Perceptual and Motor Skills, 1993, 77, 275-298.

VISUOMOTOR CONTROL OF THE RELATIVE MOVEMENT OF RANDOM-DOT PATTERNS [1,2]

RAIMOND M. WÜST, ASTRID M. L. KAPPERS, JAN J. KOENDERINK

Utrecht Biophysics Research Institute (UBI)

Summary.—A series of experiments were made on human performance in controlling optical relative movement. The aim was to test the influence of different kinds of relative movement on visually controlled steering tasks. Within adjacent displays on a computer screen random dot patterns moved in a fixed direction at continually changing speeds (Exp. 1) or at constant speed and in continually changing directions (Exp. 2). The subject was required to compensate for the unpredictable modulations of the pattern movement by means of an isometric joystick. The task was to adjust relative movements involving pure translation, symmetric convergence, divergence, or shear. Analysis indicated that the task performance was not dependent on the special kind of relative movement. However, performance was significantly higher in tasks where directionally disturbed relative movement had to be controlled compared to those situations in which relative movement varied with respect to speed.

Local illumination on the retina corresponds to the environmental layout and changes when the observer moves. Such movement-induced illumination changes, commonly known as movement parallaxes (Helmholtz, 1910), are predictable and result from displacements of the viewing direction to contrasted objects in the environment. Movement parallaxes are of basic importance for visual orientation and movement control. Within the concept of the visual array (Gibson, 1950) the observer is able to analyse his relationship to the environment using transitions in the movement parallax field. The observer has to move with respect to his environment to make the optic array change, which in turn provides the information he needs to control his movement (Gibson, 1979). This mutual relationship between visual movement perception and the observer's actions has motivated numerous studies on the detection of features in image sequences. Human observers appear to be highly sensitive to dynamic depth (Rogers & Graham, 1979), egospeed (Warren, 1982), and heading direction (Regan & Beverley, 1982; Rieger & Toet, 1985; Warren, Morris, & Kalish, 1988; Warren, Mestre, Blackwell, & Morris, 1991; Warren, Blackwell, Kurtz, Hatsopoulos, Kalish, & Griesar, 1991).

The crucial role of optic flow in an ecological approach to three-dimen-

[1]The first author is indebted to the Netherlands Organization for Scientific Research (NWO) for financial support. The coauthors acknowledge support from the *InSight* project of the ESPRIT programme of the European Community. We are grateful to Dr. J. W. Roelofs for his essential assistance during the development of the software and to P. Faber for the development of the electronic equipment. We thank Prof. D. Varjú and Dr. H. J. Dahmen for critically reading the manuscript as well as Mrs. S. McNab for improving the use of English.
[2]Address correspondence to Raimond M. Wüst, Utrecht Biophysics Research Institute (UBI), Princetonplein 5, 3584 CC Utrecht, The Netherlands.

sional (3D) vision has been well established. Various suggestions for a theoretical description of the retinal velocity field have been presented (Gordon, 1965; Koenderink & van Doorn, 1975, 1976, 1981; Longuet-Higgins & Prazdny, 1980). One of the findings of this work is that the parallax field can be decomposed locally into rotation, translation, shear, and deformation components whose relative weights vary, dependent on the egomotion parameters and the visual environment. This led to several attempts to reinterpret earlier electrophysiological evidence (Nakayama & Loomis, 1974; Koenderink & van Doorn, 1978; Poggio, Reichardt, & Hausen, 1981; Wehrhahn, Hausen, & Zanker, 1981), and several psychophysical studies concentrating on mechanisms which might selectively process special kinds of relative movement (Regan & Beverley, 1985; Regan, 1986; Nakayama, Silverman, MacLeod, & Mulligan, 1985; De Bruyn & Orban, 1990).

Conclusions concerning the existence of special mechanisms selective for higher order relative movement have been strongly dependent on experimental technique. Nakayama, *et al.* (1985) measured the threshold amplitude for the detection of one-dimensional undulation in oscillating 2D random-dot patterns. The movement contrast of the undulation was created by sinusoidally modulating the oscillation amplitudes of the dots. At higher frequencies of their spatial modulation function subjects showed a lower ability to detect shear movement than convergence movement. Regan (1986) found higher threshold elevations for the detection of oscillating shear movement than for convergence movement after subjects had adapted to the corresponding oscillating dot patterns. Nakayama, *et al.*, as well as Regan, conclude from their observations that there might exist different channels for processing relative movement.

Another experimental approach for determining human sensitivity to different kinds of transitions in random-dot movement was presented by van Doorn and Koenderink (1982, 1983). These authors used signal-to-noise-ratio adjustments to determine detection thresholds of relative movement and could not find any difference in the sensitivity to divergence, convergence, and rotation. From their observations they concluded that a transition between two adjacent pattern movements is detected whenever the two velocities can be discriminated due to their different speeds or their different directions.

Generally, relative movement between two patterns with different velocities is described by their vector difference. If special mechanisms exist which are selectively sensitive to certain types of relative movement *and* these are involved in visually controlled tasks, task performance should be independent of the average speed, i.e., the average magnitude of the velocities. We expect such a mechanism always to respond with the same strength only if the difference between the velocity vectors is the same. The upper panel of Fig. 1c below shows an example of a special kind of horizontally

diverging stimulus (HD). The arrows represent two neighboring patterns which move at the same speed $v = \|v_1\| = \|v_2\|$ in opposite directions. In the middle panel two patterns move in the same direction but one (v_2) with a speed of $3v$ faster than the other (v_1). There is a transition from one speed to the other so this stimulus might be called a horizontal transition (HT). Although the pure speed difference $\Delta v = |\,\|v_1\| - \|v_2\|\,|$ is $2v$ in the middle panel and 0 in the upper panel, the vector difference is the same in both cases as both situations represent divergence movement. The lower panel of Fig. 1c represents a situation where the speed transition in the pattern movements v_1 and v_2 disappears. The difference between this stimulus situation and those of the other two panels should be easily detected by a mechanism which is sensitive to relative movement. Whereas stimulus situations like those in the upper two panels will provide similar input to such a mechanism, the lower panel situation represents no detector input. On the other hand, velocity-sensitive mechanisms which are not selective for special types of relative movement but always respond with the same strength if the difference between the speeds of local pattern movements exceeds detection threshold should have fewer problems in discriminating between situations like the one of the middle panel and those where the speed differences disappear.

Therefore we assumed that, if relative movement-sensitive mechanisms are involved in the execution of dynamic control tasks, subjects should perform better when the relative movement of the stimulus changes according to an unpredictable perturbation signal while the mean speed of the two pattern movements is kept constant. Such a task is represented by the stimulus condition of the lower panel. The task is to compensate for any difference between v_1 and v_2 such that relative movement disappears. Since the mean speed cannot change under a given stimulus condition, this implies that if $\|v_1\|$, for instance, becomes smaller, $\|v_2\|$ grows by the same amount. However, if only those mechanisms contribute to visual stimulus control which discriminate the pattern movement with the velocity v_1 from that with the velocity v_2 on the basis of their different speeds, then performance should be similar to those stimulus conditions in which the relative movement (i.e., the vector difference) is kept constant while Δv, the difference between pattern speeds, is subjected to a random change. Under both conditions Δv varies in the same way. Such a task is represented by the scheme of the upper panel. In this case the subject is required to compensate for any speed difference between the pattern movement to the right and to the left, respectively. Also in this situation the mean pattern speed never changes.

The experimental approach which we use directly takes into account that visual perception in daily situations is interactive in the following sense: analysis of the parallax field is necessary to guide the observer's movements, but the movements determine the changes in the optic array. Following

Gibson's ideas (1950, 1979) we decided not to investigate selective detection performance at threshold but to quantify subjects' performance for tasks in which different kinds of relative movement have to be controlled. We do not ask if there merely *exist* independent channels for the processing of different kinds of relative movement in the visual system. Instead, we want to investigate whether or not visual perception of relative movement contributes to movement control. This is done by comparing the time-course of the changes in the relative movement generated by a noise-like perturbation signal with the dynamic response of the subject. The level of the task performance is given by the correlation between perturbation and response signal. The question to be answered is: what is the extent to which a human observer can exploit velocity information contained in the different stimuli in order to exert dynamic control of the stimuli themselves?

Method

Subjects

Two subjects participated in two experiments: author RW, male and aged 31 and JD, female and 22; both were highly trained for the task. One of the subjects (JD) was unaware of the aims of the experiment. Both are myopes corrected to normal, and both subjects are right-handed. Throughout the experiments the level of signal correlation differed significantly between the two subjects. For a given stimulus, the performance of one subject therefore cannot be juxtaposed directly with that of the other, although trends are qualitatively similar. Interindividual differences in dynamic control tasks are quite common, in most cases resulting from the use of slightly differing strategies (Poulton, 1974). We believe, however, that the relative values which we use to derive our main conclusions are independent of these subject-specific movement strategies.

