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PHI MOVEMENT AS A SUBTRACTION PROCESS

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INTRODUCTION

WHEN we see an object move, we see it as the same object during its motion; it retains its perceptual identity. If it does not, then we either see it as changing into something else rather than as moving, or else we fail to see any motion at all. It is true that in special cases we can see motion without any persisting object: in conditions of optimal "pure phi", or on viewing a spiral after effect of seen motion which is projected on to a blank field, some observers claim to see pure motion, unattached to any moving object. In this paper we have tried to find out what attributes of an object—its colour, brightness or form—are necessary to carry the perception of motion, and also how much correlation of these attributes must exist between the object in its successive positions for motion to be successfully perceived.

A travelling car, or a ball in flight, is perceived as a moving rigid object. A man running is perceived as a moving object, although he is not rigid: his shape changes insofar as his joints flex and his limbs assume different postures. Yet he is still seen as a single object, undergoing a simple forward motion with superimposed complex motions of arm swinging, knees bending, etc. Even a drifting cloud of smoke, which continuously changes its shape as it swirls, twists and dissipates, is still seen as a single moving object. The changes in shape are seen as variations in the movement, not as a loss of the object's identity.

How much must an object stay the same in order to be perceived as still the same object? There is some minimal identity that it must retain in order that it shall be seen as a single object that moves, rather than one object which changes into another. If a frog changes into a prince in mid-jump, we would not only refuse to *judge* it as a single moving object: we would fail even to *perceive* it as such. Between the case of the cloud and the frog lies a boundary. Our experiments examined this boundary.

If a pattern moves, than obviously its contours must move. If it changes into another pattern, then its contours must also move, otherwise it would remain unchanged. We have studied what kinds of contour displacement lead to the perception of movement, and what to the perception of change. More specifically, we have studied how much change a moving pattern can undergo before the perception of movement breaks down. When a pattern moves rigidly, then all its countours move "in one piece"; there is no relative movement between different parts of the pattern. When a pattern deforms, there is relative movement between its parts, and this relative movement constitutes the deformation. However, there is still some correlation between the "before" pattern and the "after" pattern. Even in the transformation of a frog into a prince, there is still some running correlation, as paws change into hands, warty skin into satin etc. But when one pattern is replaced by a completely different one, e.g. when a motion picture "cuts" from one scene to another, there is no correlation at all between the "before" and "after" patterns. In such a case, we do not see any movement or transformation. We simply see a complete "change of scene". If, accidentally, there is a correlation between the two scenes, e.g. cutting between cameras which are viewing the same objects from slightly different angles, we have a "jump cut", and see a disconcerting phi movement of the objects across the screen. The "jump cut" used to be regarded as a piece of bad craftmanship, but it is now used extensively as a special effect. Yesterday's oddities become today's fashions.

In this study, we have tried to see how much correlation must persist in order for us to see a single object moving, while staying the same object. We have examined the stimulus conditions necessary for the perception of rigid motion (correlated displacement of extended areas), deformation (relative motion between different areas, or correlated displacement of different areas in different directions), transformation and complete change of scene. These are arranged in order of decreasing correlation between "before" and "after". We used a phi movement set up. However, in some of our experiments we used a TV link where the presentation rate of successive frames, 25 Hz, was above the flicker fusion frequency, so that the distinction between phi and real movement became blurred. In general, we were not interested in the *timing* between frames, which turned out not to be critical in our experiments, but in the *content* of each frame. Most of the classical work on phi, from WETHEIMER (1912) and KORTE (1915) onwards, used simple spots or lines as stimuli, and studied mostly the relationship of time, intensity and distance in securing optimal phi. Our interest, however, lay in the influence upon optimal phi of the similarity between successive frames.

BORING (1942, pp. 595–599) and SPIGEL (1965) summarised the early work on phi.

> Phi is reserved for the experience of movement which appears to connect the flashing targets. Such movement has direction but is not itself perceived as having object quality. Beta movement is the name given to optimal apparent movement where a single object is perceived to be in motion. Delta movement, the reverse of beta movement, is movement whose direction is from the second stimulus to the first, and which may be produced by increasing the intensity of the later flash with respect to the earlier.
>
> (Quoted from SPIGEL, 1965)

A few workers have studied similarity between successive frames as a variable in phi movement, using ambiguous patterns which permitted alternative motions to be seen. SCHMIDT (1936) and THURSTONE (1952) found that a red square suddenly replaced by a green square slightly to the left and a red circle slightly to the right could be seen as moving to the left or right according to whether form or colour predominated perceptually for the observer. RATTLEFF (1956) used both grey and coloured figures, and took the precaution of equalising the brightness of the different colours he used. He concluded that if a competition was established between the perceptions of movements based on colour and of movement based on form, then the form determined the perceived movement if the figures differed but slightly in brightness. When there were considerable differences in brightness between the figures, the movement perceived was always determined by brightness. Our results confirm and extend his findings.

Our basic procedure was to start with two identical pictures, usually lantern slides which were projected in alternation on to a screen, almost but not quite in registration, so that there was a small displacement between them. We adjusted the displacement and the rate of alternation until optimal phi movement to and fro was perceived. We then altered one of the two pictures, making it less and less like the other picture, to see at what point of dissimilarity the perception of phi broke down.

We asked two questions. The first was: How *similar* must successive pictures be for phi movement to be seen between them? We found that phi could easily be seen between identi-

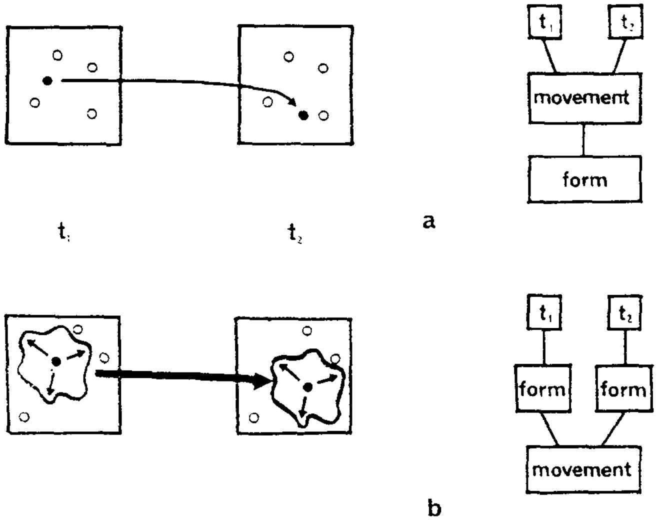


FIG. 1. The kind of similarity between successive pictures which allow phi movement between them may suggest how we see phi.
(a) Common elements between pictures, or temporal connectivity. Movement would be seen by point-for-point comparison of successive pictures, and would precede form recognition.
(b) Forms within each pictures, or spatial connectivity, would be recognised first, and compared with similar forms within the next picture. Form perception would precede movement perception. Our experiments indicate that (a) not (b) is probably correct.

cal pictures: between similar pictures such as Goya's Clothed Maja and Naked Maja: and between two male faces, one smiling and one frowning. Subjects saw a face which moved its eyes, alternately smiling and frowning, and changed its personal identity while remaining a face. A changing expression was carried by a face which itself changed.

Our second question was: what *kind* of similarity between successive pictures is necessary for phi movement? Are similar common elements *between* pictures sufficient, or are similar perceived patterns or meanings *within* pictures necessary? (Fig. 1) For instance, each red element in a face might be compared with the nearest red element in the succeeding face. Movement perception would be a simple process, not dependent upon prior pattern perception. Alternatively, it might be that red elements within one picture need to be grouped together perceptually, and a mouth seen, which is then compared with a perceived mouth in the succeeding picture. Movement perception would be more complicated, and dependent upon prior pattern recognition. Our experiments indicate that the first, simple account is correct, and that movement is perceived by a local, point-for-point correspondence of elements between successive pictures: thus movement perception can precede pattern recognition. However, it is difficult to quantify the results obtained from pictures of real-life objects, so for the formal experiments we used abstract patterns where the degree of correlation could be specified more accurately.

