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ILLUSORY REVERSAL OF VISUAL DEPTH AND MOVEMENT DURING CHANGES OF CONTRAST

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Abstract—The visual system usually sees phi apparent movement when two similar pictures are exposed successively, and stereoscopic depth when the pictures are exposed one to each eye. But when a picture was followed via a dissolve by its own photographic negative, overlapping but displaced, strong apparent movement was seen in the *opposite* direction to the image displacement ("reversed phi"). When both eyes saw a positive picture, and one eye also saw an overlapping low-contrast negative containing binocular disparity, "reversed stereo" was seen, with the apparent depth opposite to the physical disparity. Results were explained with a model of spatial summation by visual receptive fields.

It is well known that phi apparent movement (stroboscopic movement) can be seen if two stationary neighbouring points are illuminated successively (Wertheimer, 1912; Korte, 1915), or if two nearly identical, overlapping movie frames are exposed successively. It is also known that two identical or near-identical pictures, presented simultaneously and fused binocularly with a stereoscope, give an impression of depth if there is a small horizontal shift or disparity between them. Uncrossed disparity is the stimulus for distance and crossed disparity is the stimulus for nearness.

In both phi and stereo, the visual system is faced with the task of comparing two similar pictures. We have found new illusions for both, by presenting two pictures, monocularly in sequence for phi movement or dichoptically (one to each eye) for stereoscopy. When a black-and-white pattern was followed, via a fade or dissolve, by its own photographic negative, overlapping but slightly displaced, the perceived apparent movement was in the *opposite* direction to the image displacement. We have called this effect "reversed phi" (Anstis, 1970). Analogous stereoscopic illusory effects were found with dichoptic presentations, with the perceived depth being in the direction opposite to the physical disparity. This can be called "reversed stereo". Reversed movement and reversed stereo could be obtained from almost any black and white patterns. They were elicited weakly by a single edge, and more strongly by a spot (Fig. 2). For contour-rich stimuli such as bars or random-dot patterns (Figs. 3 and 4), they have been easy to demonstrate to classrooms of naive observers.

A slide projector projected a pattern *a* on an aluminized screen. A second projector superimposed either its positive or the negative copy *e* (Figs. 1 and 2), overlapping but with a small (3–20′) horizontal displacement. The projectors were polarized at 0° and 90° respectively. To give apparent movement, the two patterns were exposed alternately, either via a cut with one pattern switching on as the other switched off, or else via a dissolve, with one pattern fading up as the other simultaneously faded down. This was done by slowly turning a polaroid filter in front of the eye: or alternatively, by turning s.c.r. dimmers up and down manually. A dissolve varied the relative intensity of *a* and *e* making the double-image stimulus run continuously through the sequence *abcde* (Figs. 1 and 2). To give stereoscopy, stationary polaroid filters were set at different angles over each eye (say 20° and 40°) so that stationary double-image composites were presented, a different one to each eye. For example, the left eye might see *a*, the right eye *c*. Or, the left eye might see *b*, the right eye *c*. These composites were like frozen stages of a dissolve from *a* to *e*. So each eye always saw the same two images, but the brightness balance between the two was different in the two eyes.

PHI MOVEMENT: POSITIVE TO POSITIVE

Phi movement from *a* to *e* in Fig. 1 gave phi movement in the direction of displacement (to the right, as expected). A dissolve, either continuous or in steps (*a*–*b*, *b*–*c*, etc.), gave continuous or stepped apparent movement, also to the right. During the dissolve, an unexplained effect was noticed: the disk had only two physical positions, *a* and *e*, but it appeared to move through five or six closely spaced positions on the screen.

STEREOSCOPY: POSITIVE TO POSITIVE

Stereoscopy between positive patterns gave results like those of Kaufman, Bacon and Barroso (1973). Stereo results were also consistent with the movement results. Double image composites as in Fig. 1 were presented, one to each eye. If the left eye saw *a* and the right eye saw in turn, *a*, *b*, *c*, then *S* did not see one image in the plane of the screen becoming dimmer with a second, more distant fixed image becoming brighter, as one might have expected. Instead, he saw a single fused image at first in the plane

