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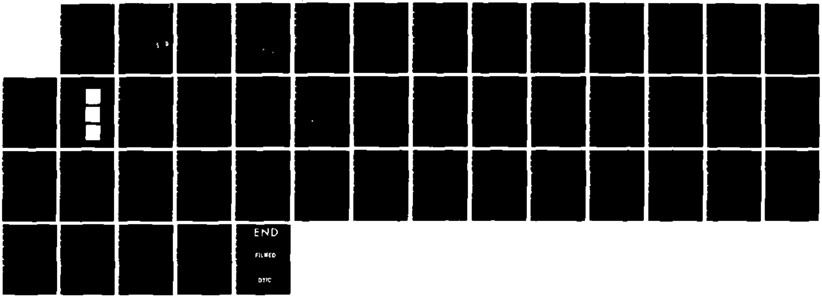

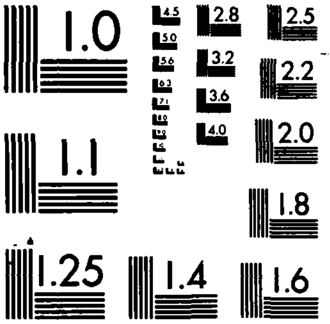

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Vision; flying performance; spatial form vision; motion perception; size discrimination; orientation discrimination; camouflage

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We report four studies. (1) An individual's ability to discriminate small differences in size and small differences in orientation about 5% and 0.5 deg respectively contrasts with the coarse size and orientation selectivity of neurons in the visual cortex of the brain. We report evidence that these fine discriminations are achieved by means of opponent processing: size discrimination is determined by antagonism between neurons that are coarsely selective for size, and orientation discrimination is mediated by neurons that are coarsely

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selective for orientation. Opponent processing implies that the neurons that determine detection are not the neurons that determine fine discrimination: we have experimentally verified that prediction. (2) We have measured motion discrimination in pilots and attempted to predict flying performance in simulators and telemetry-tracked aircraft. Correlations between laboratory tests and flying performance were encouraging, and were much stronger than for simple visual sensitivities such as motion on contrast sensitivity. (3) Some objects are invisible unless they move relative to the background, for example, a grassy hillock viewed against grass in nap of the earth helicopter flight. We have compared human visual sensitivity to such objects, with sensitivity to conventional objects defined by brightness difference. Spatial summation area, and temporal summation area are much larger for motion-defined objects than for brightness-defined objects. (4) We report evidence that the Vector Analysis technique of mathematics may be relevant to the physiological study of visual cues in guided self-motion. Keywords

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VISUAL SENSITIVITIES AND DISCRIMINATIONS AND THEIR ROLES IN AVIATION

INTERIM REPORT - JUNE 1985

BY D. REGAN

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2a. OBJECTIVES

(1) Channeling. Further define the roles of the channeling hypothesis in describing visual performance and in specifying visual parameters likely to be important in flying and simulation.

(2) Camouflaged objects. Define visual sensitivity for camouflaged objects that are invisible except when there is motion parallax. Compare this visual sensitivity in central and peripheral vision.

(3) Self-motion. Experimentally test the idea that the human visual system is specifically sensitive to local vortices and shear as well as to looming, and that these sensitivities are involved in analyzing visual flow patterns produced by self-motion.

(4) Discrimination versus detection. Investigate the hypothesis that spatial frequency discrimination is determined by the relative activity of frequency-tuned neural elements and that orientation discrimination is determined by the relative activities of orientation-tuned neural elements.

(5) Orientation versus spatial frequency. Determine the orientation and frequency constraints on spatial discrimination.

2b. STATUS OF THE RESEARCH EFFORT

Motion-in-depth tracking technique and perturbed tracking technique

The NRC Committee on "Emergent Methods of Visual Assessment" has listed three emerging techniques for visual assessment. Our motion-in-depth tracking technique is one of these three. This is the technique we described in Reference #98. The motion-in-depth tracking device was patented by the U.S. Air Force (Regan & Beverley, U.S. Patent 4,325,697). We have used the technique in attempting to predict individual differences in subjects' ability to judge the motion and location of objects in three dimensions, especially as regards individual differences in flying performance (Refs 114, 117, 123, 131, 134). Other groups have also requested to use the motion-in-depth tracker. These include the U.S. Navy, who have used the device in a study of oversea flying performance in telemetry-tracked aircraft, and the Essex Corp. who have used the device in a study of overland flying and landing performance of telemetry-tracked aircraft. I understand that a simulator manufacturer (CAE), currently working on a project linked to Williams AFB, plan to further develop and use the technique for pilot assessment.

In brief, the rationale for the technique was the hypothesis that the visual system contains several, rather independent, functional subunits, including the "looming" subunit (discussed in Ref 112). We have previously reported evidence that the visual system contains a subunit that responds to line-of-sight motion (i.e. looming) virtually independently of visual parameters including trajectory, sideways motion, and contrast changes (Refs. 66, 82).

Conventional eye-hand tracking tests have the subject track a target that moves in the frontal plane only, i.e. it does not move in depth. This conventional tracking test will not test visual responses to motion along the line of sight. Our test has subjects track a target whose size changes continuously and unpredictably and appears to move in depth. Our technique tests visual sensitivity to line-of-sight motion. A variation of the technique ("perturbed tracking") has the subject track the target's motion in depth while the target is given random sideways motion. If motion-in-depth tracking performance is unimpaired by this random sideways motion, this shows that visual sensitivity to the line-of-sight component motion is independent of trajectory and of simultaneous frontal plane motion caused e.g. by head vibration.

Fine spatial discriminations and visual contrast sensitivity

A current idea in visual science is that the eye breaks up spatial information (e.g. size and shape) into spatial frequency bands that separately deal with fine detail, intermediate detail, and coarse detail. There is an indefinite number of such channels, each tuned to a fairly broad range of orientations. Because these spatial frequency and orientation bandwidths are broad, this analysis is crude. Consequently, it is difficult to understand how subjects are so acutely sensitive to differences in size and orientation.

We collected the first data on spatial frequency discrimination in a substantial group of control subjects (14-26 eyes in Ref. 92). Previous data were for two subjects only (Campbell et al, 1970). The subject´s task was to judge which of two sinewave gratings had the finer bars. Over a broad range it is not the absolute difference but the percentage difference in spatial frequency that determines threshold. Subjects can detect about 2% to 5% difference. Other workers have noted ripples in the curve (Hirsch & Hylton, 1982; Richter & Yager, 1984), but our spatial frequencies were not close enough to bring out that point. Our finding agrees with Campbell, Jukes and Nachmias (1970).

How is size (or spatial frequency) discrimination related to spatial detection? How does discrimination relate to the channel model? We considered several possibilities, including the following: (a) the relative activity of many channels determines discrimination; (b) Watson and Robson´s idea tht spatial frequency channels are "labelled", and the most active channels signal the target´s spatial frequency.