Experimental Set-up

During the experiments the subject sat in a dentist's chair, with the back of the head leaning against a head support to keep the distance between the head and the screen the same. The arms rested on supports and only the right hand or the fingers of the right hand were used to manipulate an isometric joystick. The stimuli were generated by an Atari mega ST computer equipped with a blitter chip and were displayed on an Atari SM 124 monochrome monitor with a resolution of 640×400 pixels on a screen area of 21.7×13.6 cm and a video refresh rate of 70 Hz. The mean luminance of the stimulus area was adjusted to about 0.2 cd/m^2. Otherwise the room was completely dark.

Moving random dot patterns were displayed within two circular 'apertures' on the computer screen. Unless stated differently in the text, the two apertures were positioned to the right and to the left of a small fixation mark. The horizontal distance between the mark and the aperture on the

screen was 0.5 cm (see Fig. 1). Since the distance between the subject and the screen was kept constant at 130 cm, the centre of the stimulus was always seen at an eccentricity of 1.56°. The size of the aperture was 2.84°, and the size of one pixel was 0.89′ of visual angle.

The subject manipulated the speed of the tracking pattern by twisting a specially developed force-sensitive joystick about its axis. The joystick was mounted upright at the end of the right arm support.

To reduce low-pass filter effects due to hand and finger movement, the force that the subject had to apply to the joystick had to be independent of the mean size of the stimulus parameter. To achieve this, we increased the amplification factor that transforms the output signal of the joystick into the corresponding speed or direction by the same amount as we had increased the mean stimulus parameter. In Exp. 1, pattern speed was the stimulus parameter. It was varied within the two apertures while the direction of movement was constant. In Exp. 2, the speed of the patterns was kept constant while the movement direction was varied.

Stimulus Configuration

The names given to the different kinds of relative movement were based partly on the movement after-effect which they caused when a white box containing an instruction either to start with the next trial or to repeat the preceding one appeared on the screen. The deformation of the box was complementary to the relative movement of the stimulus. This movement after-effect was quite pronounced when the pattern speed was low and the direction constant. It was very weak if the speed was high or the movement direction varied strongly. At higher speed the subjects perceived that the movement was stroboscopic rather than continuous, although a vivid perceived movement was reported in all cases.

In Exp. 1 we distinguished the following situations (see Fig. 1a): horizontal divergence (HD), horizontal convergence (HC), horizontal transient (HT) which was a relative movement that continuously changed between divergence and convergence, vertical rotation (VR), and vertical transient (VT). The last two situations could also be referred to as vertical shear movement. In Exp. 2 we studied horizontal divergence (HD), horizontal rotation (HR), vertical divergence (VD), and vertical rotation (VR) (see Fig. 1b).

Spatiotemporal Properties of Stimulus

Each pattern consisted of a pseudorandom distribution of white pixels (25%) on an otherwise black screen. Each pattern was stored in a rectangular computer frame buffer which the subject could see through the circular aperture. The impression of continuous pattern movement could be evoked by periodically shifting the dot pattern behind the aperture by a defined number of pixels. The image update rate was 23.3 Hz. Because the buffer

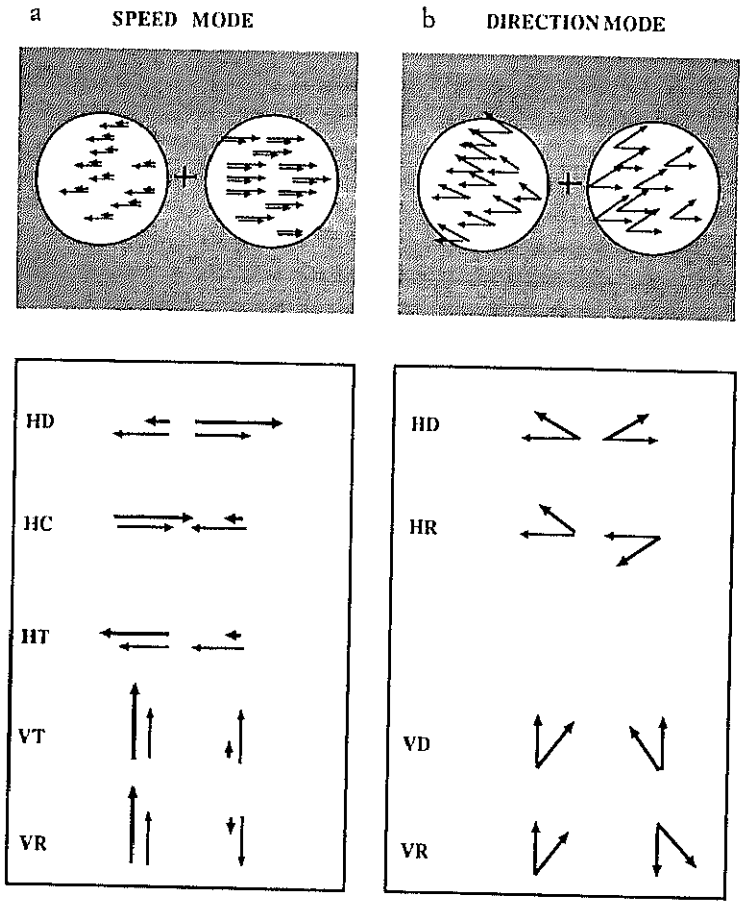


FIG. 1. Definition of the different kinds of relative movement. The circles indicate the areas on the screen where the shifting dot patterns are displayed. The subject has the impression that he is looking through a circular aperture at two separate surfaces, (continued on next page)

was circularly organized, there was no technical limitation to the duration of the sample time. However, this circular organization resulted in a periodicity which led to artificial of alliance effects at high velocities when the shift distance approached the order of magnitude of the width (or height) of the screen buffer. This led to a limitation of the velocity range that could be used.

In Exp. 1, the subject's task was to adjust the pattern speeds within both fields to the target speed $v_0 = v_{max}/2$, which was the mean speed of both fields and had a constant value in all samples of one experimental condition. The speed v of each of the two patterns varied between zero and maximum

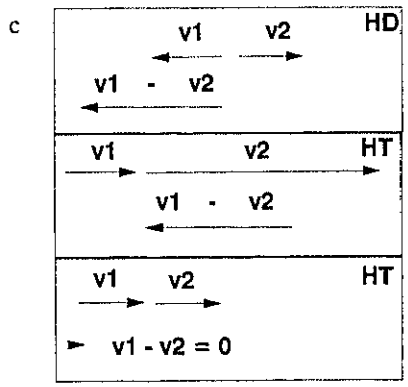


FIG. 1. (Cont'd) which are shifted with respect to each other. (a) Stimuli in Exp. 1, (b) stimuli in Exp. 2. Abbreviations: HD (horizontal divergence), HC (horizontal convergence), HT (horizontal transient), VT (vertical transient), VR (vertical rotation), VD (vertical divergence). The thin arrows represent velocity vectors of the target movement. The thick arrows represent examples of arbitrary stimulus constellations. (c) The upper and the middle panel show two different stimulus conditions, HD and HT, which represent the same relative movement as defined by the vector difference $v_1 - v_2$ of the two movement components. The speed differences $\Delta v = | \|v_1\| - \|v_2\| |$ are different in the two situations. A mechanism that responds selectively to different types of relative movement might not distinguish between the two stimuli. The lowest panel shows a situation of an HT stimulus, in which the difference of the vector velocities is different from the situation of stimulus HD. In this case, however, the speed difference is identical to the situation in the uppermost panel. If only speed-sensitive mechanisms are involved in the control task, the task performance should be similar for these two stimuli. For further explanation see text.

speed. The deviation of v from the target speed was generated by the perturbation signal v_{ps}. The maximum speed was adjusted by the experimenter. The movement in both stimulus fields was coupled in such a way that an acceleration of the pattern movement in one aperture coincided with a deceleration of the pattern in the opposite aperture by the same amount.

Similarly, in Exp. 2 the angle $\Delta\varphi$ between target direction φ_0 and actual shift direction φ varied between zero and maximum angular deviation. The perturbation signal as well as the response signal influenced the angle between the actual movement direction of the dot patterns and the target direction simultaneously. In this experiment the subject's task was to compensate for directional perturbations which were generated by the computer and to adjust the target direction defined by the given relative movement between both apertures. In both experiments the subject got the impression of symmetrical pattern flow consisting either of divergence, convergence, shear, or a translation movement in case of complete compensation for the difference between the stimulus fields. The computer-generated perturbation signal and the subject's compensative reactions were sampled simultaneously.