EXPERIMENT 1—REVERSED PHI

We have found that if two identical pictures are presented one after another, overlapping but with a slight spatial separation between them, then normal, forward phi is perceived in the direction of the later stimulus, as expected: but if one of the two pictures is the *photographic negative* of the other, then *reversed phi* is perceived in the direction of the earlier stimulus. The phi movement is unmistakably perceived in the direction *opposite* to the physical displacement. This appears to be a newly discovered effect.

This new effect has nothing to do with delta movement, which occurs when the earlier of two target spots is appreciably dimmer than the second (KORTE, 1915). In our opinion, the resulting delta movement towards the earlier spot is caused by a retinal delay in seeing the earlier, dimmer spot. Such delays can exceed 100 msec (WILSON and ANSTIS, 1969), and are equivalent to a physical delay in exposing the first spot to the subject. Thus delta "movement" is a feature of retinal delay, and not of movement of perception itself. Indeed it has been used as a technique for measuring the retinal delay between spots of different colours and intensities (SCOTT, 1964).

METHODS

The simplest method was to make a positive and a negative slide from the same master photograph, and project them alternately on to a single aluminised screen, overlapping but not quite in register, using two projectors. The pictures could be switched on and off by a rotating mechanical shutter, or by means of polaroid; the lenses of the projectors were covered with pieces of polaroid set at orientations differing by 90°, and the screen viewed through a rotating polaroid. Best results were obtained using random, granular textures (Fig. 2) but any photographs would do provided they had enough fine detail.

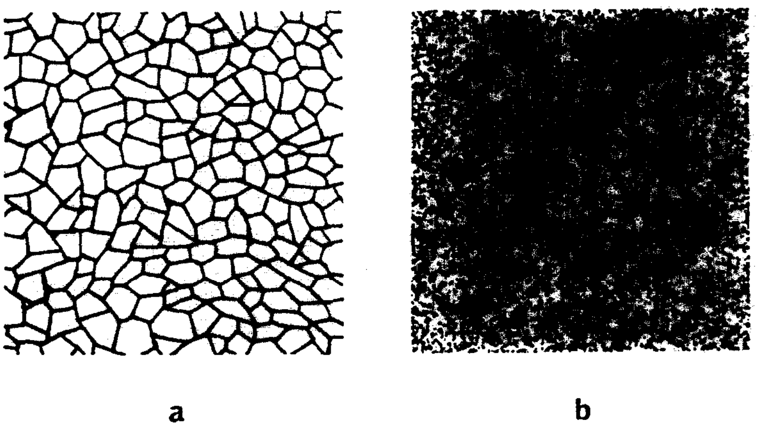


FIG. 2. Granular patterns of "visual noise". (a) Coarse (b) fine.

A brightness negative could be produced nonphotographically, by exploiting the fact that a red pattern looks lighter under red light than under blue light. A pattern of red lines on a blue ground was prepared. This was illuminated by a red flash, then displaced, and lit by a blue flash. Under the red flash, a light pattern on a dark ground was seen, and under the blue flash, a dark pattern on a light ground. Since the second pattern was a brightness-negative of the first, reversed phi was seen. Of course, if both flashes were red, or both blue, then no brightness reversal occurred, and normal forward phi was perceived.

If the pattern was rotated on a turntable under steady red light, which was suddenly switched to steady blue light, then the pattern appeared to reverse its direction of motion briefly at the moment when the illumination changed colour.

A variation on this technique required no moving parts. A stationary red-and-blue pattern was viewed under a steady red light, which was switched to steady blue light. The observer viewed this display through a stationary wedge prism, which was not colour corrected. When the colour of the illumination was changed, the pattern appeared to go negative, as before, and was simultaneously displaced optically by the prism, which refracted blue light more than red light. The result was that reversed phi movement was seen, in the direction opposite to the direction of the optical displacement.

Note that this technique used colour purely as a means of varying brightness. The effects of colour changes in themselves are described later.

This technique proved rather inflexible, and was abandoned in favour of:

Closed circuit television. When a whole series of pictures was to be presented in alternating positive and negative frames, a TV camera viewed patterns which rotated on a turntable, and the picture was displayed on a TV monitor screen. The signal from the camera was switched alternately through a non-inverting and an inverting amplifier, by means of a high speed relay oscillating at 25 Hz, before being fed to the TV screen. (Fig. 3).

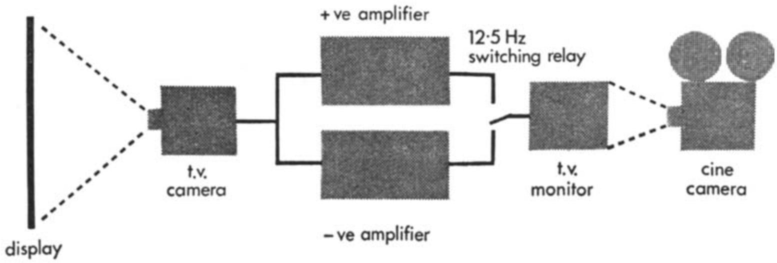


FIG. 3. Closed circuit TV link. Moving displays were seen by the TV camera and shown on the monitor screen. Alternate frames of the TV picture were made positive and negative in brightness, by switching between the outputs of the positive and negative (inverting) amplifiers at 12·5 (or 25) Hz. Result: movement on the TV screen appeared subjectively reversed in direction "reversed phi".

The effect of this was to reverse the picture brightness at a frequency of 25 Hz, so that each TV raster scan was the photographic negative of its predecessor. The TV raster scan or "field", takes approximately 1/50th sec, scanning 312·5 lines, and the next "field" scans the interlaced 312·5 lines, so that two fields together make up one TV "frame", or complete picture. We found that cycling at the field rate (25Hz) gave better reversed phi than the frame rate (12·5 Hz).

The Contrast of the positive and negative amplifiers was adjusted independently, until optimal reversed phi was obtained during movement, and the brightness-reversing picture had an easily recognisable flickering lustre when stationary, somewhat like the lustre of binocular rivalry. The display seen by the TV camera had to be very evenly illuminated, otherwise the contrast settings could not be optimised over the whole picture, and patches of the picture showed ordinary forward phi at the same time as the rest of the picture showed reversed phi.

The inverting amplifier, which made the TV picture go negative, was a piece of standard equipment. It is used for broadcasting news programmes. Since it takes time to develop positive prints from negative newsreel film stock, it is customary to project the original negative film and reverse the picture electronically for transmission. Newsreel editors become skilled at editing negative film stock, and can learn to recognise pictures of well known news personalities in their negative form.

Movie films were made by aiming an Arriflex movie camera at the TV screen. The camera was run at 25 frames/sec and the relay which switched the picture from positive to negative was run at half speed (12·5 Hz) during filming, so that the camera recorded only alternate fields, i.e. one interlaced half of each picture. The variable phase shutter on the Arriflex was set correctly by viewing through the reflex viewer. We carried out controls to ensure that reversed phi was not a physical artefact caused by strobing or by the TV link; nor a physiological artefact caused by afterimages. Reduction of afterimages by dimming the pictures, or varying the presentation rate, had no effect at all on reversed phi.

Results

Reversed phi movement was seen in all cases when the picture alternated between positive and negative. When the picture moved upwards, it was perceived as moving downwards, and *vice versa*: when it moved to the left, it was perceived as moving to the right, and *vice versa*: when it rotated clockwise, it was perceived as rotating anti-clockwise, and *vice versa*: and when it expanded (by moving the pattern towards the TV camera, or by zooming the TV camera lens), it appeared to contract, and *vice versa*. These effects were seen by both naive and practised observers, and were just as vivid as the normal non-reversed forward phi.