Our rationale was this: if one channel has its sensitivity depressed by adaptation, then model (a) predicts that discrimination will be degraded, but at a <u>different spatial frequency</u> to the contrast sensitivity loss. Model (b) is inconsistent with this prediction. Our experiments rejected model (b) and supported model (a). Figure 1 shows that, in control subjects, adapting to a grating of 5 cycles/deg elevated contrast threshold at 5 cycles/deg as expected, but also elevated discrimination threshold--not at 5 but at 12 cycles/deg (Ref. 139). We proposed that spatial frequency discrimination is determined by nonlinear size-opponent elements in the visual pathway. This hypothesis can also explain our finding that spatial frequency discrimination was not affected by randomly varying the contrast of successive gratings; the discrimination process does not confound frequency change with contrast change (Ref. 139).

In a second study we measured the effect of masking upon spatial frequency and discrimination (Ref. 152 and presented to OSA, San Diego, 1984). Although masked contrast detection thresholds were well known, masked discrimination thresholds had not been previously reported. Discrimination thresholds were measured by the standard temporal 2AFC procedure (method of constant stimuli), but a masker grating was superimposed on the test grating. With a constant frequency masker grating, subjects were able to use moiré pattern cues to frequency and achieved high discrimination (Figure 2, broken line). In order to deny the use of moiré cues we randomly changed the marker frequency between presentations (by ±10%). This procedure revealed that the masker grating produced an elevation of discrimination threshold that was greatest near the test frequency (Figure 2, continuous line). The area under the curve was a little greater above than below the test frequency. These discrimination changes are quite different from those produced by adaptation: discrimination threshold is not elevated at the adapting frequency, but the masking effect is large at the masker frequency; adaptation elevates thresholds above the adapting frequency while the minor skew shown by masked data is in the opposite

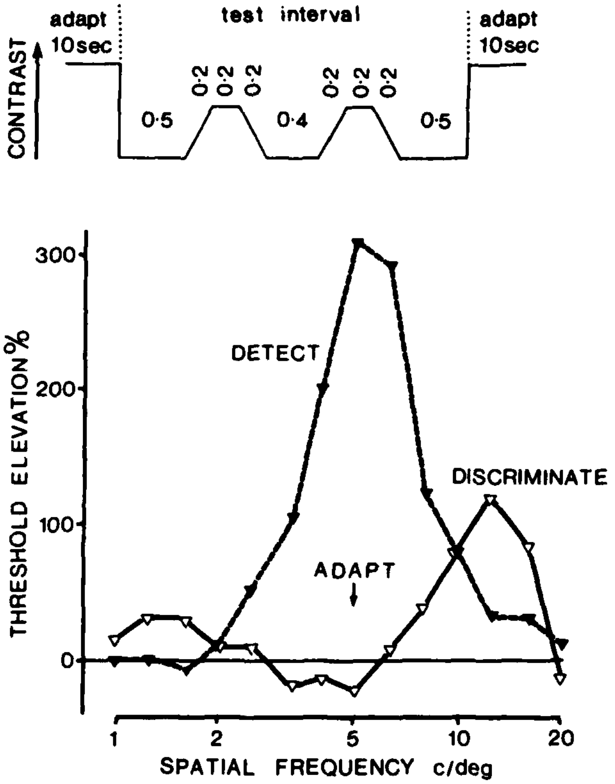

Fig. 1. Changes in contrast detection thresholds (dashed line) and in spatial-frequency discrimination thresholds (solid line) caused by inspecting a sine-wave grating of frequency of 5 c/deg. Subject DR.

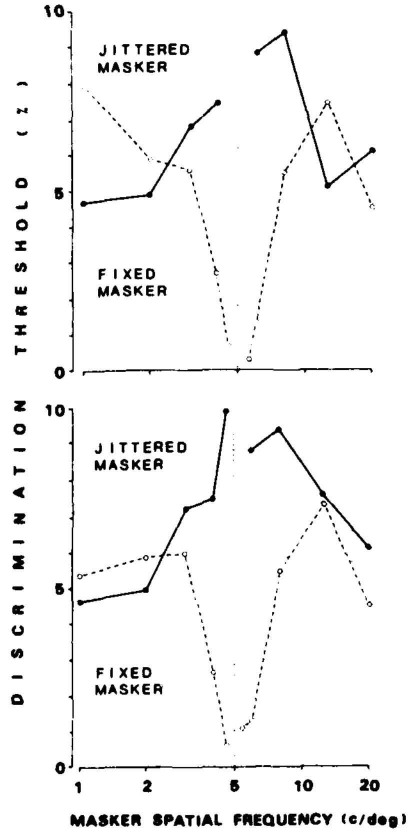

Figure 2. Masked spatial frequency discrimination thresholds (ordinates) for a vertical 5 cycle/deg test grating versus the spatial frequency of a vertical masker grating (abscissae). Broken lines (open symbols) are for a masker whose frequency was the same on every trial. Continuous lines (filled symbols) are for a masker whose frequency was slightly different on each trial (up to ±10% difference). Data are shown for two subjects.

direction.

Nevertheless, as shown in Figure 3, both masked and postadaptation discrimination can be accounted for by the same opponent-size model.

In a further study we investigated postadaptation orientation discrimination (Ref. 150). Confirming previous reports we found that adapting to a vertical grating elevated contrast detection threshold for a vertical test grating, and this detection threshold elevation had a half bandwidth of about 8 deg (Figure 4, dotted line). Our new finding was that orientation discrimination thresholds were improved rather than degraded for vertical test gratings, while for gratings inclined at 10-20 deg from the vertical, discrimination was degraded though detection was little affected. These findings can be explained if orientaton discrimination is determined by the relative activity of multiple channels, for example by opponent-orientation elements. This hypothesis can also explain our finding that changes in orientation were not confounded with simultaneous changes of contrast or spatial frequency.

Linear "opponent process" models of discrimination and linear "line element" models are formally rather similar. (Note, though, that our opponent motion is nonlinear because the opponency is a ratio rather than a subtraction; this choice was necessary to explain how discrimination is independent of contrast.) H. Wilson and I collaborated in an attempt to test his linear line element model´s ability to predict postadaptation discrimination. We carried out the experiment "blind"; I acquired data according to an agreed protocol, and he was required to predict the data after I had acquired it, but he did not know the data. Quantitative and qualitative agreement between prediction and data were good (Ref. 152). (Note that we did not attempt to predict the effects of contrast; contrast effects might discriminate between a line element

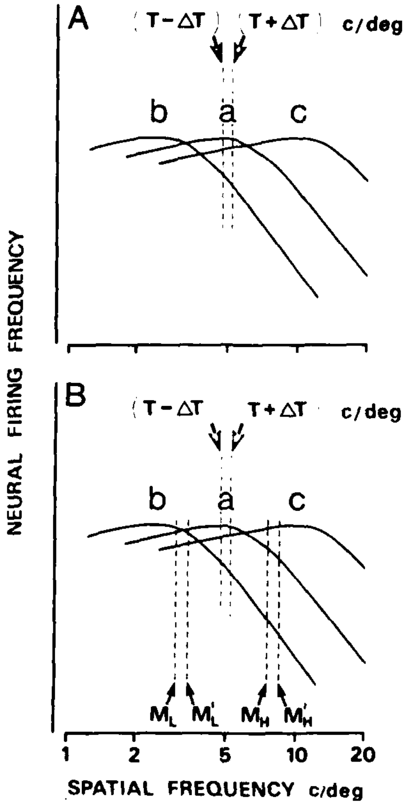

Figure 3. The continuous lines represent tuning curves of three neurons that are driven from the same retinal location. A - Opponent-size hypothesis of spatial frequency discrimination. Test grating frequency changes from (T-ΔT) to (T+ΔT) cycles/deg. A small change in the spatial frequency of the test grating produces little change in the firing of the most excited neuron (a), but a considerable change in the balance of activity between neurons (b) and (c), the greater contribution to this change in balance coming from (b). B - Opponent-size hypothesis of discrimination masking. Test grating frequency changes from (T- T) to (T+ T) cycles/deg, and simultaneously the masker grating's frequency changes between M_L and M_L' or between M_H and M_H' cycles/deg. The balance between the excitations of neurons b and c depends on the random change in masker frequency as well as on the change in test frequency. Since the slope of neuron b is lower at 3 than at 8 cycles/deg, the effect of the 3 cycles/deg masker M_L is less than the effect of the 8 cycles/deg masker M_H).