The temporal stimulus properties as well as the experimental set-up were similar to those that we described elsewhere (Wüst, Kappers, & Koenderink, 1992). The variation of the test-parameters v and φ was achieved by using

special noise functions to generate the perturbation signal. An experiment consisted of 10 sampling sessions, each based on stimulation with a different function. Such a noise function resulted from summing a series of sinusoidal functions with differing frequencies, identical amplitudes, and randomly chosen phase positions. Under all experimental conditions the same set of 10 noise functions was used to generate the modulation of the test-parameter. The order of the 10 stimulus functions in the course of an experiment was determined by a pseudorandom selection procedure. One sampling interval, which referred to one stimulus function, lasted 86 sec.

The horizontal screen velocity was defined as $v \cos \varphi$ and the vertical velocity as $v \sin \varphi$. v was given by $k(\Delta s/\Delta t)$ where k was an integer, Δs was the distance between two neighboring pixels, and Δt the time interval between two successive frames. The range of velocities in one sampling period consisted of $k \geq 10$ discrete steps. The number of steps increased with the upper limit of the velocity range. In Exp. 2 this resulted in a minimum directional resolution of 5°.

The pattern velocities were generated by scaling each noise function to the range between zero and the maximum screen velocity. In this way stimuli were obtained with normally distributed velocities that were not predictable by the subject.

Statistical Properties of Perturbation Signal

The frequency composition of the stimulus was subject to a trade-off between the predictability of the perturbation signal and the performance of the subject. An increased predictability of the perturbation signal led to high correlations whereas a broad range of signal variability led to rather low correlations. Both effectively weakened the influence of the test parameter on the task performance. In agreement with previous experiments on the influence of the signal dynamics on the signal correlation (Wüst, *et al.*, 1992), we decided to use signals of 26 frequency components, each separated from the other by a frequency interval of 0.0167 Hz, ranging from 0.017 Hz up to 0.453 Hz.

Data Evaluation

The time-course of the perturbation signal was represented by $v_{ps}(t)$ and that of the subject's response signal by $v_{rs}(t)$. Let Δt denote the time interval between two discrete sample times and let k be an integer. If the response signal is shifted by the interval $\Delta t_k = k\Delta t$ with regard to the perturbation signal, then the difference between the perturbation signal at time t_i and the response signal at time $t_i + \Delta t_k$ is written:

$$v_E^{\,k} = v_{ps}(t_i) - v_{rs}(t_i + \Delta t_k) \ .$$

Because the two signals are correlated to a certain degree, we are able to define a relative measure for the subject's performance by calculating the first order maximum of the cross-correlation function of $v_{ps}(t)$ and $v_{rs}(t)$. From

$$R_v(\Delta t_k) = \frac{\sum_{i=1}^{N-k} [v_{ps}(t_i) - v_0][v_{rs}(t_i + \Delta t_k) - v_0]}{N\sqrt{\sigma_{v_{ps}}\,\sigma_{v_{rs}}}},$$

we obtain the cross-correlation coefficient $R_v(\Delta t_k)$ as a function of the time shift Δt_k. Here $\sigma_{v_{ps}}$ is the standard deviation of the perturbation signal and $\sigma_{v_{rs}}$ is the standard deviation of the response signal. The parameter N denotes the size of the sample and i the index of the sample time t. We define the first order maximum R_v^* of $R_v^*(\Delta t_k)$ as

$$R_v^* := R_v(\tau_0) = \max\{R_v(\Delta t_k)\}\ ,$$

where $\Delta t_k < 2$ sec.

The subject's performance in Exp. 2 is described by R_φ^*, which is derived similarly. The response delay τ_0 is given as the time shift between the two velocity time courses for which the given maximum condition holds. Fig. 2a shows the first 8.5 sec. of the autocorrelation function of one out of ten stimulus noise functions [perturbation signal 1 indicated as ($ps1$) in Fig. 2a] together with five examples of cross-correlation functions between stimuli and response signals of Subject JD. For the cross-correlation function which belongs to perturbation signal 1, the corresponding time delay τ_0 is indicated on the time axis. τ_0 is defined by the location of the first order maximum of the cross-correlation. For the sample with the perturbation signal 1 in Fig. 2a one finds $\tau_0 = 1.3$ sec. In both experiments and for both subjects τ_0 usually ranged from 0.6 sec. to 1.5 sec. For one set of 10 time-samples, each based on a different velocity perturbation signal, one obtains 10 values for first order maxima of the cross-correlation. The mean delay time $\bar{\tau}_0$ did not significantly change when the experimental conditions were changed. The 10 stimulus functions which contributed to one experimental condition yielded ten correlation values. The average of the ten correlation values is depicted as a relative measure of task performance. Each experimental condition was repeated three times on different days and the mean of this R^*-triple was presented in the sequel as a single data point.

The initial sequence for a single time sample with Subject JD in Exp. 1 is represented in Fig. 2b. The plot shows the time course of the target v_{ps} and the response signals v_{rs} as well as the modulus of the difference between the two, which is indicated as the *error*.

To obtain an absolute measure for the task performance we calculated the root-mean-square-error E_{RMS} for all stimulus conditions defined as

$$E_{RMS} = \sqrt{\frac{\sum_{i=1}^{N-k} [v_E^k(t_i)]^2}{N}}\ .$$

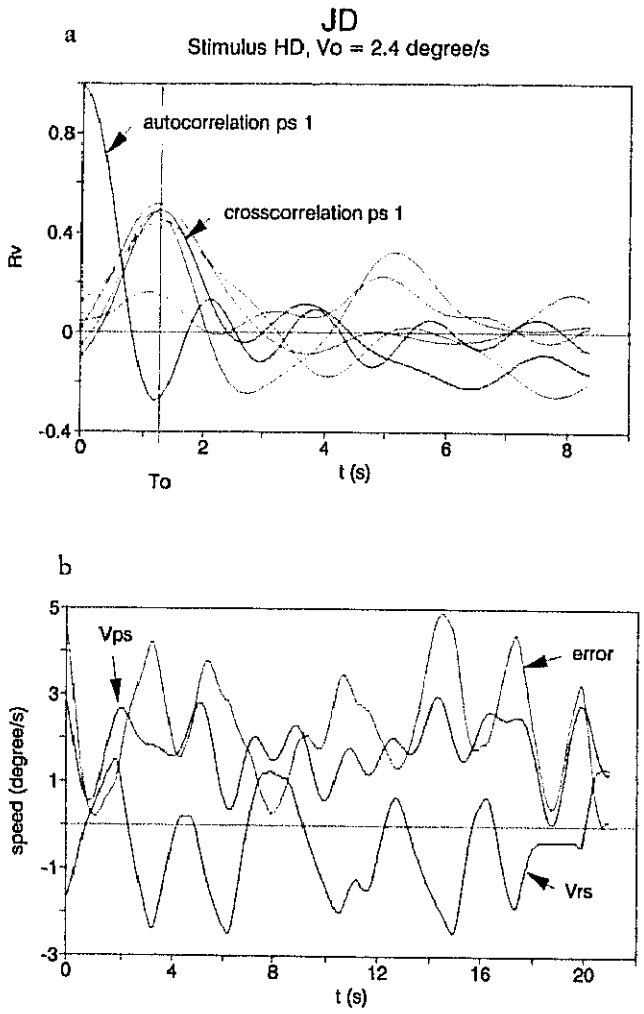


FIG. 2. (a) Initial sequences of time plots of correlation functions. The plot shows examples of cross-correlation functions of response signals to five different speed perturbation signals. The autocorrelation function of perturbation signal ps1 is plotted as well. The response delay to stimulus ps1, which is indicated by the location of the first order maximum of the cross-correlation function, is indicated on the time axis by 'τ_0'. (b) Example of the speed/time samples for the initial 20 seconds of one arbitrarily chosen trial. The 'Vps' line represents the perturbation signal, the 'Vrs' line represents the response signal, the 'error' line represents the time course of the modulus speed difference between the two signals. The experimental condition: stimulus HD of Exp. 1, $\bar{v} = 2.4$ deg/sec., Subject JD.

Here again, k stands for the number of sample points by which the response signal has to be shifted with regard to the perturbation signal in order to achieve the maximum correlation R^*. In Exp. 2 the difference vector be-

tween the target and the actual movement direction is scaled with the speed according to $|v_0|2 \sin(\Delta\varphi/2)$ (see Fig. 3). Therefore it is possible to express the observed directional error in units of speed and to compare the subjects' performance under the conditions of Exps. 1 and 2 directly by means of the vector modulus of the velocity difference.