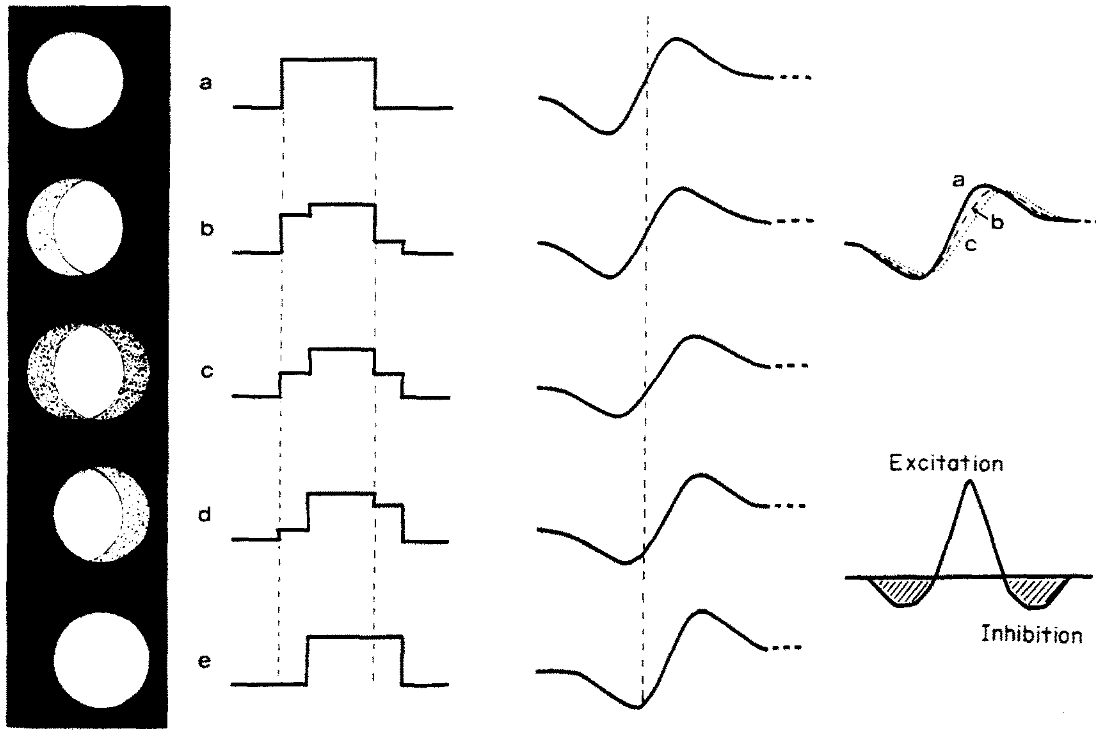

Fig. 1. The left-hand column shows the "frozen" stages (*a–e*) of a phi movement dissolve between a white spot on a black background (*a*) to an identical spot displaced to the right (*e*). The column alongside shows the intensity profiles at each of these stages. The third column gives the intensity profiles of just the left-hand edge of the spot after convolution with the receptive field profile shown on the lower right; mimicking the effect of the known properties of retinal receptive fields. The first three profiles are superimposed on the upper right to demonstrate the effective contour shift to the *right* during the dissolve.

of the projected screen (when both eyes saw *a*), but then apparently moving in steps away from him.

PHI MOVEMENT: POSITIVE TO NEGATIVE

A phi-movement dissolve from a positive to its displaced negative gave "reversed phi": apparent movement was seen in the opposite direction to the physical displacement. A positive which dissolved to its negative that was displaced to the right (reading down the column from *a* to *e* in Fig. 2) gave a pronounced slow apparent movement to the *left*. Dissolving back from negative to positive (reading up the column from *e* to *a* in Fig. 2) gave physical displacement to the left, but apparent movement back to the right. So it made no difference whether the positive or the negative picture came first.

The positioning of the positive and negative pictures was crucial, since the displacement between them had to be less than about 10′ in foveal vision. However, the timing was not at all critical. A direct cut from positive to negative did not give clear reversed phi, but a dissolve did so whether it was fast, taking half a second, or slow, taking several seconds. These dissolves, unlike a direct cut, passed through the double-image composites shown as *b*, *c*, *d* in Fig. 2. The importance of these composites is explained below in terms of our model.