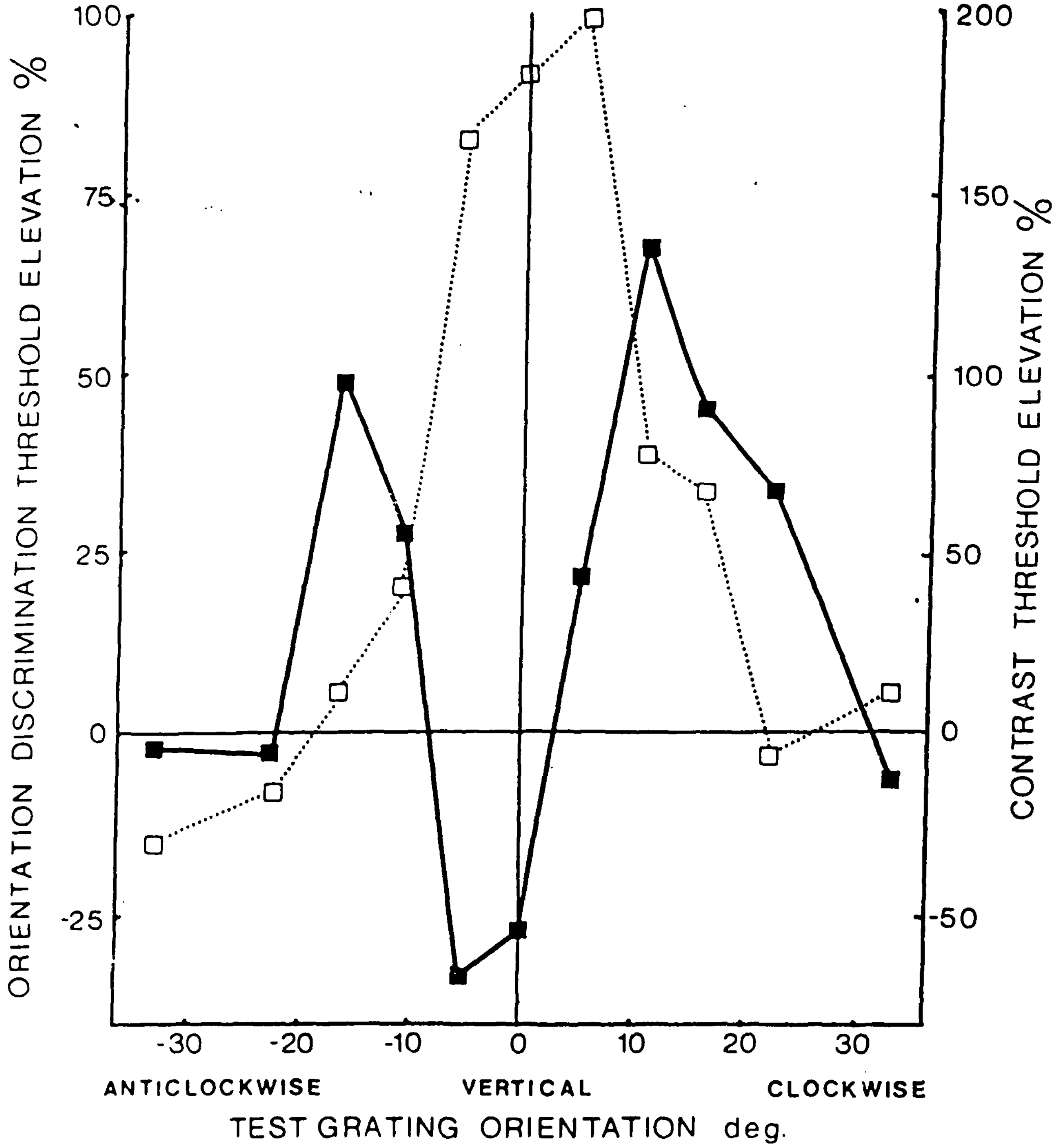

Figure 4. Postadaptation threshold elevations for orientation discrimination (continuous line) and for contrast detection (dotted line). The adapting grating was vertical (0 on abscissa).

In words, we multiply the small length dl by the component of V perpendicular to dl all the way round the dotted line and sum these products. Then we divide by the enclosed area Δa, and allow Δa to tend to zero, to obtain the value of div $\underline{V}$ at one point in the flow field. The value of curl $\underline{V}$ in the two-dimensional case is given by

$$\text{curl } \underline{V} = \lim_{\Delta a \to 0} \frac{\oint dl(V\cos\theta)}{\Delta a} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (2)$$

Both div $\underline{V}$ and curl $\underline{V}$ can be assigned a value at every point in the flow field. A property of div $\underline{V}$ and curl $\underline{V}$ that is of special interest in our present context is that their values are not affected by superimposing translational motion on the visual image as a whole. Thus, their values at any point on the image are not affected by ocular rotation. This can be understood by reference to Fig. 12C. The translational velocity v is necessarily the same at all points on the image as illustrated. Since, for every small segment dl_1 there is a diametrically-opposite segment of equal length (dl_2), it follows that, in Equation 1 above, each dl (sin θ) is cancelled by an equal and opposite contribution so that div $\underline{v}=0$. Similarly, from Equation 2, curl $\underline{v}=0$. In words, the translation velocity $\underline{v}$ does not contribute to either divergence or curl.

We have previously reported psychophysical evidence that the human visual system is specifically sensitive to div $\underline{V}$ (Regan, Beverley & Cynader, 1979; Kaufman & Regan, 1985) and evidence for specific sensitivity to rotary motion is described next.

Visual sensitivity to rotary motion

It has been suggested that the visual pathway might contain elements that are specifically sensitive to rotary motion, and are distinct from elements sensitive to linear motion (Longuet-Higgins & Prazdny, 1980). One problem in was the asymmetry of the Figure 11 curve marked by stars. There was no evidence for elements tuned to the converse V_L/V_R ratio (filled circles). Thus, the Figure 11 data can almost entirely be explained by assuming that, in contrast with the binocular analysis of motion in depth, monocular analysis is chiefly into orthogonal velocity components. These components comprise motion towards and away from the eye along the line of sight, and leftwards and rightwards in the frontal plane. [Different directions in the frontal plane would be dealt with by different frontal plane motion elements (Sekuler, Pantle & Levinson, 1978).] On the other hand, Figure 11 gives some suggestion that, in addition, there might be elements tuned to values of V_L/V_R other than +1.0 and -1.0.