After effect of seen motion. A brightness-reversing granular pattern, which was physically rotating clockwise, appeared perceptually to be rotating anticlockwise owing to reversed phi. Inspection of this display for 30 sec gave an after effect of seen motion when the gaze was then transferred to a stationary surface. This after effect was *clockwise*, i.e. appropriate to the perceived reversed phi, not to the physical direction of rotation. This is evidence that reversed phi gave a genuine percept of movement.

Eye movements. Instead of viewing a moving, brightness-reversing TV picture with his eyes stationary, the observer could move his eyes smoothly over a stationary, brightness-reversing TV picture. Results were exactly the same. When *S* gently pushed his eyeball passively with his finger through the eyelid, then normally the world would appear to move against the direction of the passive eye movement. The brightness-reversing TV picture, however, appeared to move in the same direction as his eyeball. If his eye voluntarily tracked a moving finger, then normally the world would appear to move against the direction of this eye movement. The brightness-reversing TV picture, however, appeared to move in the same direction as his eye movement. Incidentally, it is possible that this effect could be used as an experimental technique in the study of the stability of the visual world during eye movement, although we have not used it for this purpose.

If *S* made a loop with his thumb and forefinger, and tracked this as he moved it slowly across the TV screen, then the grains of brightness-reversing picture seen inside the loop appeared to move in the same direction as his hand, but about twice as fast. If *S* moved his head sharply towards the TV screen, then the pattern appeared to contract as the grains rushed together towards the point on the screen at which he aimed his head. As he drew his head back, so the pattern expanded as the grains rushed apart from the centre again.

In our opinion, the results from moving *S*'s eyes in one direction are the same as moving the display in the other, because both give the same stimulation at the retina. It is worth drawing a parallel between our results for *S* moving his eyes across a stationary brightness-reversing picture, and Mackay's (1961) quite similar results using "snowstorm" dynamic random visual noise on a TV screen. Mackay found that snowstorm noise could be subjectively drawn along the TV screen by a loop of finger and thumb, but at the same speed as the hand, not faster as we found.

Mackay writes:

> One of the most pleasing effects occurs when a portion of the random field is "framed" with a moveable contour such as the outline of loop of wire. When the wire frame is moved and followed with the eyes, the whole assembly of "Brownian particles" within it (and those immediately outside it) are unmistakeably seen to be moving with it. If the motion of the frame is rapid and oscillating, the particles show a kind of inertia, lagging behind and swirling just as if immersed in a fluid (Mackay, *op. cit*). This inertia may perhaps be related to the failure of the eyes to track perfectly a rapidly moving object.

We have also noticed that moving the head sharply towards the TV screen makes snowstorm noise apparently contract, and pulling the head back makes it apparently expand again, although these effects are less marked for the noise than they are for the stationary brightness-reversing picture.

In our opinion, our effects and Mackay's noise effects are related, and both are to be understood by considering what happens at *S*'s retina.

The reversed phi effects occur whenever the brightness-reversing picture is moved across the retina, and it makes no difference whether this is done by moving the picture or by moving the eye: all that is necessary is that successive frames fall on slightly different parts of the retina. Mackay's noise effects, however, occur only when *S* moves his eyes, and knows that he moves them: physical movement of the noisy picture on the TV screen has no perceptual effect at all, because when random noise is displaced, the displaced noise is still random, and is indistinguishable from non-displaced noise (except in the special case of noise whose bandwidth is low compared with the speed of its displacement, which we need not consider here). Indeed, it is mathematically almost the same: moving the noisy field from side to side at (say) 1 Hz simply adds 1 Hz to the power spectrum of the noise, and if the bandwidth of the noise is appreciably higher than this, which it always is on a TV screen, then it will pass completely unnoticed. The very fact that the noise is effectively unaltered by displacement gives us a clue to the explanation of Mackay's effect. When the noise moves across *S*'s retina, it is perceived by him as if it were stationary on his retina. So perceptually it behaves rather like a stabilised retinal image, e.g. an after image. When *S* moves his eyes actively, e.g. by tracking his moving hand, an after image appears to move with his hand: and so the noise appears to move with his hand, as an after image does. When *S* moves his head rapidly forward an after image appears to contract: and so does the noise on the TV screen. This apparent contraction of an after image was reported by GREGORY, WALLACE and CAMPBELL (1959) and is distantly related to Emmert's law. It is an effect of perceptual size constancy. So is the apparent contraction of a distant landscape seen through a nearby window when the head is moved rapidly forward. In all three cases, the retinal image of the distant landscape (at optical infinity), the after image, and the TV noise is effectively unaltered by the head movement. But the head movement acts as a distance cue, and the three "objects" are interpreted as nearer, but retinally unchanged. Therefore, by Emmert's law, they are perceived as physically shrinking.

When the TV noise was moved "passively" across *S*'s retina, by moving the TV screen, or a large mirror reflecting the TV screen, behind a small stationary hole in a fixed screen, the *S* perceived no movement. Because of the reduction screen, there was no visible retinal movement of any object such as the hand, so the retinal channel gave no movement information. The retinal displacement of the noise itself was not perceived. Nor was any movement information given by the eyes, which were stationary.

The situation was like viewing an after image with the eyes stationary; no movement at all was seen. But if the whole TV receiver was seen reflected in a moving mirror, then the noise did seem to move with the TV screen; the moving edges of the TV screen acted like the moving hand or loop of wire in Mackay's original demonstration. Mackay's effect certainly occurs when the eyes actively track the hand, or the edges of the screen, as described. It is difficult to decide whether it still occurred when the eyes fixated a stationary point, so that the image of the noise was moved passively across the retina: the observation was a difficult one to make. If it does occur under such passive conditions, then the noise is not simply analogous to a stabilised retinal image, for there must be other factors at work.

At events, it appears that Mackay's effects and our effects occur because the brain treats dynamic noise moving across the retina as if it were stationary, and a brightness-reversing picture moving across the retina as if it were moving in the opposite direction. In each case, the finally perceived direction of movement depends upon the integration by the CNS of retinal information with eye-movement information.

Colour. Colour slides were prepared by photographing a perforated paper doily, with the doily and the uniform background behind it, independently illuminated with red, blue and green. Pairs of these slides were projected in alternation, overlapping but displaced. We found that the perceived direction of phi movement, whether forward or reversed, depended on the *brightness* of the stimuli, not on their *colour*. For example, if a light red pattern on a dark blue ground, was followed by a dark red pattern on a light blue ground, the patterns being identical in shape, then reversed phi was seen, because the two pictures were of reversed brightness polarity (light-on-dark vs. dark-on-light). The fact that they were of the same colour polarity (red-on-blue) made no difference.

Conversely, if a light red pattern on a dark blue ground was followed by a light blue pattern on a dark red ground, then forward phi was seen, because the two pictures were of the same brightness polarity (light-on-dark). The fact that they were of reversed colour polarity (red-on-blue. vs. blue-on-red) made no difference.

It was found that the direction of phi movement depended on brightness not colour for all permutations of red, green and blue on pattern and background, both for complementary and for non-complementary colours. A remote possibility does exist that if the brightness of the colours were carefully matched for the human eye, then the direction of phi movement might depend on colours alone, in the absence of any brightness differences. We could not adjust our brightnesses accurately enough to test for such an effect. But if it were to exist, it would have been a small effect, which would normally be masked by the much bigger effect of brightness.