The apparent direction of reversed phi movement was always opposite to the physical displacement: if the stimuli were positioned so that the second picture was shifted up or to the left, or rotated clockwise, or expanded, relative to the first picture then the perceived movement was respectively down or to the right, or counterclockwise, or contracting. If reversed phi movement was inspected for about half a minute, and the gaze was then transferred to a stationary surface, visual motion after-effects were seen which were appropriate to (opposite to) the apparent movement, not to the physical displacement: a clockwise dissolve gave reversed phi apparently counterclockwise, with a clockwise after-effect. Apart from their direction, these after-effects were the same as normal motion after-effects in duration and subjective appearance. Likewise they were localised to the retinal area which had been stimulated with reversed phi movement. When the positive and negative were set so that the displacement between them was different in different parts of the picture, it was clear that reversed phi was *greater* for small displacements than for large, and disappeared for displacement greater than 10′ when viewed foveally and 20′–30′ when viewed peripherally. Reversed phi was appreciably stronger in peripheral than in foveal vision: this has been reported by several authors for ordinary phi (Exner, 1875; Biederman-Thorson, Thorson and Lange, 1971). Whatever part of the retina was used, a complete dissolve was not necessary: even the slightest changes in the relative intensity of the positive

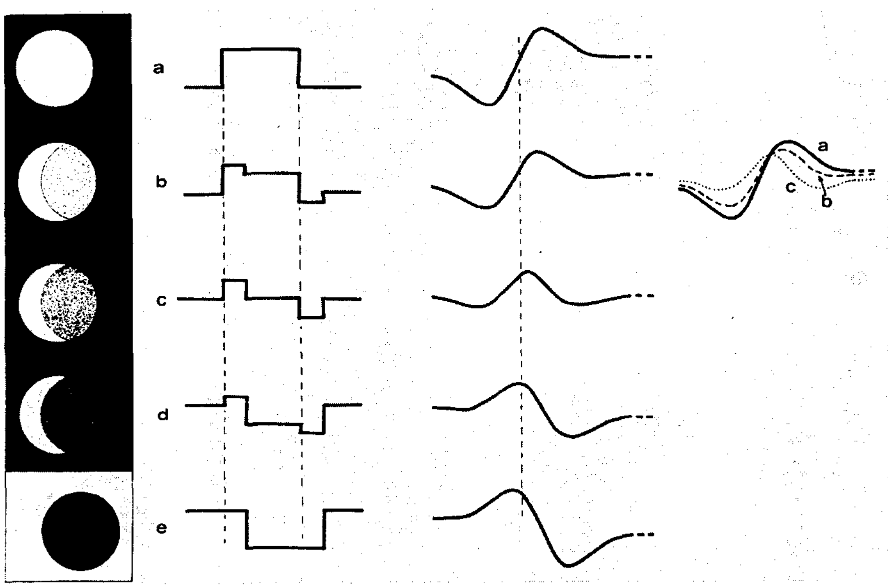

Fig. 2. The left-hand column in this figure shows the "frozen" stages of a phi movement dissolve between a white spot on a black background (*a*) and the negative version (a black spot on a white background) again displaced to the right (*e*). In this case however, when the convoluted intensity profiles of the left-hand edge during the first three stages of the dissolve are superimposed, the effective shift of the contour is to the *left*, i.e. opposite to the direction of displacement.

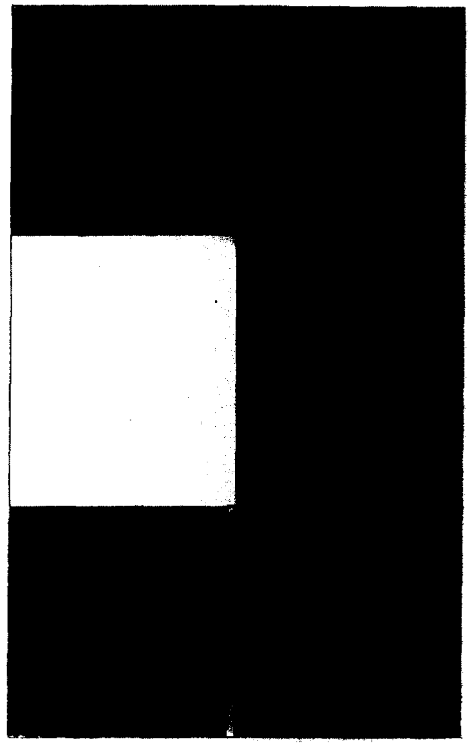

Fig. 6. The apparent vernier offset produced by using composite pictures of positive and displaced negative edges can be seen in this figure. The upper and lower parts are the first stages in a phi dissolve from a positive (black–white contour) to a negative (white–black contour) displaced to the right (as in Fig. 2*b*), or the left respectively. When the figure is viewed from a distance of 6 ft the upper and lower contours appear displaced when compared with the centre black–white border, in a direction opposite to the direction of displacement.

and negative, eg. from a to b, b to $c,\ldots d$ to e Fig. 2, gave reversed phi.