<u>The eye and Vector Analysis</u>

In the notation of Vector Analysis, the instantaneous retinal velocity field can be mathematically described in terms of the values of grad $\underline{V}$, div $\underline{V}$ and curl $\underline{V}$ at every point in the field (Koenderink & van Doorn, 1976, 1981; Longuet-Higgins & Prazdny, 1980). Treatments of Vector Analysis are available at introductory (Schey, 1973) and more rigorous (Rutherford, 1954) levels. Fig. 12A represents a snapshot of a retinal flow pattern caused by self-motion through the environment. The speed and direction of motion at any point vary over the retinal image, and are indicated by the length and direction of the arrow at that point. The dotted line in Fig. 12A encloses an arbitrary area Δa. Fig. 12B shows the dotted line and the velocity V at one point on the line. At that point the component of velocity along the line is $V\cos\theta$, and the component of velocity perpendicular to the line is $V\sin\theta$. A small segment of the dotted line, length dl, is shown in black. In this two-dimensional case.

$$\text{div } \underline{V} = \lim_{\Delta a \to 0} \frac{\oint dl(v\sin\theta)}{\Delta a} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

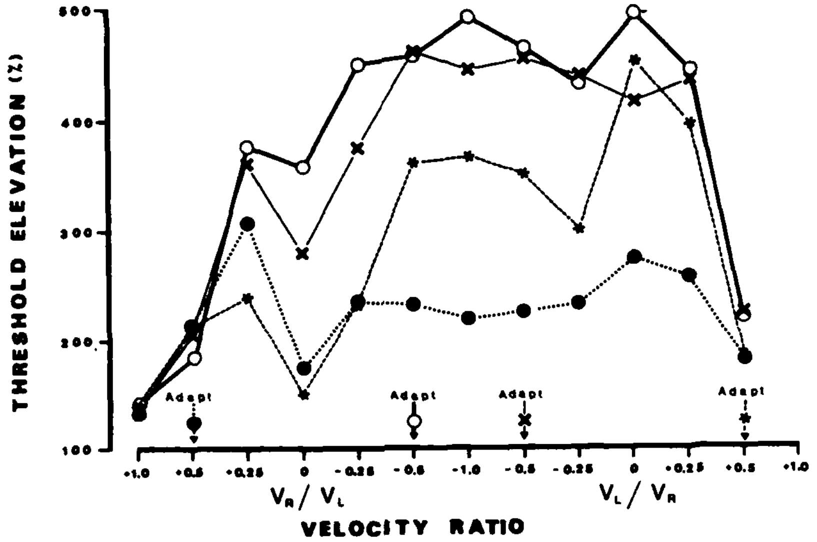

Figure 11. Monocular threshold elevations caused by adapting to different directions of motion in depth. Abscissae plot ratios between the velocities of the test square's left and right edges. The four curves are for the four adapting directions arrowed. Filled circles, fine dotted line - adapting ratio $V_R/V_L = +0.5$ (trajectory to left of eye). Open circles, heavy continuous line - adapting ratio $V_R/V_L = -0.5$ (trajectory passes through eye just left of centre). Crosses, fine continuous line - adapting ratio $V_L/V_R = -0.5$ (trajectory passes through eye just right of centre). Stars, broken line - adapting ratio $V_L/V_R = -0.5$ (trajectory to right of eye).

rationale was analogous to the binocular experiments of Figure 9. In the monocular experiment, subjects set oscillation thresholds for stimuli A and B before and after adapting to stimulus A, and before and after adapting to stimulus B. Figure 11 plots postadaptation threshold elevations versus the V_L/V_R ratios of the 12 different test stimuli. Test and adapting squares were centrally viewed, 1.0 deg side length and of luminance 12 cd/m^2 superimposed on a 10 deg x 10 deg background of luminance 25 cd/m^2. Each edge oscillated sinusoidally with a frequency of 1.0 Hz. The initial adaptation period was 15 min. The trial interval was 6 sec with 20 sec readapt between trials. Four different adapting stimuli were used: L12R6 inphase (filled circles, fine dotted line); L12R6 antiphase (open circles, heavy continuous line); L6R12 antiphase (crosses, fine continuous line); L6R12 inphase (stars, broken line), where L and R refer to the left and right edges and the numbers are oscillation amplitudes in min arc.

Figure 11 clearly rejects the idea that threshold elevations were entirely determined by the oscillations of individual edges. For example, the two L12R6 adapting stimuli had identical oscillation amplitudes and velocities, but gave quite different threshold elevations (compare filled and open circles). These two adapting stimuli differed only in the phase relation between opposite edges. On the other hand, the Figure 11 monocular data differ from the Figure 9 binocular data in that adapting to trajectories inclined just to the left and right of center did not produce clearly different elevation curves (compare open circles and crosses in Figures 9 and 11) so that, in contrast with the binocular findings, there was no evidence for elements that sharply distinguished between trajectories inclined slightly to the left and right of a collision course. The only evidence for a monocular element that preferred increasing size with rightward motion and decreasing size with leftward motion

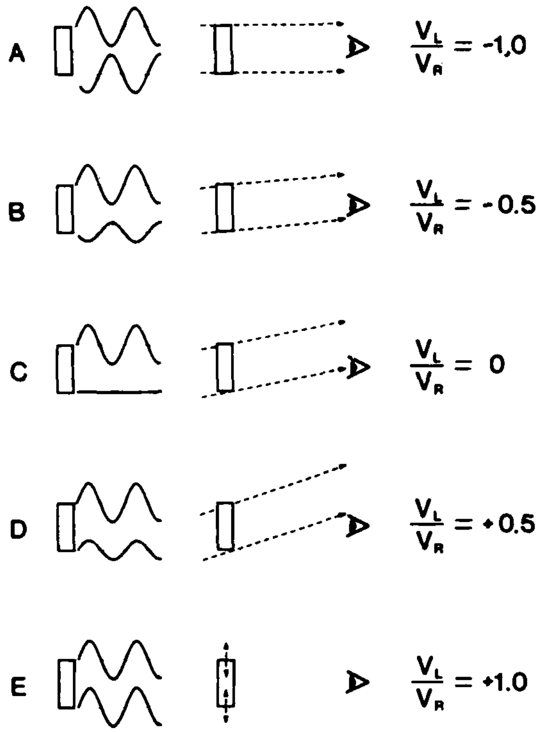

Figure 10. Monocular correlate of the direction of motion in depth. A-E show a square object oscillating along various directions of motion in depth with respect to the eye. F-J show the oscillations of the object's left and right edges seen by the eye. V_L and V_R are the instantaneous angular velocities of the left and right edges. A negative sign means that V_L and V_R are in opposite directions. When $0 < (V_L/V_R)$ 1.0, the square would pass to the right of the eye. When $(V_L/V_R) = 0$ the left edge of the square would just graze the eye. When $-1.0 <$ $(V_L\ V_R) < 0$ the square would hit the eye. Similar relations hold for (V_R/V_L).

direction of motion in depth. This is a different problem to the binocular stereomotion case just described, but it can be approached analogously to the binocular case. An object moving along an arbitrary trajectory is simultaneously changing size and moving in the frontal plane. Figure 10 illustrates how the ratio between the velocities of a square's vertical edges is related to its direction of motion. When the center of the square moves directly through the eye, the speeds of the left and right edges are equal and opposite ($V_L/V_R = -1.0$ in Figure 10A). When the square moves to the right as it comes towards the eye but still hits the eye, the left and right edges move in opposite directions with the left edge moving slower than the right ($V_L/V_R = -0.5$ in Figure 10B). When the square's left edge just grazes the eye, the left edge appears stationary ($V_L/V_R = 0$ in Figure 10C). When the square passes to the right of the eye, the left and right edges move in the same direction, the left edge slower than the right ($V_L/V_R = +0.5$ in Figure 10D), and when the square moves in the frontal plane, left and right edges move identically ($V_L/V_R = +1.0$ in Figure 10E). Subjects are quite sensitive to differences in the V_L/V_R; the trajectory $V_L/V_R = 1.1$ is seen to be clearly tilted in depth compared with $V_L/V_R = 1.0$.