Grain size. Fine-grained patterns gave the best reversed phi. A grain size of about half a degree across, or less, gave the best results. Clusters of grains gave much more vivid reversed phi than a single grain. Large or isolated patterns often failed to give reversed phi at all in foveal vision, though they would do so in peripheral vision. For instance, the patterns in Fig. 4 gave indeterminate results in foveal vision, but good reversed phi when viewed peripherally.

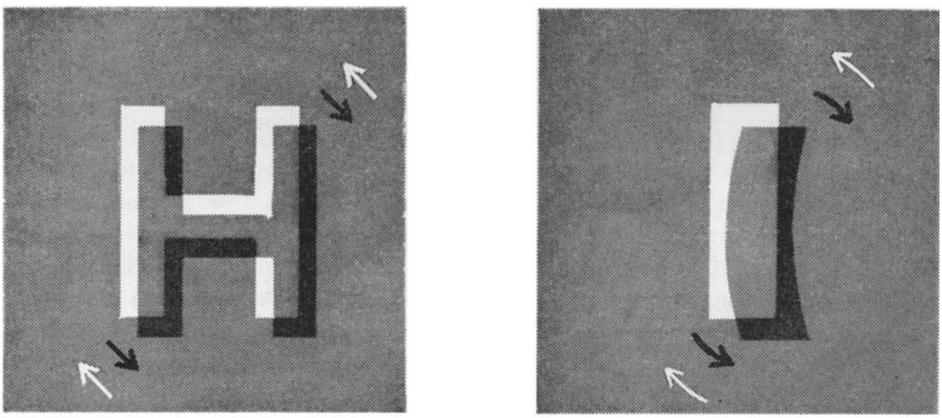


Fig. 4. Letters H and I, displaced and superimposed on their own negatives. When the white letter was followed by the black letter the physical displacement was down to the right (black arrows), but the perceived phi was in the reverse direction, up to the left (white arrows). In addition I underwent a curvature concave to the right, but was perceived as curving to the left. These reverse phi effects could be obtained only in peripheral, not foveal vision. Finer grained patterns (e.g. Fig. 1) gave reversed phi in both peripheral and foveal vision.

For this reason, we mostly used granular or random-dot textures in our experiments.

Within these limits, however, it was found that for a given physical displacement between successive pictures, large grains gave a greater apparent amplitude (displacement) of reversed phi than did smaller grains. Reasons for this also are given in the Discussion.

Physical displacement and speed. Reversed phi had the greatest amplitude for small displacements between successive positive/negative pictures. When a rigid textured disc rotated, reversed phi was greatest near the centre, where the physical displacement was least, so that a swirling rotation like a vortex was seen. In general, as the physical displacement increased from zero, the amplitude of reversed phi *decreased* from about one grain diameter towards zero. That is, each grain in a picture must overlap with its corresponding negative grain in the next picture, otherwise no reversed phi was seen. It follows from what has been said that there is an interaction between grain size and displacement in determining the amplitude of reversed phi.

Similarly, there was an inverse relationship between speed of physical movement of a brightness-reversing TV picture, and speed of reversed phi. As the speed increased from zero, the speed of reversed phi *decreased*, and the reversed phi disappeared entirely when the picture moved through more than one grain's diameter between successive frames. For slow speeds, e.g. rotation at 16 rev/min, this could easily be observed. At faster speeds, an artefact appeared; the poor time resolution of the TV system turned each grain into a streak, which greatly increased the effective grain size. Speed of reversed phi increases with grain size, and caused an anomalous effect; the speed of reversed phi artefactually increased with physical speed.

But in the absence of such artefacts, it was found that the amplitude of reversed phi *decreased* as the displacement between successive frames, *increased* reaching zero when the displacement exceed the diameter of the pattern's grain. Amplitude of reversed phi *increased* as the grain size *increased*. These findings are explained by our model, which is described below.

Discussion

We believe that forward and reversed phi both result from the same visual processes. The visual system perceives phi movement between individual points of corresponding brightness in successive frames, and phi movement is determined on a local, point-for-point basis, mediated by brightness; not on a global basis, mediated by form.

Thus, normal forward phi movement is perceived between corresponding points when a textured pattern is presented in successive displaced frames. Reversed phi is perceived between successive positive and negative frames, because the visual system searches for points of corresponding brightness. Since each successive frame is the photographic negative of its predecessor, the one direction in which points of corresponding brightness will *not* be found, is in the direction of the physical displacement: so the average direction in which phi will be perceived, is the opposite (reverse) direction. This process can now be analysed in detail.

To understand reversed phi, we must bear in mind two well known phenomena which occur with certain *repetitive* patterns. These are:

(1) The fact that brightness-reversal can be identical with displacement.

(2) The "wagon wheel" stroboscopic effect.

Brightness-reversal. Reversing the brightness of a repetitive pattern such as a chess board has exactly the same result as displacing the board through one square's width. Either procedure has the effect of replacing each black square by a white square, and *vice versa.*

"*Wagon wheel effect*". A rotating wheel seen intermittently, on a movie film or under stroboscopic light, can appear stationary, or apparently moving slowly backwards or forwards. Its apparent speed results from the beat frequency between its physical velocity, its spatial period, and the stroboscopic flash rate (or film rate).

This principle is used in the segmented stroboscopic discs used to regulate the speed of gramophone turntables. The rotating segments appear stationary under 50 Hz mains flicker from a fluorescent light (or failing that, an incandescent light). It can be shown that

$$\text{rev/sec} = \frac{\text{flashes/sec}}{\text{number of black segments}}.$$

The effect is not peculiar to rotary motion, but can occur for translatory motion of a repetitive pattern such as a strip of wallpaper or a chessboard.

Suppose that a chessboard pattern, with spatial period (two square's width) equal to $2c$, passes a stationary point at a frequency f_s. This frequency is defined as the number of black squares that pass a stationary point per second. The physical velocity of the pattern is given by:

$$v = 2c. f_s.$$

If the moving pattern is illuminated with a stroboscope with a flash frequency of f_l, then the apparent velocity of the resulting phi motion is given by

$$v_a = 2c\,(f_s - f_l).$$

$(f_s - f_l)$ Is the beat frequency, at which the pattern's spatial periods appear to pass a stationary point. When the pattern's motion is exactly in step with the strobe frequency, $f_s = f_l$, the beat frequency is zero, and pattern appears to be stationary. If the pattern moves a little faster, then $f_s > f_l$, and the pattern appears to move slowly forward. If the pattern moves more slowly, then $f_s < f_l$, and the pattern appears to move backwards. So much is well known.

Now, if these two effects are combined, they can produce reversed phi motion—not only for regular, repetitive patterns, but for random, non repetitive patterns as well.

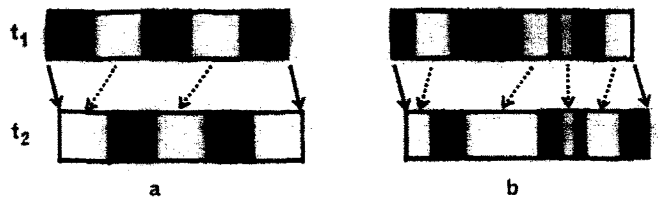


FIG. 5. Black and white patterns, presented at time t_1 and followed at time t_2 by their photographic negatives, superimposed but displaced to the right (black arrows). For clarity positive and negative are shown here one above the other. Result: phi was perceived in the reverse direction, i.e. to the left (dotted arrows).
(a) Regular chessboard pattern. Reversed phi and equal amplitudes for all black and white areas (dotted arrows parallel). Reversed phi represented the best correlation for both brightness and form.
(b) Irregular patterns. Reversed phi had unequal amplitudes for different black and white areas (dotted arrows not parallel). Reversed phi represented best correlation for brightness, but not for form.
Conclusion. Phi depends on brightness not form.