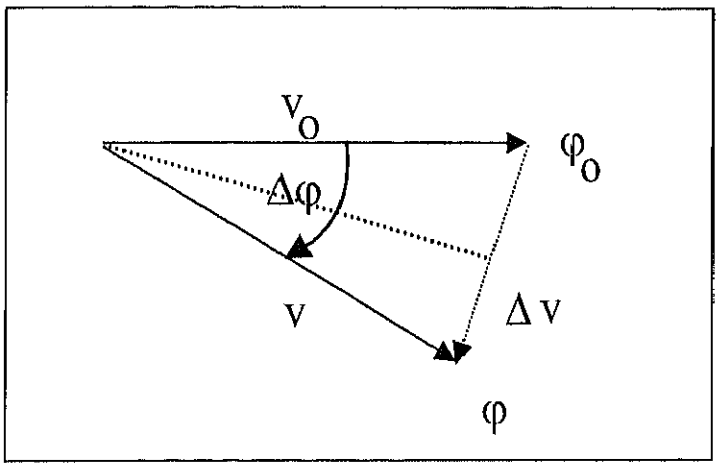


FIG. 3. Directional differences between two velocity vectors v_0 and v with the same length $|v_0|$ are scaled according to $\Delta v = |v_0|2 \sin(\Delta\varphi/2)$.

RESULTS

Experiment 1

To compare the visual sensitivity to speed asymmetry of relative motion of unstructured textures we determined R_v* for three kinds of horizontally oriented and two kinds of vertically oriented stimuli. Figs. 4a and 4b show data for Subject RW and Subject JD as a function of v_{ps}, respectively. One can see that in the whole range of parameters v_{ps} there are no significant differences in the task performance. This is of special interest with regard to the horizontal transition (HT) stimulus and the horizontal divergence stimuli (HC and HD). If we assume that all horizontal stimuli are processed by relative movement detectors, then we expect the signal correlation for stimulus HT to be different from those for the stimuli HD and HC. This is because in the first case the movements of both patterns have the same direction and therefore should provide a comparatively weak detector input, whereas in the latter cases they move in opposite directions which represent high pattern divergence.

A slight decrease in correlation for Subject RW, especially in the case of vertically oriented stimuli, is observed at mean velocities higher than 10 deg/sec. For the given stimulus size, this is just the speed at which the sen-

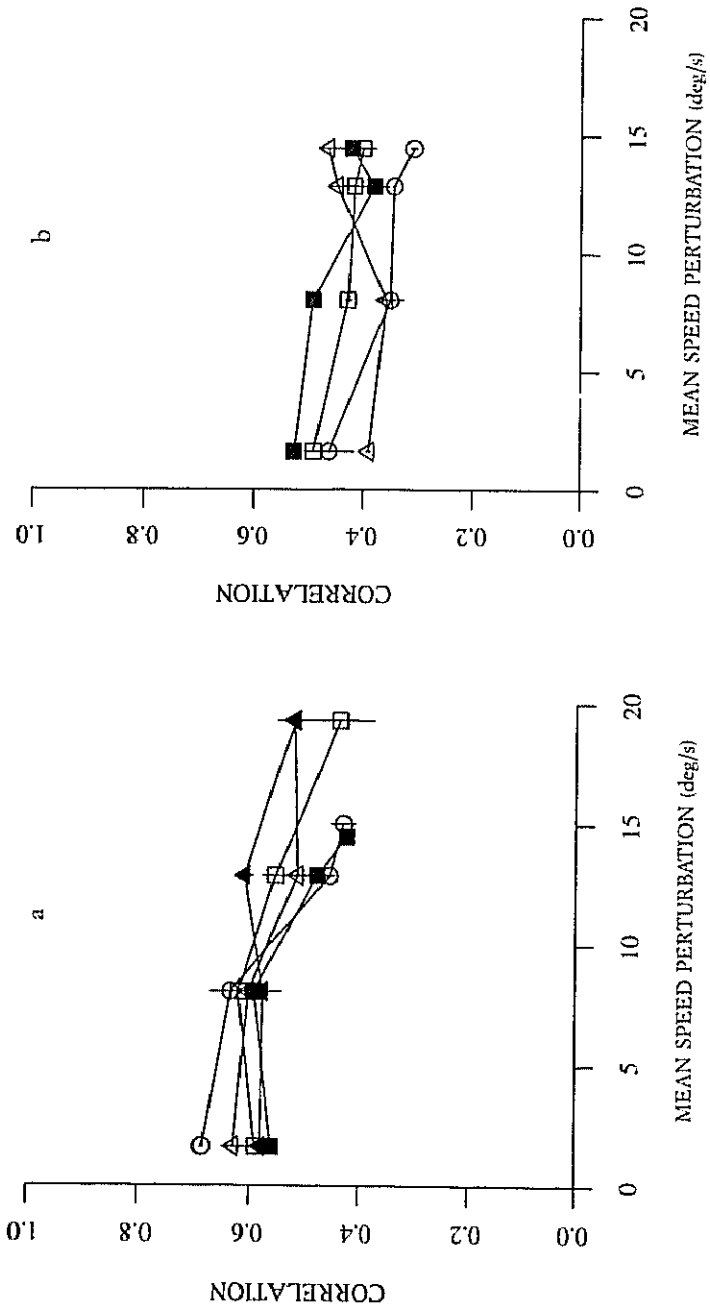


FIG. 4. Exp. 1, R_e^* versus $\bar{v}$. Vertical bars indicate standard deviations of three measurements (this applies to all other figures as well). (a) Data for Subject RW; (b) data for Subject JD. The symbols represent the following stimuli: HD (△), HC (▲), HT (□), VR (■), VT (○).

sation of movement begins to fade away. For Subject RW the decrease in the correlation is more sudden and pronounced than in the horizontal stimulus situation. At low stimulus velocities, however, the performances with both vertical stimuli are still quite similar to each other and to those with the horizontal stimuli. In the case of the vertical transition stimulus (VT) pattern movement in the left aperture is in the same direction as in the right one, whereas in the vertical rotation stimulus (VR) both patterns move in opposite directions. In both situations the subject has to compensate for speed differences. The task performance should be different in both experiments if the response is controlled by relative movement detectors. As was observed already for the horizontal stimuli, performance is similar in both cases. For Subject RW the difference between horizontal and vertical stimuli is rather weak in general and for Subject JD it is not observable at all.

Experiment 2

The second experiment was designed to test the influence of angular distortion on the control of movement direction. The magnitude of pattern velocity within both stimulus areas of the screen was kept constant in this experiment. If not indicated otherwise, the speed was adjusted to 10.4 deg/sec.

As in Exp. 1 we used several kinds of relative movement as stimuli. In the case of horizontal divergence the velocities have opposite direction when they match the target and they have the same direction in the case of a horizontal rotation (see Fig. 1b). In the case of vertical divergence, pattern movements are parallel when the target direction is matched, whereas they are antiparallel for a vertically rotating target direction. Fig. 5 shows $R_\varphi{}^*$ versus $\bar{\varphi}$ for both subjects. The results obtained in the different experimental situations were very similar. The correlation increased monotonically with $\bar{\varphi}$, showing that the task was facilitated by increasing the mean perturbation angle. The performance levels of the two subjects differed significantly. It is important to note, however, that the different experimental conditions did not lead to any variation in the performance of each subject.