One possible explanation for monocular discrimination of the direction of motion in depth would be that the visual pathway contains several elements tuned either to different V_L/V_R ratios (Figure 10) or to different combinations of changing size and frontal plane motion. For example, one kind of element might prefer increasing size combined with rightward motion (stimulus A), while a second kind preferred increasing size combined with leftward motion (stimulus B). Discrimination would be determined by the relative activity of these notional elements. In order to test for the presence of such selective sensitivities, a monocular adaptation experiment was carried out whose

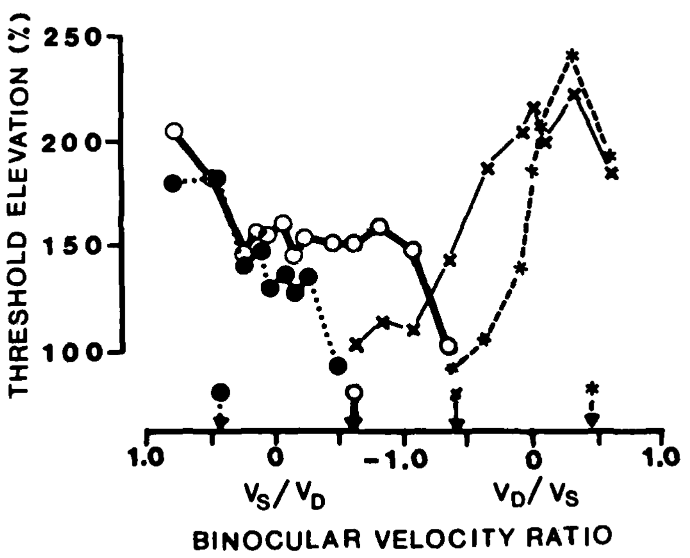

Figure 9. Thresholds for the detection of motion in depth were measured for different ratios of the left (V_D) and right eye's (V_S) retinal image velocities. Threshold elevations were plotted as ordinates versus the velocity ratio of the test oscillation after adapting to four different directions of motion in depth. A negative sign means that V_S and V_D are in opposite directions. Filled circles, fine continuous line - adapting ratios $V_S/V_D = +0.5$ (trajectory to left of left eye). Open circles, heavy continuous line - adapting ratio $V_S/V_D = +0.5$ (trajectory passes between eyes to left of centre). Crosses, fine continuous line - adapting ratio $V_D/V_S = -0.5$ (trajectory passes between eyes to right of centre). Stars, broken line - adapting ratio $V_D/V_S = +0.5$ (trajectory passes to right of right eye). Arrows mark the adapting stimulus ratios.

proposed that this acute discrimination can be explained in terms of sensitivity to relative motion, in this case a velocity ratio. Because the two eyes are a few cm apart, the left and right eyes' images of an object moving in depth move with different velocities, V_D and V_S respectively. The ratio V_D/V_S is uniquely related to the direction of motion in depth. We reported psychophysical evidence that the human visual system contains elements tuned to the velocity ratio (Ref. 34). In the experiment of Figure 9 the subject viewed two dot patterns, one with each eye. Each pattern oscillated from side to side at the same rate, but with different velocities. The subject's task was to set thresholds for just-visible motion in depth. Figure 9 shows threshold elevations caused by separately adapting to four different V_D/V_S ratios. The data can be understood if the visual system contains eight kinds of binocular element, each tuned to a different value of V_D/V_S, four preferring movement towards the head and four preferring movement away from the head. These elements are not arranged orthogonally. For the purpose of the following discussion, note that adapting to a direction inclined just to the left of the nose (open circles) gives a clearly different threshold elevation curve than adapting to a direction inclined just to the right of the nose (crosses), consistent with the idea that the two central elements sharply differentiate between trajectories to the left and right of the nose. By analogy with Hering's theory of color vision we suggested that, in binocular vision, directional discrimination is mediated by interaction between these overlapping elements, much as color discrimination is mediated by difference signals between the three color mechanisms (Ref. 49). According to this suggestion, directional acuity would be determined, not by the bandwidths of these ratio-tuned binocular elements, but by the noise level of the elements.

During the past year, we have investigated monocular discrimination of the

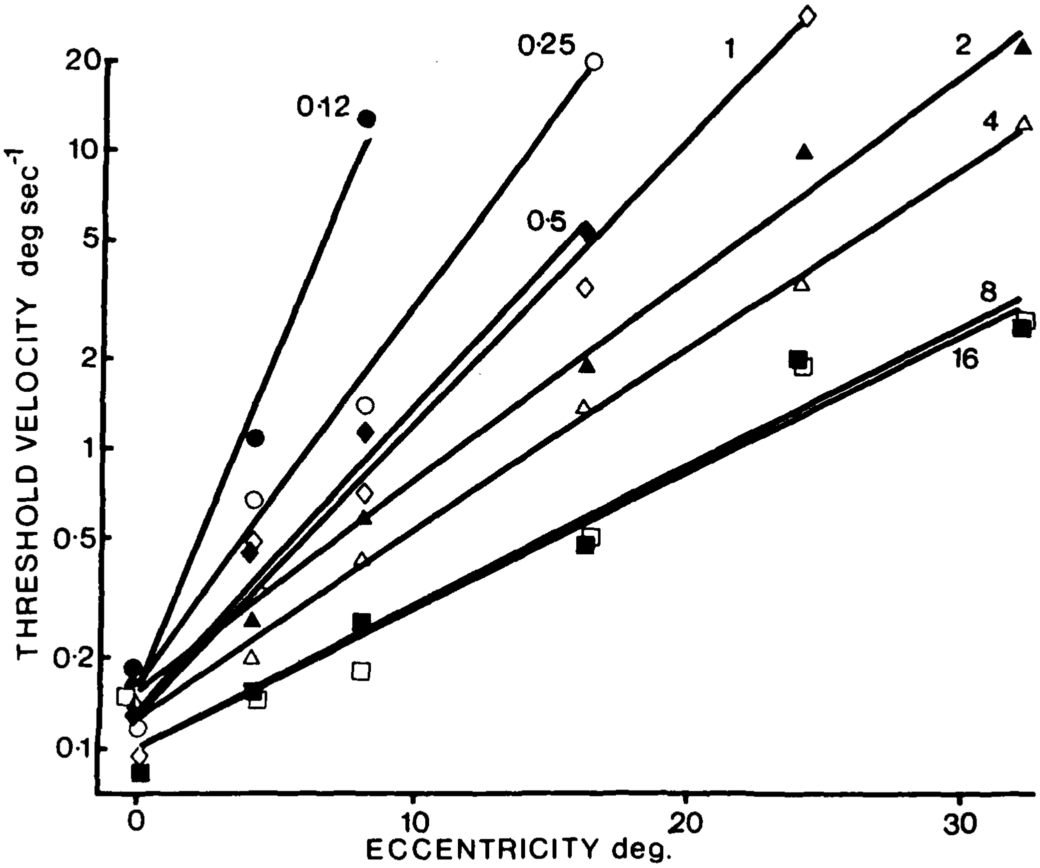

Figure 8 - Log detection threshold for camouflaged dot targets is proportional to eccentricity. The effect of eccentricity is less for larger targets.

