that velocity cannot be coded in terms of a single analogue variable. This can be understood in terms of movement detection with a large set of elementary correlation detectors with mutually different parameter values. In such a system the magnitude of the velocity is coded in terms of the group of correlation detectors that responds, and not in terms of the magnitude of these responses. In such a case it is very well possible that more than one group of correlation detectors are simultaneously excited. If this interpretation is correct, our measurements allow an estimation of the number of significantly different groups involved. We will be presenting an experimental estimate in a subsequent paper.

Comparison with Previous Results

There are few psychophysical data that can be compared with the data presented here. The problem is that very few authors have used either the stimulus patterns or the method of quantifying the sensitivity used by us. Most authors that have used noise patterns, have used patterns composed of relatively sparse clouds of specks (Bell and Lappin 1973; Lappin and Bell 1976; Levinson and Sekuler 1976). Most of these experimenters have been interested in the movement after-effect, and such results cannot be compared to ours (Levinson and Sekuler 1976), e.g., the transparency effect is absent in the after-image, instead a kind of vector addition prevails.

Braddick (1974) and Morgan and Ward (1980) used dense dot displays, just as we did, but they presented only two successive frames in order to study the apparent motion. Our results accord with theirs, although the conditions under which we perceived smooth flow were somewhat broader than the conditions under which apparent motion for pairs was observed. As did Braddick (1974) and Morgan and Ward (1980), we find the classical Korte's laws (Graham 1965) inapplicable to our stimuli.

Electrophysiologic studies in the field of movement sensitive receptive fields are very abundant and cannot be cited exhaustively here. Several of these studies throw light on the problem of whether movement is coded as a simple analogue variable or by way of velocity specific groups. It seems that examples of both types are to be found in the animal kingdom. An example of "speedometer type coding" is described by Grüsser-Cornehls (1968). This author reported on motion detectors in the frog's retina. She found units for which the firing rate increased monotonically with the velocity over a large range. On the other hand, in the cortices of mammals the second type of coding has often been reported. For instance, Orban and Callens (1977) described velocity specific and velocity sensitive units in the cat's visual cortex. Some of these units were also directionally specific. Their results suggest that patterns moving in the same direction with velocities differing by a factor of 4–10 excite distinct units.

Acknowledgements. We are grateful to Prof. Dr. M.A. Bouman for his critical remarks on the manuscript.

References

Adler B, Grüsser O-J (1979) Apparent movement and appearance of periodic stripes during eye movements across a stroboscopically illuminated random dot pattern. Exp Brain Res 37: 537–550

Barlow HB, Levick WR (1965) The mechanism of directionally sensitive units in rabbits retina. J Physiol (Lond) 178: 477–504

Bell HH, Lappin JS (1973) Sufficient conditions for the discrimination of motion. Percept Psychophys 14: 45–50

Braddick O (1974) A short-range process in apparent motion. Vision Res 14: 519–527

Clarke PGH (1977) Subjective standstill caused by the interaction of moving patterns. Vision Res 17: 1243

Foster DH (1971a) The response of the human visual system to moving spatially-periodic patterns: further analysis. Vision Res 11: 57–81

Foster DH (1971b) A model of the human visual system in its response to certain classes of moving stimuli. Kybernetik 8: 69–84

Graham CH (ed) (1965) Vision and visual perception. Wiley, New York London Sydney

Grüsser-Cornehls U (1968) Response of movement-detecting neurons of the frog's retina to moving patterns under stroboscopic illumination. Pflügers Arch 303: 1–13

Julesz B (1971) Foundations of cyclopean perception. The University of Chicago Press, Chicago London

Koenderink JJ, Doorn AJ van (1980) Dual percept of movement and spatial periodicity in stroboscopically illuminated moving noise patterns. J Opt Soc Am 70: 456–458

Lappin JS, Bell HH (1976) The detection of coherence in moving random-dot patterns. Vision Res 16: 161–168

Levinson E, Sekuler R (1976) Adaptation alters perceived direction of motion. Vision Res 16: 779–781
Morgan MJ, Ward R (1980) Conditions for motion flow in dynamic visual noise. Vision Res 20: 431–435
Nes FL van, Koenderink JJ, Nas H, Bouman MA (1967) Spatiotemporal modulation transfer in the human eye. J Opt Soc Am 57: 1082–1088
Orban GA, Callens M (1977) Influence of movement parameters on area 18 neurones in the cat. Exp Brain Res 30: 125–140
Reichardt W (1961) Autocorrelation, a principle for the evaluation of sensory information by the central nervous system. In: Rosenblith WA (ed) Sensory communication. MIT Press, Cambridge, Mass., pp 303–317
Schouten JF (1967) Subjective stroboscopy and a model of visual movement detectors. In: Wathen-Dunn W (ed) Models for the perception of speech and visual form. MIT Press, Cambridge, Mass., pp 44–55

Received January 27, 1981