Figure 5a shows a strip from a regular chessboard pattern, and below it the same pattern reversed in brightness and slightly displaced to the right. Figure 5b shows the same thing for a strip from an irregular, non-repetitive pattern. It will be seen that the two cases are very alike. If the upper and lower strip are presented in sequence, then reversed phi is seen in each case. For the regular chessboard, (Fig. 4a) movement is seen from each upper square to the nearest lower square of the same brightness, which in this case is displaced towards the left. For the random pattern, movement is also seen from each upper "cell" to the nearest lower cell of the same brightness, which is also displaced to the left.

From Fig. 5 it can be seen that, if d = physical sideways displacement between the upper (positive) and lower (negative) pattern,

$\bar{c}$ = average cell width,

c_n = width of the nth cell or square of the pattern,

and r = amplitude of perceived, reversed phi displacement,

then

$$r = c_n - d.$$

Therefore the amplitude of reversed phi will increase as the cell size, c_n increases, or the physical displacement d decreases. This is what we found experimentally for reversed phi. Also, when the displacement was greater than the cell ($d\ c_n$), reversed phi broke down, and random motion only was seen.

For the regular chessboard, $c_n = \bar{c}$, because all the squares were the same size, and so the amplitude of movement r was the same over the whole field, giving rigid movement of the whole pattern. for the random pattern, all the cells were of different widths (c_n), and so each cell moved through a different distance (r_n), giving an impression of non-rigid motion like streaming sand with each cell or particle moving in the same direction, but each with its own separate amplitude. Geometrically, since r_n varies in step with c_n, the largest particles moves fastest, but perceptually this was not apparent to the observer.

The situation for the regular and the random patterns of Fig. 5 is so similar that it is tempting to treat them as identical. Superficially, it looks as though reversed phi can be explained in both cases by means of physical rather than psychological principles. In the "wagon wheel" effect of Fig. 5a, the first pattern is succeeded by a second pattern displaced to the right, but any given black square in the first pattern is succeeded by a black square in the second pattern displaced to the left. Since one black square is exactly like another, in both form and brightness, it is scarcely surprising that the visual system perceives this reversed movement to the left, which represents the best correlation available. Form and brightness conspire to give the observed perceptual outcome. The situation is a little different for the random pattern of Fig. 4b. Here the cues of form and brightness are in conflict. The visual system is faced with a choice between seeing phi movement forwards (to the right), towards an appropriate form of inappropriate brightness, or else backwards (to the left), towards and inappropriate form of appropriate brightness. In fact, we have found that the visual system sees phi movement backwards. This shows that the *perception of phi movement is mediated predominantly by brightness not by form.* The movement system searches for areas of correlated brightness, and is not too critical about the shape or form of these areas.

In other words, in the "wagon wheel" stroboscopic phenomenon, both form and brightness operate together to generate phi movement, in a direction that happens to be the opposite of the original physical motion in front of the movie camera or stroboscope. It occurs only with repetitive patterns such as chessboards, or radially symmetrical wheels, and only in circumstances where the information about the original direction of movement is thrown away, and is therefore irrelevant. Almost any seeing machine would have to see the reversed moment of the "wagon wheel" effect, for there is no information available to make it see anything else. With a random pattern, however, the information of the original forward motion is still present in the shapes of the brightness-reversed cells of the pattern, and is available for any seeing machine designed to take advantage of it. It appears that the visual system is not so designed. Faced with the choice provided by the conflict of form and brightness, which contain the information necessary for seeing forward and reversed phi respectively, the visual system plumps for the brightness information. What we have explored are the conditions under which brightness wins over form, and what we have found is that brightness usually does win.

It is now clear why granular patterns give better reversed phi than large isolated objects. In granular patterns, each point is statistically likely to be near another point of similar brightness in the succeeding negative frame, and reversed phi between this pair of points will result. A large isolated object (e.g. Fig. 4) is unlikely to be near a large object of similar brightness in the succeeding negative frame, so it will assimilate to the nearest patch of background of similar background. This gives poor and unconvincing reversed phi. However, it passes muster in the periphery, where acuity and discrimination are poor.

So good reversed phi requires good point-for-point correlations of brightness between succeeding frames.

EXPERIMENT 2—RANDOM-DOT COMPUTER-GENERATED PATTERNS

JULESZ (1960, 1961, 1965) has devised stereograms, in neither field of which is the form visible. He presented two nearly identical random matrices of dots stereoscopically, one to each eye. In one eye's view a square central region of dots was cut out of the matrix and displaced slightly sideways. Since this produces a binocular disparity for these dots, the central square appeared to float in front of the remaining dots. He then systematically degraded one eye's view by adding progressive amounts of random noise and grid-like perturbations, which reduced the possibility of monocular micro-pattern recognition, to see at what point depth perception broke down. He concluded that forms can be presented postretinally, and that binocular fusion can occur without monocular pattern perception: and that binocular fusion is achieved by point-for-point comparison of one eye's view with the other.

In a further experiment, JULESZ and PAYNE (1968) exposed in alternation two such random-dot stereograms. Each stereogram displayed a grid of vertical lines, instead of a central square. One stereogram was slightly translated or rotated with respect to the other, and all monocular cues of form and of movement were eliminated by arranging that one stereogram was uncorrelated in texture with the other. They found that a binocularly perceivable grid was perceived in translational or rotational movement, with optimal phi occurring at a presentation rate of about 4 Hz, and subjective simultaneity of the two grids at about 10 Hz. At an intermediate rate, about 5–6 Hz, a new perceptual response could be experienced, namely a single stationary ("binocular standstill") grid.

In the experiment reported here, we exposed in alternation to one eye the left and right halves of a single Julesz stereogram. This removed monocular form cues but retained monocular micro-texture cues.

Results

Phi movement of the central square was seen clearly. When the patterns were degraded by noise, the phi movement was not always visible immediately, but built up over a period of seconds or even minutes. In addition, some kind of perceptual learning took place. Practice at observing made the phi more readily visible, and experienced observers could see the phi some time before naive observers. This parallels the build-up reported by Julesz in perceiving stereo in the random-dot patterns.

If the two images alternated for a time, giving phi movement, and then one image was kept steadily visible, the central square persisted for about a second before fading away.

This parallels the brief persistence of a square, seen steadily in stereo; when the image to one eye is switched off, the square persists for about a second. Presumably there must be some kind of central short term storage, both in stereo vision and in phi movement perception.

Mixing between the two images (fading one down as the other faded up) gave much more impressive phi than cutting between them. Dichoptic phi, with alternate eyes viewing alternate pictures was far less impressive than monocular phi, and was often difficult or impossible to achieve. This is consistent with the findings of AMMONS and WELTZ (1951), who used simple spots as visual stimuli. Phi movement and stereoscopy could interact. If one eye saw the left image of a stereo pair, and the other eye saw the left and right images alternating, then the central square appeared to jump to and fro in depth.

The central square and the surround could be seen moving independently in different directions, by adjusting the registration of the two images. If the two backgrounds were placed in register, then the central square appeared to oscillate on a stationary background, and *vice versa*. Or, the central square could be set to move to the left as the background moved to the right, and *vice versa*. If one image was made 10 per cent larger than the other, the phi movement took the form of alternate expansion and contraction towards and away from a central node. Owing to the disparity of the central square, two nodes of expansion could be set up, one on the central square and one on the background. In these conditions the central square itself was not seen during phi movement.

When two identical granular images were projected on the screen simultaneously, overlapping but not quite in register, a characteristic pattern of stationary fringes could be seen, provided that the displacement between the two images was small. The fringes lay along the lines of displacement between the two images, forming straight horizontal or vertical lines when one image was displaced respectively sideways or upwards, and circles when one image was slightly tilted with respect to the other (Fig. 6). However, if the displacement was made too large, they disappeared.

If the two images were exposed alternately, then normal (forward) phi movement was seen along the direction of the fringes, i.e. along the direction of displacement.