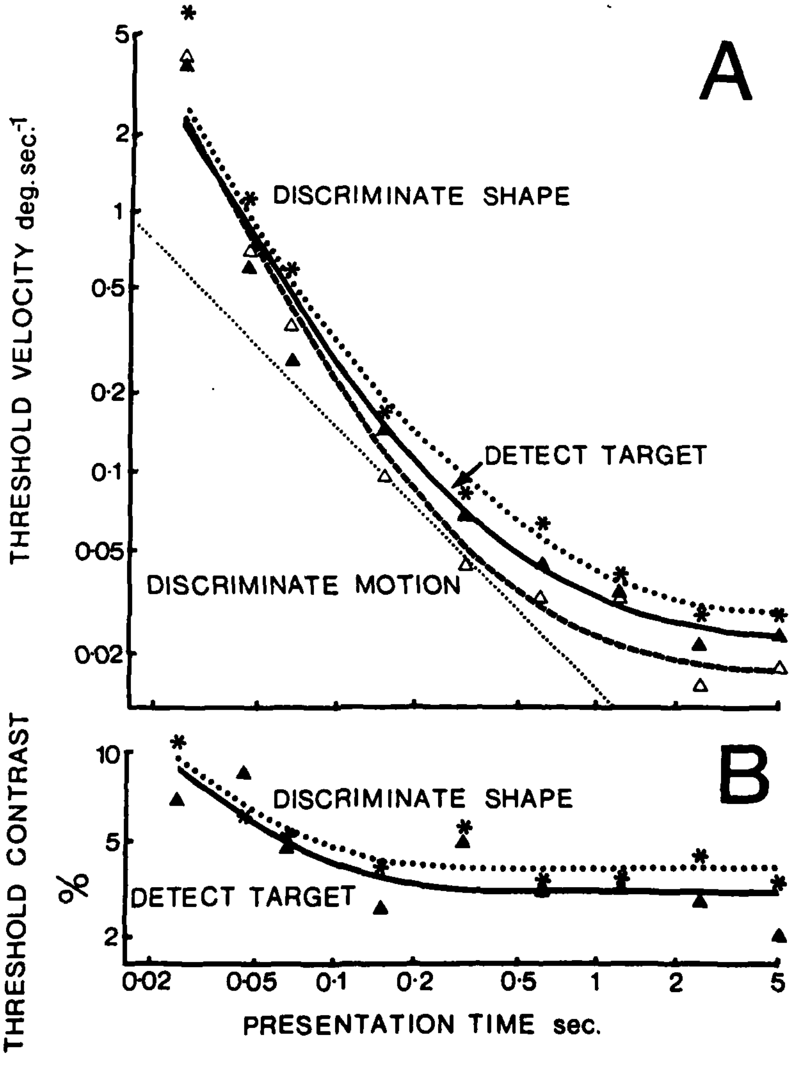

Figure 7 - Effect of presentation duration. A is for camouflaged targets whose boundaries were defined by relative motion, and B is for conventional targets whose boundaries were defined by luminance contrast. The dotted line in A plots a constant-displacement law, displacement being 1 min arc. The curves in B are theoretical fits assuming a single integration time constant τ_1. The theoretical curves in A assume a two-stage temporal integration, the same time constant τ_1 being followed by a time constant τ_2 over 12 times larger. The rectangular targets were of constant shape (K = 2.8) and 1 deg^2 area.

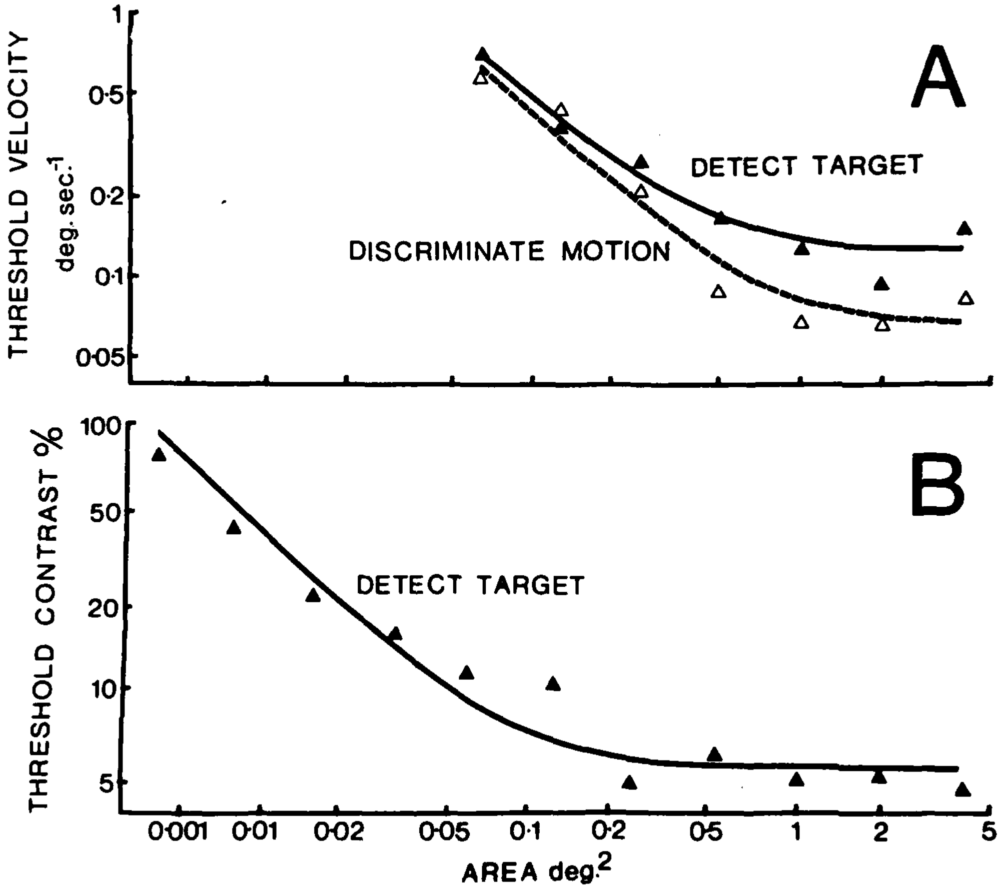

Figure 6 - Effects of target area. A is for camouflaged targets whose boundaries were defined by relative motion, and B is for conventional targets whose boundaries were defined by luminance contrast. The curves in A and B are theoretical fits assuming a gaussian sensitivity profile for summation fields. Spatial summation area is about 5 times larger for targets defined by relative motion (A) than for targets defined by luminance contrast (B). Targets were square and presented for 150 msec.