As shown in Fig. 6 for Subject RW and stimulus HD (open triangles), the maximum level of task performance was reached at 30° to 40° mean angular perturbation. Further increase of the perturbation signal's amplitude did not improve the task performance. This saturation effect can be compared to what is observed when the orientation of small straight lines has to be controlled (HL, filled triangles). The orientations of the two line elements change similarly to the orientation of the pattern movement. If the stimulus orientation in the left aperture is turning clockwise, it turns anticlockwise in the right aperture. (For technical reasons there is an offset in the performance level of the task to control the line orientation. The real time display of straight lines could not be made fast enough to achieve the same frame rate

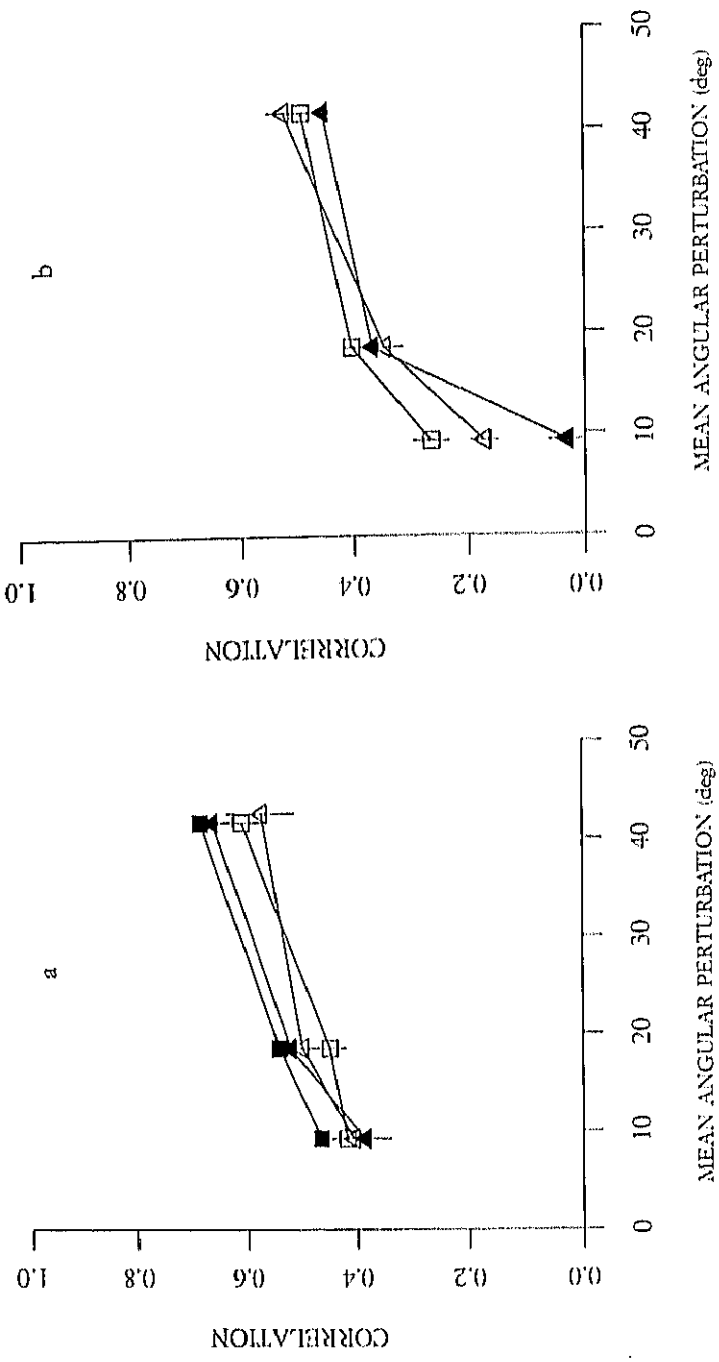


FIG. 5. Exp. 2. R_φ^* versus $\bar{\varphi}$. (a) Data for Subject RW; (b) data for Subject JD. The symbols represent the following stimuli: HD (△), HR (▲), VD (□), VR (■).

as with dot movement. As a consequence the spectrum of the perturbation signal shifts downward along the frequency axis. Lower frequencies, however, result in an increase in the level of correlation.) In the HD experiment the value at which R_φ^* reaches saturation level lies around 30° on the $\bar{\varphi}$-axis. This is comparable to what the HL curve shows. In the given task, the sensitivity to the orientation of pattern movement seems to be determined by the same sensory limitation as that for the orientation of simple objects like line elements.

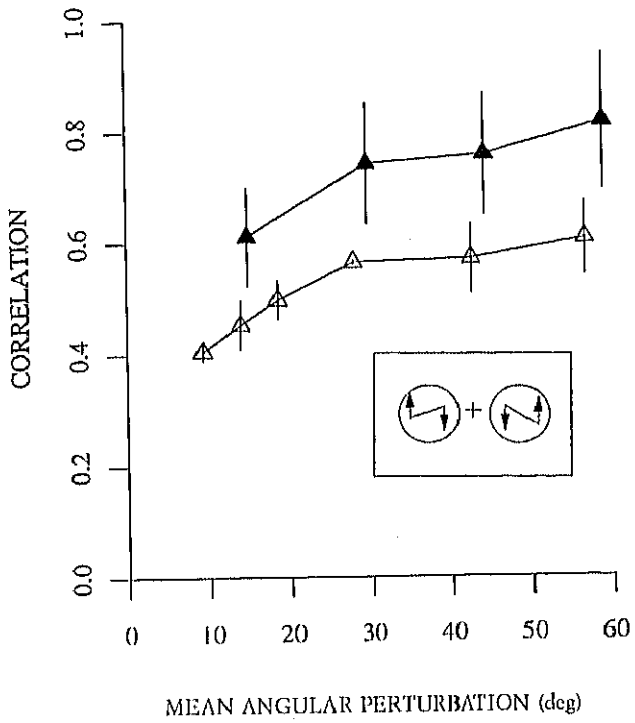


FIG. 6. R_φ^* versus $\bar{\varphi}$ for relative pattern movement (HD, △) and for the control of line orientations (HL, ▲, see inset). The offset in the data of the line orientation experiment is an experimental artefact (see text).

In the control tasks which we have described till now, the target direction of the pattern movement has always been horizontally or vertically oriented. Both orientations are known to play an exceptional role in human visual perception (Mittelstaedt, 1983). The question arises whether this fact might facilitate the task, or possibly even dominate the extra information that is given by the relative movement of the patterns within the two stimulus fields. Therefore we asked subjects to control the orientation of the pattern movement while only one stimulus field was displayed on the screen.

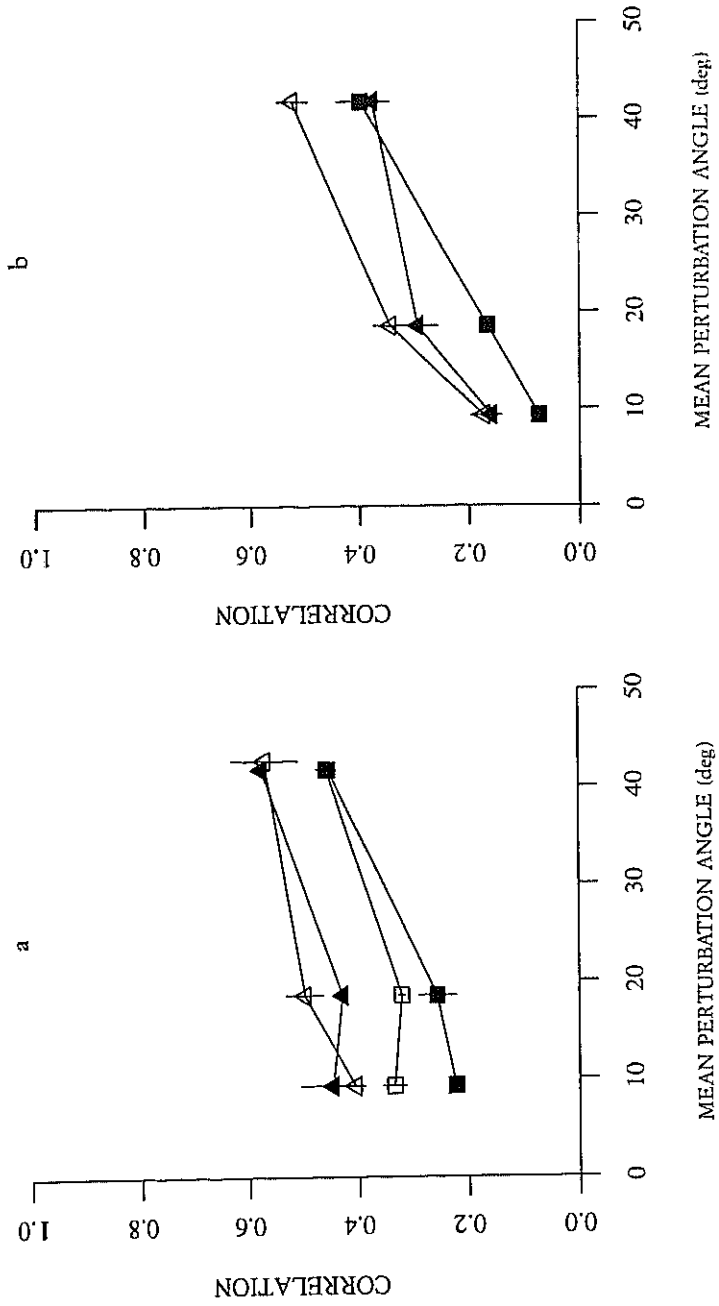


FIG. 7. $R_{\bar{\varphi}}^*$ versus $\bar{\varphi}$, (a) for Subject RW, (b) for Subject JD. Comparison of the performance in controlling the direction of relative movement HD (△), DD (diagonal divergence only shown for Subject RW, □), and the direction of uniform movement (single stimulus field) HO (horizontal orientation, ▲) and DO (diagonal orientation, ■).