Such intensity changes were far too small to generate appreciable after-images: we conclude that after-images are not implicated in reversed phi. Unlike ordinary phi, a direct cut from positive to negative (from a to e) gave indeterminate perceptual results, with very little reversed phi. Thus reversed phi required the presence of the double-image composites b, c, d.

Normal and reversed phi could be compared side by side when a positive picture dissolved to a second picture whose upper half was positive, as in Fig. 1, and whose lower half was negative, as in Fig. 2. This ruled out eye movement effects as a possible cause of ordinary phi and of reversed phi in this situation. In Fig. 3, the black bars (*a*) dissolved to a set of bars displaced 3–20′ to the right (b). Normal phi movement to the right was seen in the upper half, and reversed phi movement apparently to the left in the lower half. The reversed phi was as marked as the normal phi, and for small displacements ($<6'$) it was actually stronger than the normal phi. A curious perceptual paradox resulted: the upper and lower halves of each bar appeared to move in opposite directions with a shearing motion, yet the bars were correctly seen at the beginning and end of each dissolve as straight and unbroken, with no vernier displacement at the centre line. The dynamic information of movement was in perceptual conflict with the static information of contour position and of object identity. Perhaps movement and position are coded separately in the visual system (Kaufman, Cyrulnik, Melnic and Stoff, 1971). A radial random dot pattern containing a large number of contours gave the most powerful demonstration of reversed phi. Fig. 4*a* dissolved to a second pattern Fig. 4*b* rotated slightly clockwise, which was identical except for an annular zone midway between the centre and the circumference where all the dots were complemented: i.e. each white dot was changed to black and vice versa. The annular zone could not of course be seen in either pattern alone, but exists as a correlation between the two patterns and was readily perceived during a dissolve, when the centre and outside of the disc gave normal clockwise phi movement and the annulus gave counter-clockwise reversed phi movement. This is directly analogous to the way the disparate centre square of a Julesz random dot stereogram is perceived as a result of the correlation between the two random dot patterns although it is not visible in either alone.

To sum up, phi movement by cuts or dissolves between positives gave apparent movement in the direction of displacement. Phi movement by dissolves between a positive and its displaced negative gave apparent movement in the reverse direction, while direct cuts gave indeterminate effects.

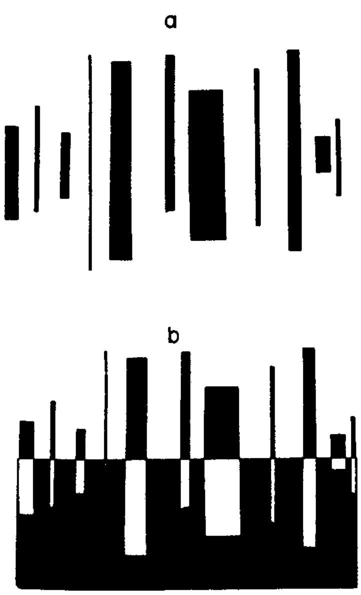

Fig. 3. These two pictures can be use to demonstrate normal (forward) and reversed phi effects simultaneously. Picture b is an exact copy of a except that the lower half of b is in photographic negative. During a dissolve between a and b slightly displaced, (say to the right) the upper half of the figure will give apparent motion to the right (in the direction of displacement) whilst a strong impression of motion to the left (reversed phi) is seen in the lower half.

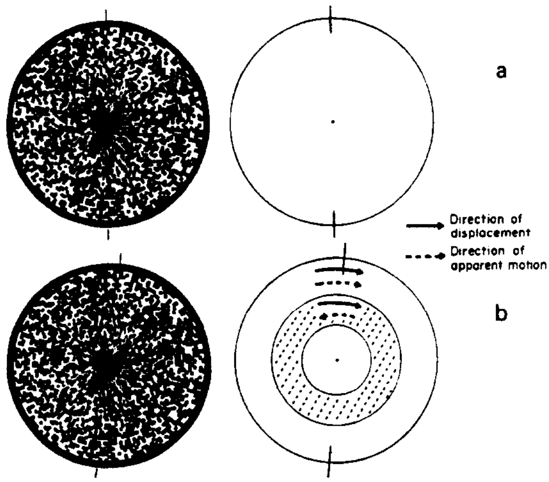

Fig. 4. The lower dot pattern (*b*) in this figure is identical to the upper pattern (*a*) except that all dots in an annulus midway between the centre and the circumference are reversed in brightness. In a phi movement dissolve between the upper figure and lower figure rotated slightly clockwise about its centre, the centre and the periphery give phi movement in the direction of displacement, whilst the annulus produces reversed phi in the opposite (counter-clockwise) direction.