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Figures 6 and 7 compare target parafoveal detection thresholds for: (a) a dot target whose edges are defined by motion contrast, and (b) a conventional target whose eyes are defined by luminance contrast. Figure 6 shows how target detection thresholds depend on stimulus area. The lines are theoretical fits assuming that receptive fields have gaussian sensitivity profiles. Receptive field area is about five times larger for targets whose boundaries are defined by motion contrast, the areas for camouflaged targets being about 0.16 deg^2 in the parafovea.

Figure 7 shows how target detection threshold depends on presentation duration. The line in Figure 7B is a theoretical fit assuming a single stage exponential integration process. The time constant is 60 msec, consistent with classical data. The theoretical curve fitting the new data in Figure 7A assumes a two-stage exponential integration process. The first stage has the same time constant as the luminance integration stage of Figure 7B. The second stage has a time constant of 750 msec. Thus, temporal integration extends over about 12 times longer duration for a target whose edges are defined by motion contrast than for a target whose edges are defined by luminance contrast.

Figure 8 shows how thresholds varied as a function of eccentricity for different target areas. Log threshold was linearly proportional to eccentricity between 0 deg and 32 deg eccentricity at least. The slope of the plot depended on target area, sensitivity to larger targets being less affected by eccentricity.

Judging the direction of motion in depth from looming information alone

Discriminating the directions of motion in depth. The direction of a target's motion in depth can be discriminated with a remarkably fine acuity of about 0.2 deg when viewing is binocular (Beverley & Regan, 1975). It has been

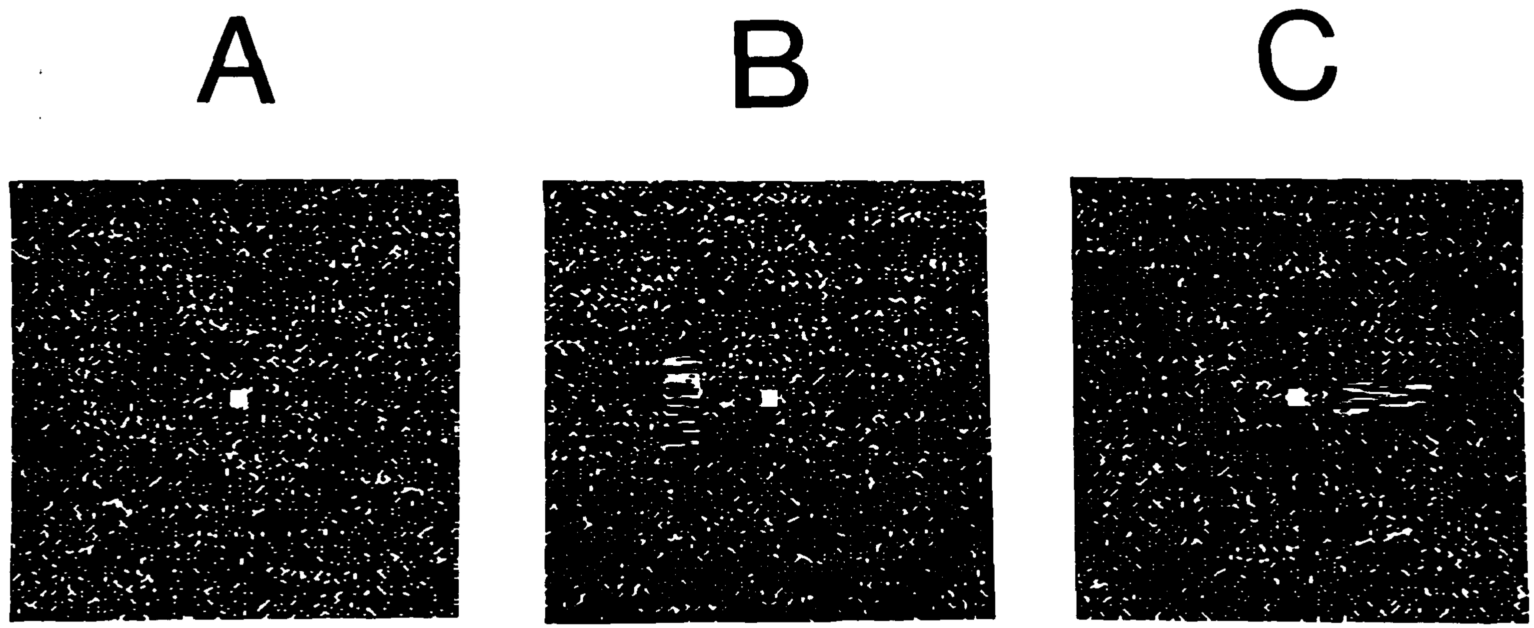

Figure 5 - Camouflaged target stimulus. **A** - The rectangular target is invisible in the absence of relative motion. **B** and **C** - The rectangular target's boundaries are defined by relative motion.

model and an opponent model.]

Spatial vision: extraction of figure from ground by motion

It is well known that some objects that cannot be seen in the absence of motion become visible when there is relative motion between the object and its background. A practical example is that grassy hillocks and ridges that cannot be seen from a hovering helicopter can become clearly visible when the helicopter is moving.

Figure 5 illustrates a laboratory version of such a target. These are photographs of a dot pattern on a CRT. **A** contains a camouflaged rectangle. In **B** and **C** the dots within this rectangle move and the rectangle becomes visible (the moving dots appear as streaks in the two exposures). The boundaries or edges of the rectangle are made visible (i.e. the camouflage is broken) by motion: in the absence of motion the rectangle is invisible. Compare this with a conventional target. A conventional target's boundaries are brightness steps. Clearly, these are two quite different types of object. One is defined by spatial transients of motion, the other by spatial transients of brightness.

We, and others, have previously explored target visibility produced by abruptly displacing part of a dot pattern. Providing that the abrupt displacement does not exceed about 20 min arc and take longer than 100 msec, the "short range" process operates so that the target's camouflage is broken and it becomes visible (Anstis, 1970; Regan & Spekreijse, 1970; Julesz, 1971; Braddick, 1974; Baker & Braddick, 1981). However, these previous studies did not use continuous motion, and thus confounded the effects of dot displacement and stimulus duration. We used continuous velocity and explored the effect of velocity on target visibility, looking at temporal and spatial summation in fovea and periphery; our evidence extends previous work by directly bringing out the effect of relative velocity at the motion-defined object boundary (Ref