The fringes are produced by the proximity of corresponding points in the two identical images. If the displacement between the two images was increased to more than the diameter of a grain in the pattern, then statistically the nearest same-brightness neighbour of a grain in one image was not its corresponding grain on the other image, but was instead some uncorrelated grain. The fringes disappeared, and it was also found that if the two images were exposed alternately at this displacement, then phi movement broke down.

This is interesting for two reasons. Firstly to see the fringes is to see a shape or form. The fringes exist because of a correlation between the two images. But they could only be seen when each grain on one image abutted its corresponding grain on the other. When the displacement was increased, the fringe disappeared. The correlation between the two images still existed but it could no longer be extracted if the increased displacement made uncorrelated grains intervene, between the corresponding grains to the two images. This tells us something about the limits of the visual system in extracting information for form perception.

Secondly, the fringes and phi movement co-vary. The displacement which was just large enough to make the fringes disappear, leaving only a perceptually random field, was also just large enough to make phi movement along the displacement line disappear, leaving only phi movement in random directions all over the field. The necessary condition for both fringe perception and for phi movement perception was that each grain in one image should have, as its nearest same-brightness neighbour in the other image, its corresponding identical grain. Neither for form nor for movement can the visual system correlate two identical grains which are spatially separated by a same-brightness grain between them. The correlation is made on the basis of brightness and proximity of grains. The similar behaviour of fringes and of phi movement indicates that form perception and movement perception operate in similar ways.

When an image was superimposed on its own tilted negative, the fringes were not circular, but formed a chrysanthemum-like pattern of opposed logarithmic spirals (Fig. 6). Alternate exposure of the two images gave reversed phi. Again, fringes and reversed phi co-varied; when the displacement was increased just enough to cause the fringes to disappear, it was found that reversed phi also disappeared, leaving only phi movement in random directions all over the field.

A stereogram containing a square area of repetitive vertical stripes of random noise can give ambiguous depth. The square appears either to float in front of its background plane or to lie behind it (JULESZ, 1962). There is an example of the "wallpaper effect". When the two images of the stereogram were presented alternately to one eye, phi movement was produced, but its direction was ambiguous. A given stripe in one image could appear to jump to either its left-hand neighbour or its right-hand neighbour in the succeeding image. Either of the two directions of phi could be selected by tracking it with the eyes.

JULESZ (1961) used a series of stereograms, introducing progressive amounts of visual noise and grid-like perturbations, which reduced the possibility of monocular micro-pattern recognition. We found that *all those of Julesz's figures which gave stereo, when viewed binocularly, gave phi movement, when viewed in monocular alternation. Those which did not give stereo, did not give phi movement.*

When one field of a stereogram was presented in alternation with the photographic negative of the other field, reversed phi was seen for those stereograms which gave stereo, and no phi was seen for those stereograms which did not give stereo.

The figures in Julesz' paper which gave neither phi nor stereo were:

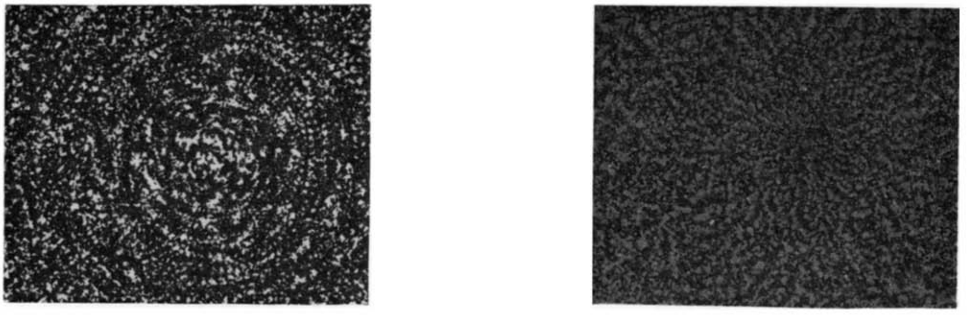
Fig. 7: two planes of depth

Fig. 15: mixed regular perturbation grid

Fig. 22: meshlike perturbation grid.

We conclude from this that *the properties, discovered by Julesz, which characterise the binocular fusion system, also characterise the movement detection system.* Depth perception and movement perception are very different tasks, which are carried out by different parts of the visual system, but it appears nonetheless that they are accomplished by very similar methods. The brain, with its usual economy of means, uses a good trick wherever it can be applied.

Both depth perception and movement perception can occur without the prior recognition of form in the monocular (or stationary) field. Forms can be perceived as a result of depth or movement perception, either as a form floating in depth above a background, or as a form moving across a background. Julesz constructed his fields in such a way that the form does not exist in either of the two fields on its own. It exists only as a correlation between the two fields. Julesz conjectured that the visual system took a point-by-point difference between left and right fields, but that prior to subtraction, the two fields were shifted horizontally by increasing amounts. The act of localisation consisted of finding points of minimum difference value (same brightness in the two fields) which formed dense areas. The process can be simulated by shifting a negative transparency of one field over a positive of the other,



a b

FIG. 6(a). Granular pattern of Fig. 1b superimposed and slightly rotated on its own duplicate. Circular moire fringes are seen, where each dot's nearest neighbour is its own duplicate. (b) The same pattern, superimposed and slightly rotated on its own negative. The moire fringes now take the form of a chrysanthemum-like pattern of opposed logarithmic spirals. Wherever circular fringes were obtained by superimposing two identical pictures, normal phi was obtained by presenting them alternately, and wherever spiral fringes were obtained by superimposing a picture on its negative, reversed phi was seen by presenting them alternately. Any displacement which was too great to give fringes, was too great to give phi.

until some parts lie in register. These parts then appear as dense grey areas, and the amount of shift is an index of their binocular disparity. Binocular perception is a much simpler process than previously believed, since it is based on a simple point-by-point comparison of the two fields, not on any Gestalt factors.

Julesz' difference field model can be applied almost as it stands to movement perception. Whereas depth is perceived by comparing the left and right fields, movement is perceived by comparing the fields seen by one eye at successive instants in time. The field seen at time t_n is subtracted from that seen at time t_{n-1}, but prior to subtraction the two fields are shifted, until dense difference fields are found. The shift is equal to the physical displacement between successive fields. So movement perception, like depth perception, is based on a point-for-point comparison of the brightness of the visual field.

JULESZ (1963) has written a computer program called Automap which automates depth perception. The program scans stereoscopic aerial photographs and constructs relief maps from them. Possibly a modified version of this program could be written ("Automobile"?) to automate movement perception. This might have applications in scanning dynamic radar displays and extracting information about moving targets from a background of clutter.