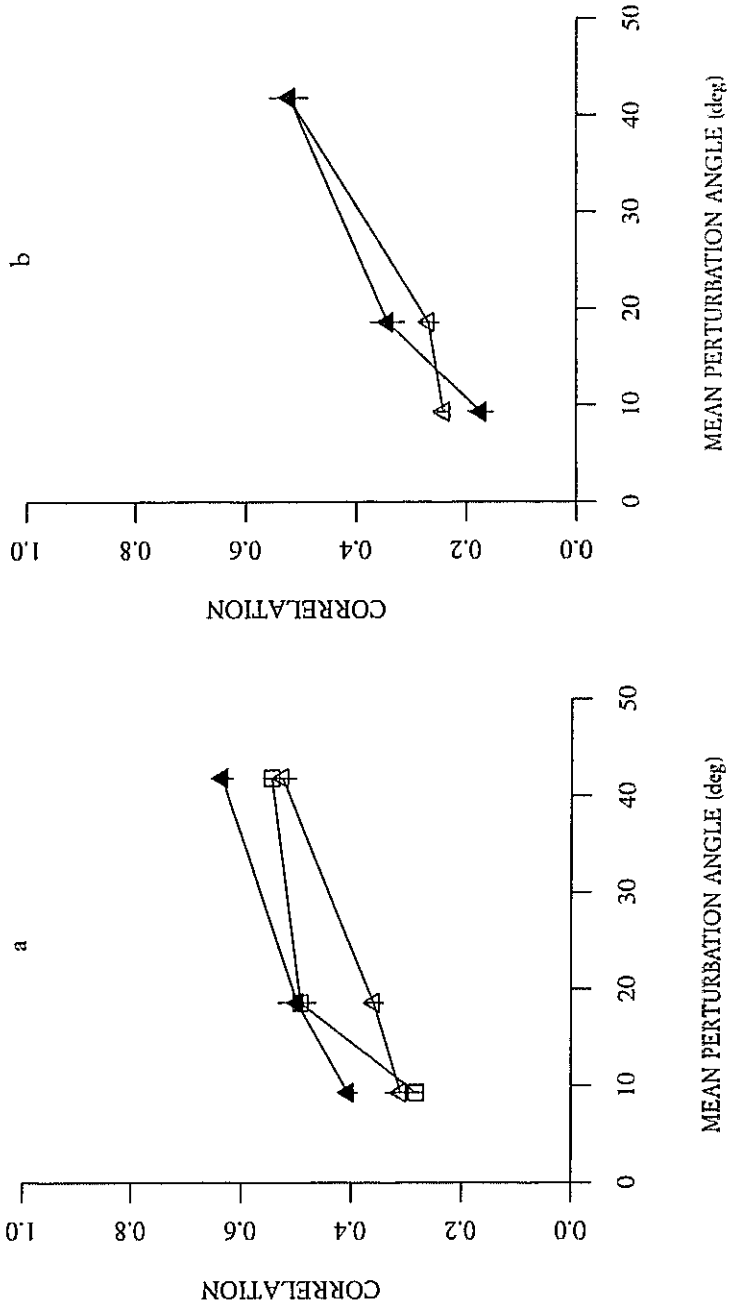
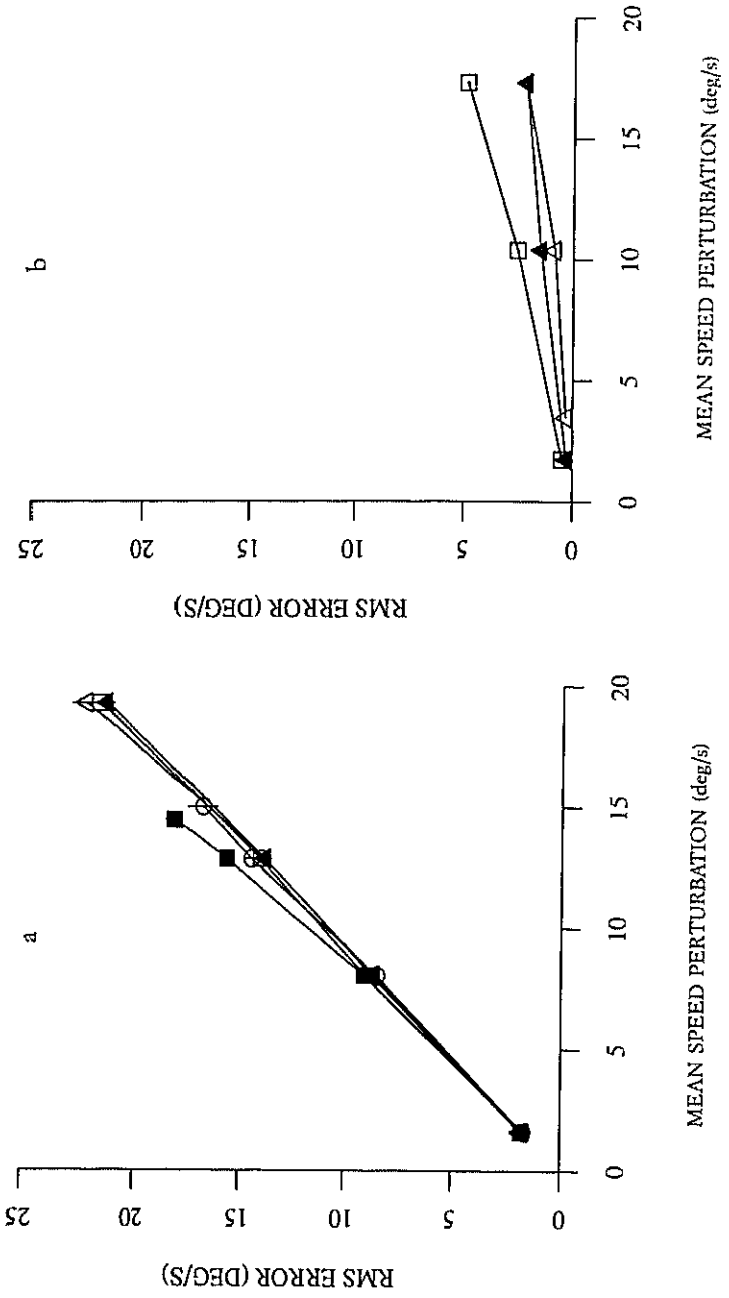


FIG. 8. R_φ^* is shown as a function of $\bar{\varphi}$ at different velocities. (a) Subject RW: 2.4 deg/sec. (△), 10.4 deg/sec. (▲), and 17.3 deg/sec. (□). (b) Subject JD: 3.5 deg/sec. (△) and 10.4 deg/sec. (▲).


a
RMS ERROR (DEG/S)
0
5
10
15
20
25
0
5
10
15
20
MEAN SPEED PERTURBATION (deg/s)
b
RMS ERROR (DEG/S)
0
5
10
15
20
25
0
5
10
15
20
MEAN SPEED PERTURBATION (deg/s)