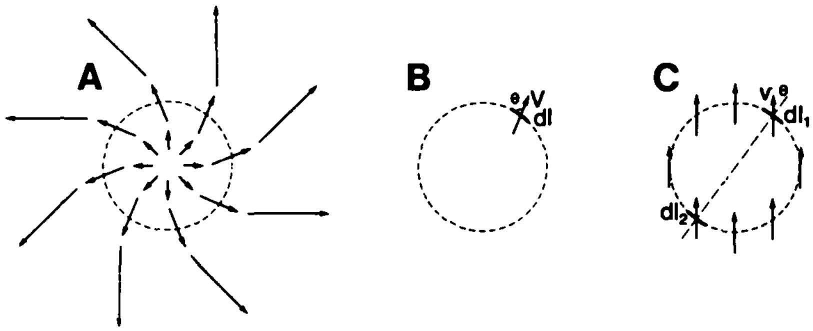

Figure 12. A - illustrates one part of a flow pattern in the retinal image caused by self-motion. The speed and direction of motion at any point vary over the retinal image, and at any point are represented by the length and direction of the arrow at that point. The circular closed line enclosing an arbitrary small area Δa is shown again in B and C. C - the magnitude and direction of velocity v is the same at every point on the retinal image. Velocity v represents bodily translation of the entire retinal image caused, for example, by moving the point of gaze across the visual field.

testing this suggestion is that rotary motion can be approximated by many short linear trajectories, so that a rotary stimulus will stimulate many visual fields sensitive to linear motion. In an attempt to circumvent this problem, threshold elevations caused by two adapting stimuli were compared (Regan & Beverley, 1985). One had a rotary component of motion, but the other did not. The test stimulus was pure rotary motion. Fig. 13 illustrates the rationale. A 2 deg diameter circular area of random dots was divided into four quadrants. The dots in any given quadrant oscillated sinusoidally along a straight line, all with the same peak to peak amplitude. The amplitude and frequency of oscillation were the same in Fig. 13A and B. The only difference between adapting stimuli 13A and B was in the relative phasing of different quadrants. In 13A, all the dots moved clockwise or counterclockwise together so that the circular disc had a strong rotary component of motion about the center. In 13B, the relative phasing of the four quadrants was as shown by the arrows, giving the circular disc zero net rotary component of oscillation about the center. Although the adapting stimulus had a net rotary component in A but not in B, the linear oscillations within any given quadrant were the same in A and B; both adapting stimuli consisted of four linear oscillations, and nothing else. The 1 deg diameter test stimulus (Fig. 13C) was pure rotary motion. Subjects adjusted the amplitude of oscillation until rotary oscillation of the whole area was just visible. Adapting stimulus A produced greater threshold elevations than adapting stimulus B, consistent with the idea that responses to rotary motion cannot entirely be explained in terms of responses to linear motion. It is unlikely that the different effects of the two adapting stimuli can be attributed to the finite receptive field size of linear motion elements since this implies that, after adapting to stimulus B (Fig. 13), motion sensitivity would be higher along the quadrant boundaries than within the

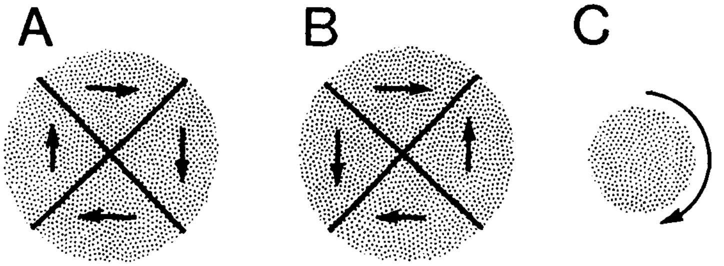

Figure 13. Rotary motion. Adapting stimuli (A and B) and test stimulus C. In both A and B every dot oscillated sinusoidally along a straight line. Every dot had the same amplitude and frequency of oscillation. In A and B the stimulus areas were divided into four quadrants. The arrows show how the relative phases of oscillation were arranged so that A had a component of rotation about the center, but B had not. Test stimulus C was an area of dots that rotated sinusoidally to and fro about its center.

quadrants. There was no evidence of this inhomogeneity in the subsequently-presented test stimulus C (Fig. 13).

Julesz and Hesse (1970) found that regions of a textured pattern composed of thousands of small elements could not easily be discriminated solely on the basis of differences in the direction of rotation of individual small elements. There is, however, an important difference between the pattern used by Julesz and Hesse and the patterns used in the present study: The Fig. 13A and C patterns rotated bodily about a single axis while, in Julesz and Hesse's pattern, each of the many small elements rotated about its own geometric center. Julesz and Hesse's finding makes it unlikely that the visual system contains detectors with small receptive fields that respond specifically to the mathematical quantity curl $\underline{V}$, but this does not conflict with our proposal that the visual system contains elements that are sensitive to rotary motion over a substantial area of the field, the rotation being about a single axis. They would not, strictly, be curl $\underline{V}$ detectors because the area Δa in Equation 2 would be roughly 1-2 deg in diameter rather than being vanishingly small. Such detectors would be stimulated weakly, if at all, by Julesz and Hesse's pattern. Retinal flow patterns involving multiple, closely-spaced centers of rotation are not, however, commonly produced by self-motion through everyday environments. On the other hand, local rotary motion about a single axis in the retinal image can be produced, for example, when an observer fixates an external object at an angle to his or her direction of motion.

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2d. PROFESSIONAL PERSONNEL

D. Regan, Ph.D., D.Sc., A.R.C.S., Professor of Ophthalmology and Medicine

Joint research was carried out with M. Morgan, Ph.D. (Professor of Psychology, University College, London, England); H. Collewijn, M.D. (Professor of Physiology, Erasmus University, Rotterdam, Holland); C. Erkelens, Ph.D. (Erasmus University); H. Spekreijse, Ph.D., F. Roy. Acad. (Deputy Director, National Eye Institute, University of Amsterdam, Holland).

2e. INTERACTIONS

Interactions with Armed Forces

Session chairman at Tri-Services meeting on vision, Pensacola.
Invited paper on vision in aviation at Tri-Services meeting, Pensacola.

Joint research with U.S. Navy (Pensacola, Cmdr Wm. Monaco) on the use of our motion-in-depth tracker and flow pattern tests in predicting flying performance in Navy pilots flying telemetered aircraft (Oceana). [Subject of a Naval Technical Report.]

Joint research with Essex Corp. (Drs. G. Lintern and R. S. Kennedy, Orlando) on the use of our motion-in-depth tracker and flow pattern tests in predicting flying performance in Navy pilots at Yuma, Arizona.

Papers presented at meetings, conferences, seminars, etc

Spekreijse, H., Dagnelie, G., Maier, J. & Regan, D. Flicker and velocity constituents of the motion response. Association for Research in Vision and Ophthalmology (ARVO), Sarasota.

Regan, D. & Beverley, K.I. Postadaptation orientation discrimination. Association for Research in Vision and Ophthalmology (ARVO), Sarasota.

Regan, D. Opponent processes in visual hyperacuities. European Vision Research Conference, Cambridge, England.

Formal lectures

Max Forman Research Prize lecture (Vision and the brain).

Royal Society of the Netherlands, International Vision Workshop (Four kinds of relative motion).

Massachusetts Institute of Technology, Lecture Series (Visual processing of form and motion).

London University, England, Lectures in Neurosciences.

University of Manitoba, Distinguished Scientists Series (Vision research and practical applications).

Mount Allison University, Distinguished Scientists Series.

IEEE Conference, Halifax (Biological cybernetics in vision).

Seminars

U.S.A.: Navy Vision Research (Orlando), Smith-Kettlewell Institute (San Francisco), University of Utah, University of California (Berkeley, Santa Barbara, San Diego)

Canada: University of Manitoba, University of British Columbia

Netherlands: University of Amsterdam