EXPERIMENT 3

Spatial vs. temporal connectivity. Form is perceived by virtue of spatial connectivity between points in a stationary field. Movement is perceived as we have shown, by virtue of

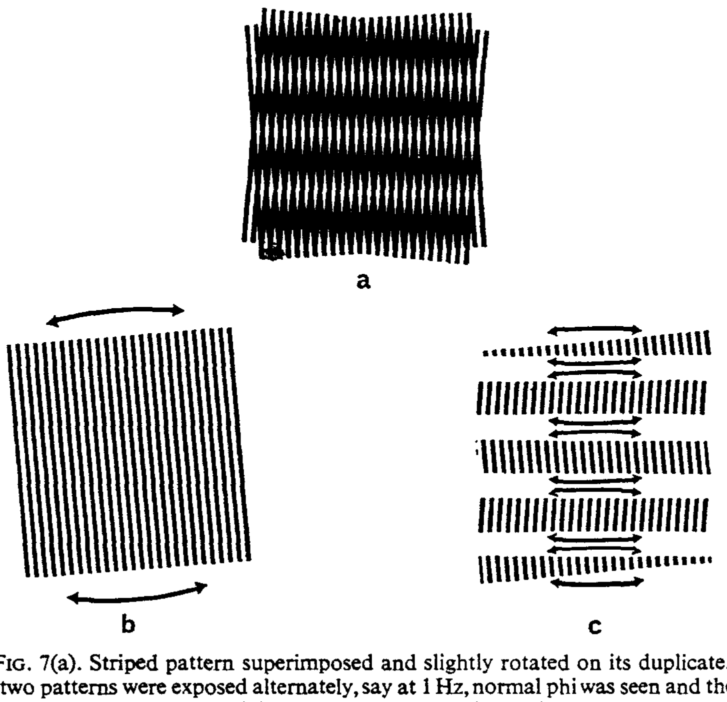


FIG. 7(a). Striped pattern superimposed and slightly rotated on its duplicate.
(b) If the two patterns were exposed alternately, say at 1 Hz, normal phi was seen and the pattern appeared to rotate rigidly as a whole, as indicated by the arrows.
(c) If the patterns were made more difficult to see, alternating at say 2 Hz and lit dimly, then the pattern seemed to break up along the black moire fringes into independent areas, each area showing independent local phi movement.

temporal correlation between points in successive fields. We have also found that form perception could be pitted against movement perception, by putting spatial connectivity *within* a stationary field into opposition with temporal correlation *between* successive fields. As one or the other dominated, so the percept changed.

Two identical fields of black and white stripes were exposed alternately on a screen. One field was vertical and the other tilted about 5° to the right. If they were exposed simultaneously, they would interact to give three or four moire fringes (Fig. 7) but in fact they were always exposed alternately, never simultaneously.

Results

When the fields were exposed alternately at rates slower than 1 Hz, the whole field was perceived as oscillating to and fro, like a single rigid unit pivoted about its centre. The form, or spatial connectivity, of each field was preserved. When the fields were made more difficult to see, by increasing the exposure rate to 2 Hz or faster, and by reducing the intensity, then the spatial connectivity within each field broke down, and the field appeared to split up along the black moire fringes into horizontal segments. Within each segment, each short length of stripe was perceived as pivoting independently towards the nearest corresponding length of stripe in the other field. Local, point-for-point brightness correlation between the two alternating fields dominated over the spatial connectivity of each field on its own, and the field appeared to break up into separately moving areas.

CONCLUSIONS

Movement perception and depth perception compared. Movement perception depends, like depth perception, on the correlation of points of similar brightness, and can be independent of form perception. Movement is mediated by brightness information, and can be perceived in the absence of global form information (Experiment 2, using Julesz patterns) and even when the global form information is in conflict with the brightness information. (Experiment 1, reversed phi). But there are big differences between depth perception and movement perception. Firstly, depth perception depends upon dense areas of similar disparity and movement does not: secondly, depth is produced only by small horizontal disparities, while movement can be produced by large disparities in any direction: and thirdly, making one pattern the photographic negative of its partner gives reversed movement, but completely eliminates stereo.

These three differences show that the conditions for seeing depth are much more critical than for seeing movement, and they give clues for sketching out a tentative model of the two visual processes. Firstly, dense areas of similar disparity are not necessary for seeing phi. Two uncorrelated fields of random noise readily give phi movement, twinkling in all directions, when presented successively (the dynamic noise on a detuned TV set is a good example). But they do not give depth when exposed in a stereoscope. Statistically, many disparate pairs must exist, and if fused would give a 3D array of points, deployed randomly in depth and filling a volume of visual space. But no binocular fusion occurs. It seems that disparate pairs of points are not accepted by the fusion mechanism: points must belong to extended areas which share a common binocular disparity. Julesz' model of depth perception shifts and subtracts the fields of each eye to give a difference field, until it finds dense areas in the difference field. Although it does not require patterns within each eye's field, it does require patterns (dense areas) within the difference field. Movement perception, on the other hand, does not. Our data suggest that we can construct a movement-perception analogue of Julesz' stereo model (Fig. 8). The movement model shifts and subtracts fields, like the stereo model, but does not need to look for dense areas.

Secondly, the binocular fusion system will only accept small horizontal shifts (disparities). Until recently it was thought that Panum's fusional areas defined the maximum acceptable shift as being about 5–10 min arc wide in the fovea, and about 30–40 min arc in the periphery. Recently Julesz has shown that these fusional limits can be exceeded if random-dot pairs are fused and then the disparity between them is gradually increased. However, it is still true that disparities must be horizontal and not too large.

The movement system, on the other hand, will accept shifts in any direction, and the shifts can be very large if the objects looked at are large, or are well spaced and have no distracting other objects visible anywhere between them. For example, a pair of small spots flashing alternately in an empty field can give phi movement across tens of degrees. However, if there are intervening spots in the field, phi movement will be perceived between the *nearest* pairs of successive spots, provided these are of sufficiently similar brightness, and will not jump over the intervening spots.

Thirdly, a positive–negative pair can give reversed phi, but can almost never give stereo. Julesz stereograms and ordinary stereophotographs give no depth at all (neither normal nor reversed) when one eye's view is made negative. There is one exception, which was described by Helmholtz: a stereogram outline of a polyhedron can be fused to give normal depth, even though one eye's view is negative. Whittle (personal communication) has suggested that the lines in the drawing are so fine that the "wrong" edges of the lines in one eye are fused with those in the other eye. I tried to thicken the line in such a stereogram, so that the line thickness exceeded the amount of binocular disparity. If Whittle is right, as seems likely, then fusion of the "wrong" edges of the thickened lines would result in a perception of reversed depth, and this would be the stereo analogue of reversed phi. But the stereogram proved impossible to fuse.

Probably, a positive–negative pair gives reversed phi but not reversed stereo because the conditions necessary for seeing stereo are much more critical than for seeing phi. Consider a positive picture containing many random blobs. Its negative is superimposed and shifted slightly to the right. Each positive blob can be paired with a blob of similar brightness in the negative, which is shifted to the left. The blobs will be different shapes, because they correspond to different objects in the original picture. If the two pictures are presented successively, reversed phi will be seen between the blobs. Movement can be seen despite the shape differences. If the two pictures are presented in a stereoscope, no stereo will be seen. The shape difference debars binocular fusion. Also, the separation between each pair of blobs is usually different, so no dense areas of similar disparity (i.e. separation) exist. Movement can still be seen despite this, and looks like irregularly streaming sand, but no stereo is seen. Julesz has explained how depth perception is dependent upon finding dense areas of similar disparity in a difference field.

All these features of depth and movement perception can be summarised in the tentative model sketched in Fig. 8. The model for depth perception is after Julesz. The fields of the two eyes are subtracted one from the other to give a difference field.