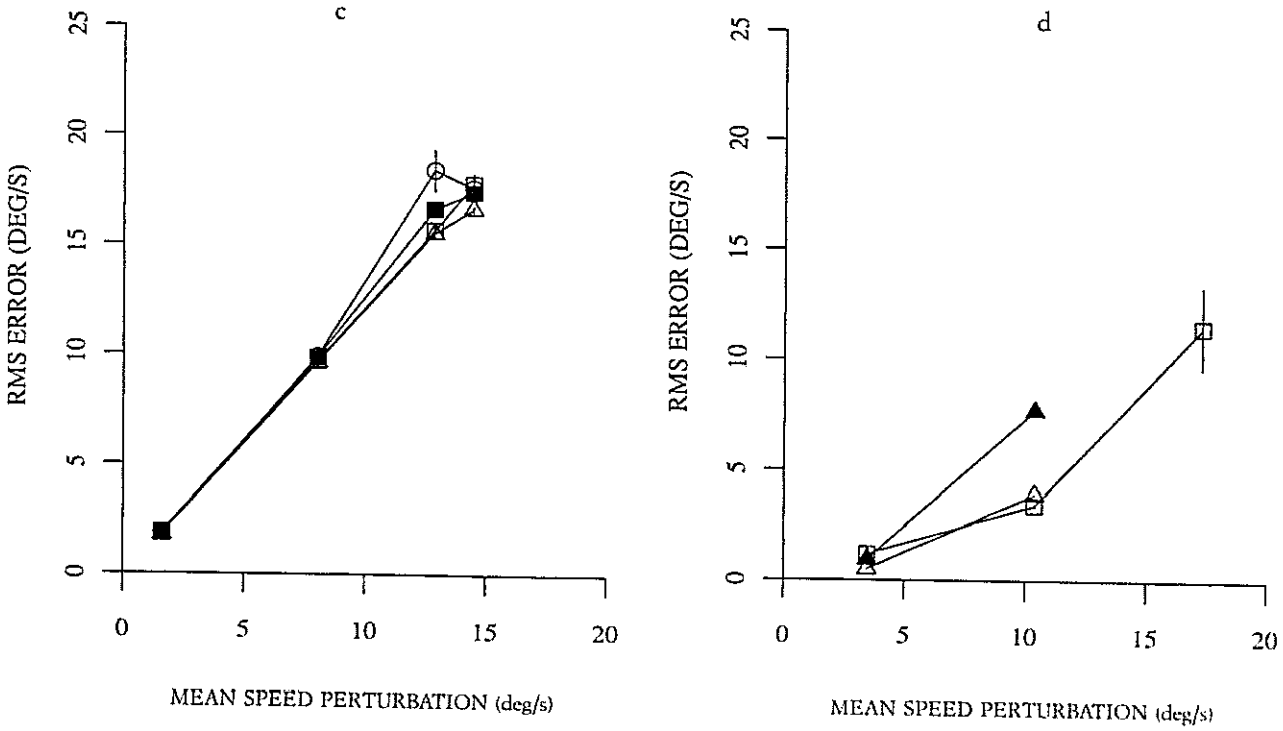


FIG. 9. E_{RMS} as a function of $\bar{v}$ (a) Subject RW; (c) Subject JD and as a function of $\bar{\varphi}$ (b) Subject RW; (d) Subject JD. The symbols in a and c represent data obtained from the following experimental conditions: HD (△), HC (▲), HT (□), VR (■), VT (○) [regression coefficient for whole set of data in (a): $W_v^* = 1.09$ and in (c): $W_v^* = 1.2$. In b the coefficients of the single curves are $v = 2.4$ deg/sec. (△): $W_\varphi^* = 0.09$, $v = 10.4$ deg/sec. (▲): $W_\varphi^* = 0.12$, and $v = 17.3$ deg/sec. (□): $W_\varphi^* = 0.27$. In (d) again all data are taken together. The regression results in $W_\varphi^* = 0.56$. For the calculation of the W^*-values see text.]

Figs. 7a and b show R_φ^* plotted against the mean perturbation angle for stimulus HD (open triangles). These are the same data that we showed already in Fig. 5. The filled triangles represent data that result from a single-field experiment where the task was to adjust horizontal movement in left direction (HO in Fig. 5). For both subjects there is significant overlap in the R_φ^*-curves for stimulus HO and stimulus HD. The situation deteriorates, however, when the movement direction has to be adjusted to a diagonal orientation (DO) which does not have such a clear internal representation as the horizontal or the vertical orientations (filled squares). For small perturbation angles the correlation in the task requiring adjustment of diagonal orientation of a single pattern movement dropped to $R_\varphi^* = 0.2$ in the case of Subject RW and to $R_\varphi^* = 0.08$ in the case of Subject JD. Finally, the curve indicated by DD (diagonal divergence, open squares) in Fig. 7a shows that the extra information contained in the relative movement of the two stimulus fields facilitated the task somewhat. This effect was, however, not significant.

Next we want to investigate how far the control of movement direction is affected by speed. The decrease in correlation with decreasing perturbation angle is shown in Fig. 8 for low (open triangles), intermediate (filled triangles), and high (open squares, shown only for RW) mean velocities. Horizontal divergence was the stimulus in all conditions. One can see that the influence of the mean stimulus velocity was not very strong. The decrease in correlation with the perturbation amplitude is similar for all three velocities. For Subject RW, the over-all performance level seems to be slightly higher at the intermediate velocity of 10.4 deg/sec. This is the velocity that we used throughout the other conditions of Exp. 2.

Discussion

Comparison of the Performances in Exps. 1 and 2

If one compares stimulus HD in Fig. 4a and in Fig. 6, one notices that at lower velocities R_v^* is at about the same maximum level as R_φ^* for higher mean perturbation angles. However to compare the performances in the two experiments, it is not sufficient to take only the saturation level of the correlation into account. Large differences between the amplitudes of perturbation and response signal can still result in high correlation if there is only high phase-coherence. In Fig. 9 E_{RMS} versus $\bar{v}$ is shown for both parameters, speed and direction (Figs. 9a and b, Subject RW, Figs. 9c and d, Subject JD). For both subjects the data points obtained with all stimuli in Exp. 1 lie close enough together to allow them to be pooled for a linear regression with a common coefficient $W^* = \frac{E_{RMS}}{\bar{v}}$. From the data of Exp. 1, we calculate a value of $W_v^* = 1.1$ for Subject RW and of $W_v^* = 1.2$ for Subject JD. In Fig. 8 we have seen already that the influence of the speed on R_φ^* is rather

weak. Figs. 9b and d show the directional error obtained from the same data samples that we refer to in Fig. 8. In Figs. 9b and d, however, the velocity is considered as the independent variable instead of the mean perturbation angle. Since the slopes of the three lines in Fig. 9b are quite different, we calculate the coefficient for each mean perturbation amplitude separately. For Subject RW we obtain the following values: for $\bar{\varphi} = 10°$, $W_\varphi{}^* = 0.09$; for $\bar{\varphi} = 20°$, $W_\varphi{}^* = 0.12$; for $\bar{\varphi} = 45°$, $W_\varphi{}^* = 0.27$. Since Subject JD did not do the experiment at high speed and low perturbation amplitudes, there are fewer data available for regression. Therefore we pooled all data in this case as well, obtaining a value of $W_\varphi{}^* = 0.56$.

General Conclusions

It has been suggested that there are several physiological mechanisms which are selectively sensitive to certain features in the movement parallax field. These suggestions are based partly on theoretical considerations (Nakayama, *et al.*, 1974; Koenderink & van Doorn, 1975, 1978; Longuet-Higgins & Prazdny, *et al.*, 1980) and partly on psychophysical evidence (Nakayama, 1981; Nakayama, *et al.*, 1985; Regan & Beverley, 1985; Regan, 1986).

The results of Exps. 1 and 2 suggest that there is no significant difference in the performance of speed control for the kinds of relative movement and the extended velocity range tested. The decrease in the correlation between perturbation and response signal with decreasing directional perturbation amplitude appears to be independent of the kind of relative movement. Further, the performance that we observe for the directional control of relative movement is not distinguishable from that for the control of uniform horizontal movement within one stimulus field. In the latter case only an internal representation of the target direction is available to the subject. Both the performance for controlling the orientation of two line elements with respect to the horizontal and the performance for the corresponding task of adjusting horizontal movement direction reach their maximum correlation when the stimulus has about the same mean perturbation amplitude. This result, together with the observation that the special kind of relative movements do not have any influence on the performance, suggests that subjects, while performing visually controlled tasks, exploit relative movement whenever different velocity components can be discriminated.

A similar idea has been proposed by van Doorn and Koenderink (1982), who determined discrimination thresholds for the detection of relative movement in two half-fields of a stimulus consisting of moving random dots masked with dynamic white noise. Instead of finding variations in the detection threshold which depended on the special kind of movement transients in their stimulus, they found a universally applicable Weber-law. In a restricted range in the two-dimensional velocity space this Weber-law described sensitivity to variations in speed and direction simultaneously. From these

data, one can conclude that threshold sensitivities to differences in speed and movement direction are equivalent and can be described by a Weber-ratio of about 1. By calculating the rms-error for the adjustment of target direction at different speeds and for the control of speed at constant movement direction we are able to compare the task performances under the two different conditions. The definition of the characteristic magnitude W^* is related to that of the Weber-fraction in the sense that both represent the relative error. The Weber-ratio W^* defining the task performance in our experiments does not represent a purely visual error, as there is always a certain contribution from the dynamics of the motor system involved. We tried to keep this contribution from the dynamics of the motor system constant under all experimental conditions.