STEREOSCOPY: POSITIVE TO NEGATIVE

To investigate stereoscopy, the same double-image composites of positive and negative pictures were presented dichoptically, but motionless. The perceived depth that resulted was apparently reversed, just like perceived movement. For instance, the left eye looked at Fig. 2*a*. If the right eye saw b (Fig. 2), the physical disparity was uncrossed, but the *apparent* disparity was crossed and the fused image appeared to lie in front of the projection screen. If the right eye saw c, this reversed apparent depth was increased. However, presentation of Fig. 2 d or e to the right eye led to binocular rivalry and complete loss of stereoscopy. This was because *a*, the spot seen by the left eye, was predominantly lighter than its surround. Spot *b* or *c* seen by the right eye was also lighter, giving binocular fusion, whilst spot *d* or *e* seen by the right eye was predominantly darker than its surround, giving binocular rivalry.

In general, depth and phi movement perception behave alike both being based upon a comparison between a pair of pictures. Two obvious differences are that movement perception requires some kind of storage or integrating time, while stereo does not (Julesz, 1971, p. 223): also that stereoscopy can tolerate only small horizontal displacements while movement perception can work on large or small displacements in any direction.

In our experiments, every combination of positive and negative pictures that gave reversed movement during successive presentations also gave reversed stereoscopy with dichoptic presentation. (We only obtained these effects when the displacement or disparity between pictures was less than about 10′.) However for reversed stereoscopy, the positive (or negative) needed to predominate in both eyes, otherwise binocular rivalry occurred (Julesz, 1971; Helmholtz, 1924). For reversed phi, there was no such restriction.

Movement perception in man may be mediated by directionally selective, movement sensitive units in the visual nervous system as have been found in many non-human species (Hubel and Wiesel, 1959, 1962; Baumgartner, 1964; Michael, 1966; Barlow and Levick, 1965: reviewed by Grüsser and Grüsser-Cornehls, 1973). It may be noted that the units found respond equally to white on black and black on white: direction only is important. We have found that such units in the visual cortex of the cat showed reversed phi effects (Blakemore and Anstis, unpublished). A unit with a preferred direction upwards responded to real movement or phi movement upwards but not downwards. However, a spot, edge, bright slit or dark bar followed by its displaced negative elicited a response when the displacement was downwards but not upwards. Thus, whenever the experimenters watching the screen in front of the cat saw reversed phi, the cat unit fired vigorously, so reversed phi may reflect a physiological mechanism.

Adaptation of these units is probably responsible for the negative after-effect of seen movement (Barlow and Hill, 1963). It is therefore interesting to note that in humans the direction of the after-effect was appropriate to the apparently-reversed direction of movement, not to the physical image displacement. Visual units selectively sensitive to binocular disparity have also been reported (Barlow, Blakemore and Pettigrew, 1967; Pettigrew, Nikara and Bishop, 1968; Bishop, 1973). It would be interesting to expose such units to reversed-stereo stimuli.