Prior to subtraction, one field is progressively shifted over the other, until dense areas emerge in the difference field which represent planes lying in depth. The amount of depth corresponds to the amount of shift. The model for phi perception is broadly similar. The field at time t_1 is subtracted from the same field seen at time t_2 to give a difference field. Prior to

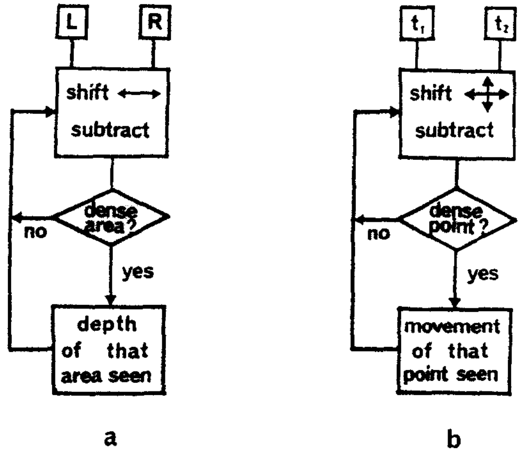


FIG. 8(a). Model of depth perception (after Julesz). The model compares left and right fields point-by-point and subtracts the brightness of each point from its counterpoint. Where an area of the two fields match, the difference is zero, and that area is seen at a depth plane determined by the shift. The model repeats the point-by-point comparison after shifting one field horizontally (both left and right) by one until, two units, and so on. Form recognition is not needed. (b) Model of movement perception. The model compares the field seen by the same receptors at different instants in time, and subtracts the brightness of each point from its counterpoint. Where points of the two fields match, the difference is zero and the amplitude of movement of each point is given by the amount of shift. The model repeats the point-by-point comparison after shifting one field in all directions (up, down, left, right and c) by varying amounts. Each point makes the shortest possible movement to the nearest same-brightness point in the succeeding field. Form recognition is not needed. Both models are coincidence detectors, but the depth model has a higher threshold than the movement model.

subtraction, one field is progressively shifted over the other until dense points emerge; these are points which have the same brightness at times t_1 and t_2. There is no need for dense areas to be found: movement is assigned point by point, and the amount of seen movement corresponds to the amount of shift. Thus each point in the field at time t_1 is perceived as moving towards the nearest point that happens to have the same brightness at time t_2. The model will perceive phi movement between identical fields, and reversed phi between a positive and a negative field, as a human does. When looking at two uncorrelated fields of noise, the model will perceive random phi movements in all directions between adjacent points of corresponding brightness, as a human does.

The main difference between the two models is that the depth model requires dense areas in the difference fields, corresponding to extended areas lying in a given depth plane, while the movement model does not require such dense areas, which would correspond to extended areas moving rigidly. The two models mimic the human perception of depth and movement fairly well. Of course, the same input can be processed independently by both mechanisms. The left eye's view at time t_1 can be compared in time with the view at t_2 by the movement mechanism, and in space with the right eye's view by the depth mechanism.

It may be speculated that the movement and depth systems have evolved to match the range of stimuli which they are likely to encounter. Many objects—a wheeling flock of birds, or a leafy tree blowing in the wind—show small random "noisy" motions superimposed on an overall direction of movement, so it makes sense for the movement system to accept such randomised streaming motions, as in the reversed phi situation. On the other hand, the difference in the left and right eye's view of a single object are simple and geometrical, undisturbed by randomness, so it makes sense for the stereo system to reject such random differences and to refuse to see depth in a positive-negative stereo pair.

The maximum disparity in the views of the two eyes is limited by the small separation of the eyes in the head. A capacity for seeing depth at greater disparities would scarcely be used. But the maximum visual movement which organisms can encounter is limited only by the speed at which other physical bodies can move. And for a hungry animal, or an edible one, the speed at which prey or predators move can be alarmingly high. Only those animals with efficient perception of movement can expect to survive.

Movement perception evolved long before stereoscopic vision. Movement has sometimes been regarded as the most ancient and primitive aspect of vision, and it is found in many simple animals, such as insects, which lack stereo vision. Yet the mechanisms for seeing movement and stereo are curiously similar, as we have shown. It is tempting to speculate that the differencing methods, which evolved in primitive animals for the perception of movement, may have been taken over wholesale and modified to allow stereoscopic vision, higher up the phylogenetic scale and later in time. This take-over of visual technique, if it did occur, would have allowed stereo vision to evolve rather rapidly and economically.

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Abstract—How similar must two successively presented patterns be for phi movement to be perceived between them?

Phi movement between two granular patterns, one being the photographic negative of the other, appeared to be *reversed*, towards the direction of the earlier stimulus. Moving objects, displayed on a TV picture which was made positive and negative on alternate frames, appeared to move backwards. (The backward movement could generate its own after effect of movement.) Conclusion: phi movement was perceived between nearby points of similar brightness, irrespective of form or colour.

Phi movement was studied between two positive random-dot Julesz patterns. Pairs that gave stereo when presented dichoptically also gave phi movement when presented alternatively to one eye. When one pattern was degraded with noise, both stereo and phi broke down at the same noise level. Conclusion: phi, like stereo, depended upon point-by-point comparison of brightness between two patterns. It could precede the perception of form.

Résumé—Quelle ressemblance doit-il exister entre deux figures présentées successivement pour que l'on perçoive un mouvement phi entre elles?

Entre deux figures granulaires dont l'une est le négatif photographique de l'autre, le mouvement phi apparaît *inversé*, dans la direction du premier stimulus. Des objets mobiles, vus en TV de façon que les images soient alternativement positives et négatives, semblent se déplacer à l'envers. (Ce mouvement à l'envers peut engendrer son propre effet consécutif de mouvement.) On conclut que le mouvement phi est perçu entre des points voisins de luminosité semblable, indépendamment de la forme et de la couleur.

On étudie le mouvement phi entre deux figures de Julesz composées de points positifs au hasard. Les paires qui donnent l'effet stéréo quand on les présente chacune à un oeil, donnent aussi le mouvement phi quand on les présente alternativement au même oeil. Quand on dégrade une figure par du bruit, la stéréo et le mouvement phi disparaissent au même niveau de bruit. On en déduit que le mouvement phi, comme la stéréo, dépend d'une comparaison point par point de luminosité entre deux figures; elle peut précéder la perception de la forme.

Zusammenfassung—Wie weit müssen zwei emander folgend Muster emander ähneln, um die θ-Bewegung hervorzurufen? Die θ-Bewegung zwischen zwei körnigen Mustern, deren eines das photographische Negativ des andern war, schien umgekehrt zu sein, d.h. sich in der Richtung des früheren Reizes zu bewegen. Bewegungsgegenstände, welche auf einem Fernsehschirm abwechselnd positiv und negativ dargestellt waren, schienen sich zurückzubewegen. (Die Rückbewegung konnte ihren eigenen Nacheffekt erzeugen.) Folgerung: die θ-Bewegung war zwischen benachbarten Punkten ähnlicher Helligkeit ohne Rücksicht auf Form oder Farbe zu sehen. Die θ-Bewegung wurde zwischen zwei positiven Juleszschen Zufallspunktmustern untersucht. Die Paare, welche beidäugig das Tiefensehen erlaubten, erzeugten auch die θ-Bewegung, wenn wechselnd jedem der beiden Augen dargeboten. Geräuschstörung eines der Muster führte zum Zusammenbruch des Tiefensehens und der θ-Bewegung bei demselben Geräuschgrad. Folgerung: θ sowie das Tiefensehen benötigen die Helligkeitsvergleichung der beiden Muster Punkt für Punkt. Sie könnte der Formwahrnehmung vorangehen.

Резюме — В какой мере должны быть сходны два паттерна предявляемые последовательно, чтобы между ними возникло фи-движение (*phi-phenomenon*)?

Фи-движение между двумя гранулированными паттернами, из которых один является фотографическим негативом второго, воспринимается как *обратное*, направленное к более раннему стимулу. Движущиеся объекты на телевизионном экране, которые были сделаны позитивными и негативными в попеременно сменяющихся кадрах, казались движущимися в обратном направлении. Собственное последействие движения может так же генерировать обратное движение (фи-движение).

Заключение: фи-движение воспринимается между близко-расположенными точками сходными по светлоте, независимо от формы и цвета их.

Фи-движение изучалось между двумя случайными позитивными точками фигур Юлеша (Julesz). Пара их, дающая стереоскопический эффект, когда они предъявлялись двум глазам, вызывала так же и фи-движение, если эти точки предъявлялись попеременно одному глазу. Если изображение исчезает из за помех, то оба и стерео и фи-эффекты нарушаются при том же самом уровне «шума».

Заключение: фи-феномен, как и стерео-эффект зависят от поточечного сравнения светлот двух паттернов. Это может предшествовать восприятию формы.