The present data suggest that for the control of pattern movement, it is easier to exploit directional information than to exploit speed information. While for both subjects the magnitude of W_v^* is in good agreement with the Weber-ratio for speed discrimination found by van Doorn and Koenderink, our W_φ^* is significantly lower than their Weber-ratio for the detection of directional differences. If we depict our results in the two-dimensional velocity space (see Fig. 10), we obtain elliptic areas containing indistinguishable (v_x, v_y)-parameter conditions; these are elongated in radial direction by a factor of at least 5 in the case of Subject RW and of around 2 for Subject JD. This is due to the fact that the major to minor axis ratio of the ellipse is determined by the ratio of W_v^* (radial part) to W_φ^* (directional part). Although the axis ratios of more than 5:1 and 2:1 are quite different for both subjects, our data provide evidence that there is a much higher sensitivity to directional perturbations of the relative movement than to speed perturbations. On the basis of detection threshold measurements done by Levinson and Sekuler (1976), Nakayama and Tyler (1981), and McKee (1981), Nakayama (1985) reports an axis ratio of 3:1 while van Doorn and Koenderink's results even show a ratio of 1:1. These apparent discrepancies can perhaps be explained by the strongly differing experimental techniques with which the different data were obtained.

The different contributions made by the two velocity components, direction and speed, to the precision of visuomotor control might impose important constraints on the estimates of the parameters of egomotion from optic flow. Recent measurements made by Warren, *et al.* (1991) show that subjects are equally accurate in the determination of heading direction in rectilinear and curvilinear motion no matter whether they are presented a real velocity field as a stimulus or a direction field which contains no speed information. This is not the case if the directions of the velocity fields are randomized instead of the speed components. In the context of our experiments their results give an indication that subjects make use of their relatively higher sensitivity for directional information in optic flow for solving navigational problems. They conclude further that any mechanism in the visual system which is specialized in solving the 'heading from optic flow-problem' is unlikely to be based on few but exact velocity measurements. Data from De Bruyn and Orban (1990), who measured discriminability between four different types of flow fields (translation, rotation, divergence, and shear), suggest that the mechanism which

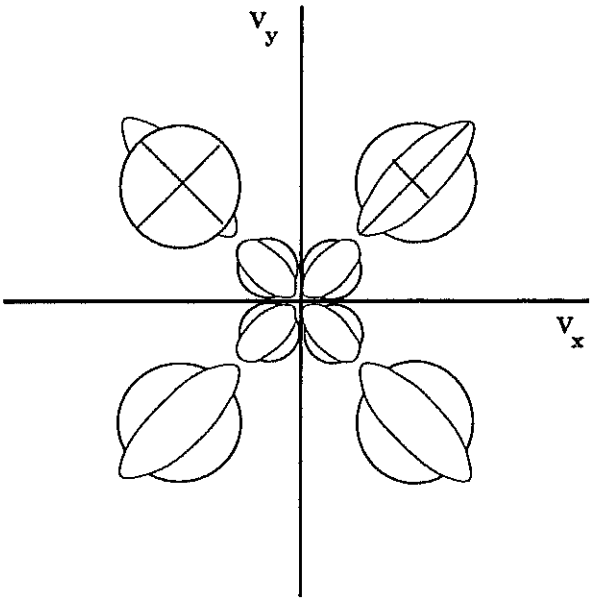


FIG. 10. Schematic diagram of two-dimensional velocity space. Circular areas depict results of measurements done by van Doorn and Koenderink (1982). Elliptic areas illustrate the trend in our results for higher sensitivity to the directional components of velocity fields (represented by the length of the short axis) than to its speed component (represented by the length of the long axis).

extracts the directional information in relative movement is rather robust. These authors report a tolerance of their subjects to directional perturbations of the individual velocity vectors up to 180°. The constraint that they find is that around 4 to 10% of the points in their stimulus have to be displaced in directions which represent the unperturbed flow with an accuracy of ± 15°. As we, these authors did not find any difference in the tolerance to directional noise for the different types of relative movement.

REFERENCES

DE BRUYN, B., & ORBAN, G. A. (1990) The role of direction information in the perception of geometric optic flow components. *Perception & Psychophysics*, 47, 433-438.

DOORN, A. J. VAN, & KOENDERINK, J. J. (1982) Visibility of movement gradients. *Biological Cybernetics*, 41, 167-175.

DOORN, A. J. VAN, & KOENDERINK, J. J. (1983) Detectability of velocity gradients in moving random-dot patterns. *Vision Research*, 23, 799-804.

GIBSON, J. J. (1950) *The perception of the visual world*. Boston, MA: Houghton Mifflin.

GIBSON, J. J. (1979) *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.

GORDON, D. A. (1965) Static and dynamic visual fields in human space perception. *Journal of the Optical Society of America*, 55, 1296-1303.

HELMHOLTZ, H. VON. (1910) *Treatise on physiological optics*. (Translated by J. P. C. Southall, 1925) New York: Dover.

KOENDERINK, J. J., & VAN DOORN, A. J. (1975) Invariant properties of the movement parallax field due to the movement of rigid bodies relative to an observer. *Optica Acta*, 22, 773-791.

KOENDERINK, J. J., & VAN DOORN, A. J. (1976) Local structure of the movement parallax of the plane. *Journal of the Optical Society of America*, 66, 717-723.

KOENDERINK, J. J., & VAN DOORN, A. J. (1978) How an ambulant observer can construct a model of the environment from the geometrical structure of the visual flow. In G. Hauske & E. Butenandt (Eds.), *Kybernetik*. Munich: Oldenbourg Verlag. Pp. 224-247.

KOENDERINK, J. J., & VAN DOORN, A. J. (1981) Exterospecific component of the motion parallax field. *Journal of the Optical Society of America*, 71, 953-956.

LEVINSON, E., & SEKULER, R. (1976) Adaptation alters perceived direction of motion. *Vision Research*, 16, 779-781.

LONGUET-HIGGINS, H. C., & PRAZDNY, K. (1980) The interpretation of a moving retinal image. *Proceedings of the Royal Society, London, B*, 208, 385-397.

MCKEE, S. P. (1981) A local mechanism for differential velocity detection. *Vision Research*, 21, 491-500.

MITTELSTAEDT, H. (1983) A new solution to the problem of the subjective vertical. *Naturwissenschaften*, 70, 272-281.

NAKAYAMA, K. (1981) Differential motion hyperacuity under conditions of common image motion. *Vision Research*, 21, 1475-1482.

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

NAKAYAMA, K., & LOOMIS, J. M. (1974) Optical velocity patterns, velocity-sensitive neurons, and space perception: a hypothesis. *Perception*, 3, 63-80.

NAKAYAMA, K., SILVERMAN, G. H., MACLEOD, D. I. A., & MULLIGAN, J. (1985) Sensitivity to shearing and compressive motion in random dots. *Perception*, 14, 225-238.

NAKAYAMA, K., & TYLER, C. W. (1981) Psychophysical isolation of movement sensitivity by removal of familiar position cues. *Vision Research*, 21, 427-433.

POGGIO, T., REICHARDT, W., & HAUSEN, K. (1981) A neuronal circuitry for relative movement discrimination by the visual system of the fly. *Naturwissenschaften*, 68, 443-446.

POULTON, E. C. (1974) *Tracking skill and manual control*. New York: Academic Press.

REGAN, D. (1986) Visual processing of four kinds of relative motion. *Vision Research*, 26, 127-145.

REGAN, D., & BEVERLEY, K. I. (1982) How do we avoid confounding the direction we are looking and the direction we are moving. *Science*, 215, 194-196.

REGAN, D., & BEVERLEY, K. I. (1985) Visual responses to vorticity and the neural analysis of optic flow. *Journal of the Optical Society of America*, 2, 280-283.

RIEGER, J. H., & TOET, L. (1985) Human visual navigation in the presence of 3-D rotations. *Biological Cybernetics*, 52, 377-381.

ROGERS, B., & GRAHAM, M. (1979) Motion parallax as an independent cue for depth perception. *Perception*, 8, 125-134.

WARREN, R. (1982) Optical transformations during movement: review of the optical concomitants of egospeed. (Final technical report to Grant No. AFOSR-81-0108) Columbus, OH: Ohio State Univer., Department of Psychology, Aviation Psychology Laboratory.

WARREN, W. H., BLACKWELL, A. W., KURTZ, K. K., HATSOPOULOS, N. G., KALISH, M. L., & GRIESAR, W. S. (1991) On the sufficiency of the optical velocity field for perception of heading. *Biological Cybernetics*, 65, 311-320.

WARREN, W. H., MESTRE, D. R., BLACKWELL, A. W., & MORRIS, M. W. (1991) Perception of circular heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 28-43.

WARREN, W. H., MORRIS, M. W., & KALISH, M. L. (1988) Perception of translational heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 646-660.

WEHRHAHN, C., HAUSEN, K., & ZANKER, J. (1981) Is the landing response of the housefly (*musca*) driven by motion of a flow field? *Biological Cybernetics*, 41, 91-99.

WÜST, R. M., KAPPERS, A. M. L., & KOENDERINK, J. J. (1992) Visually controlled matching of pattern movement. *Perception & Psychophysics*, 51, 569-579.

Accepted May 28, 1993.