We believe that reversed phi and reversed stereo are really brightness effects which can be explained by the spatial properties of visual receptive fields.[1] In our model, all visual stimuli are spatially summated, either optically or neurally, within an excitatory receptive field which might be about 5′ wide in the fovea, and progressively larger further out into the periphery (Hallett, 1963; Fischer, 1973; Anstis, 1974). This spatial summation, or neural blurring, is the opposite process to the well known spatial differentiation, or neural sharpening, resulting from lateral inhibition between retinal cells. Spatial or lateral inhibition enhances contours and alters the brightness of various luminance profiles such as spatial ramps, and is the probable cause of Mach bands (Ratliff, 1965, 1974). Our proposed neural blurring would tend to degrade contours very slightly, and presumably to alter perceived brightness somewhat: but this is not what interests us here. The important point is that with the special stimuli that consist of double-image composites, i.e. of superimposed positive and negative patterns, the effect of spatial summation will be to *shift the apparent position* of the double-image contours in a direction opposite to the physical displacement. We have simulated the effects of neural blurring on reversed phi and reversed stereo stimuli, using a computer. Results are shown in Figs. 1 and 2. The luminance profiles of *positive-plus-positive* edges (Fig. 1, column 2) were convoluted with the response profile of a "receptive field" (Fig. 1, bottom right) on the computer. This convolution spatially smoothed out the effective luminance profiles into S-shaped curves (Fig. 1, column 3), which when presented in a temporal sequence *abcde* gave apparent movement to the right, as expected. However, when the luminance profiles of *positive-plus-negative* edges (Fig. 2, column 2) were convoluted with the same receptive-field profile, the resulting S-shaped curves (Fig. 2, column 3) when presented in the same temporal sequence *abcde*, gave a progressive shift to the left—opposite to the direction of physical displacement. This can be seen more easily in Fig. 2, top right, where the S-shaped smoothed profiles of *a*, *b*, *c* have been superimposed to allow ready comparison. This explains why a dissolve through *a*, *b*, *c*, *d*, *e* gave reversed phi movement apparently to the left, and why presenting (say) *a* to the left eye and *c* to the right eye gave an effective reversal of binocular disparity, from physically uncrossed to perceptually crossed, and a resulting percept of reversed stereo.

In our simulation, the reversal effects depended only on the summatory centre of the receptive field, and were independent of the presence of the inhibitory surround: without inhibition, the S-shaped luminance profiles had a slightly different shape, but they still shifted in the reverse direction. The width of the summatory centre set the maximum displacement between positive and negative which would give reversal effects. For greater displacements, the S-shaped curves did not show systemmatic shifts to the left, and reversal broke down. Note that the model is not dependent upon the summation's being neural. Optical blurring of the physical stimuli with a lens would simply add to the neural blurring produced by the posited receptive fields, and increase the area over which summation took place.

We have confirmed five predictions from the receptive-field model. Firstly, foveal reversed-phi should, and does, break down when the displacement is greater than the known width of foveal receptive fields (about 5′). Secondly, reversed phi should, and does exist for greater displacements in the peripheral

[1] We no longer accept the explanation of reversed phi as a special case of the "wagon wheel" effect given in Anstis (1970).

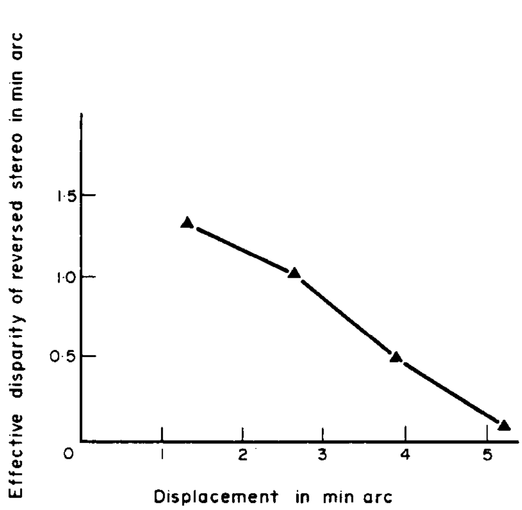

Fig. 5. This graph shows the experimental results for one subject of the effect of varying the displacement on the amount of reversed stereo. The curve decreases monotonically so that the maximum reversed depth is obtained for the smallest displacement of the negative in the composite (1·5'). There was no reversed depth when the displacement exceeded 6' when viewed foveally.

retina than in the fovea, since receptive fields are larger in the periphery. Thirdly, neural blurring by receptive fields should, and can, be supplemented by optical blurring of reversed phi pictures projected on a screen with the lens de-focussed. By doing this, it is possible to produce foveal reversed phi with displacement of up to about 1°, when the extent of optical blurring exceeds 1°. Fourthly, the amount of reversed phi and reversed stereo should, and does, *increase* as the displacement between (sharp) positive and negative pictures *decreases* (Fig. 5). Fifthly, since the effective position of a stationary positive-plus-negative profile is changed by receptive fields, such a profile should, and does, show an apparent vernier offset when aligned with a stationary positive edge (Fig. 6).

In summary, the phenomenon of reversed phi and reversed stereo have led to a supposition about the nature of the underlying neural mechanisms and a computer model has been developed permitting certain predictions which have been confirmed. Hence the three reversal effects we have found—for movement, stereo and vernier offset—may not characterise the movement, depth and acuity systems themselves, but may result from a single receptive-field mechanism for pre-processing brightness information.

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