Low-Level and High-Level Processes in Apparent Motion [and Discussion]

O. J. Braddick, K. H. Ruddock, M. J. Morgan and D. Marr

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Low-level and high-level processes in apparent motion

By O. J. Braddick
Department of Experimental Psychology, University of Cambridge,
Downing Street, Cambridge CB2 3EB, U.K.

When a group of dots within a random-dot array is discontinuously displaced, it appears as a moving region perceptually segregated from its stationary surround. The spatial, temporal and other constraints governing this effect are markedly different from those classically found for the apparent motion of isolated stimulus elements. The random-dot display appears to tap a low-level motion-detecting process, distinct from the more interpretive process elicited by the classical displays.

The distinct contributions of these processes can be identified in 'multi-stable' displays which yield alternative percepts of apparent motion depending on which one or both of the processes is activated. Such experiments illustrate the interaction of relatively stimulus-constrained and relatively autonomous processes in visual perception.

Two contrasting approaches dominate much recent work on visual perception. One is to explore how properties of the stimulus may be decoded in the patterns of activity of neural channels or detectors, each of which has its own selective tuning (Braddick *et al.* 1978). The other approach (exemplified by Gregory 1970) considers perception as a problem-solving process that must interpret the sensory input as evidence for some external object or event, and has tended to cast its explanations in functional terms rather than as hypothetical neural mechanisms.

Generally these two approaches have been adopted to attack rather different problems. However, the perception of smooth continuous motion from discontinuous stimulation (variously called beta apparent motion, stroboscopic motion, or the phi phenomenon) has attracted accounts of both kinds. It may therefore provide an opportunity to consider how selective-detector models and interpretive theories of visual perception conflict or interconnect.

Neural units that respond selectively to a particular direction of motion have been widely studied. Such units can be effectively stimulated by a succession of stationary flashed spots or lines, similar to the stimuli yielding apparent motion for a human observer. In fact, such discontinuous stimulation has been an important means for analysing the mechanism of directional selectivity (Barlow & Levick 1965; Bishop *et al.* 1972; Emerson & Gerstein 1977).

However, perceptual research has given a number of results that would not be expected if stroboscopic motion perception resulted simply from the activation of directionally selective 'movement detectors'. There are reports that the critical parameter is not retinal separation but apparent separation (Attneave & Block 1973), and that apparent movement can occur between stimuli too widely separated to fall in any plausible receptive field (Smith 1948). The occurrence or direction of apparent motion can depend on the subject's attitude (Neuhaus 1930) and past experience (Neff 1936). The interpretation of the pattern as an object can determine the apparent motion (Sigman & Rock 1974) and this can lead to perception of motion in depth between plane figures (Kolers 1972). These last observations in particular would tend to support a view of apparent motion as a 'perceptual hypothesis' to account for the sensory evidence provided by successive images.

Segregation of random-dot patterns by apparent motion

The classical method for studying the parameters that control apparent motion has been for observers to judge whether a sequence of simple stimuli appears simultaneous, in motion, or successive. However, in practice these perceptual categories are not very stable or well defined. In fact, a more complex stimulus can provide a perceptual criterion of apparent motion that is easier to use. This is a 'random-dot kinematogram' (Julesz 1971) consisting of successive matrices of black and white square elements. In any one matrix, the pattern of elements is random, but on successive exposures the elements in a central region of the pattern are all displaced through the same distance, while those in the surrounding area remain in the same positions. The elements in the central region appear to move as a coherent object, with a clearly perceived boundary between this moving zone and the static surround. Now this segregation is not defined in any single random pattern. It can only appear as a result of some visual mechanism that detects the spatio-temporal relation between elements in successive exposures; that is, in some sense, a motion detecting mechanism.

When such perceptual segregation of random dot patterns is used as the criterion for apparent motion, one finds rather different properties and parameters from those obtained in studies of classic apparent movement of isolated stimulus elements. Table 1 summarizes some of the significant differences.

Table 1. Determinants of apparent motion found with two perceptual criteria

criterion of segregation in random-dot display	criterion of smooth apparent motion for isolated element
spatial displacement must be 15′ or less (Braddick 1974)	spatial displacement may be many degrees (see, for example, Neuhaus 1930; Zeeman & Roelofs 1953)
interstimulus interval (i.s.i.) must be less than 80–100 ms (with 100 ms stimulus exposure) (Braddick 1973)	i.s.i. may be up to at least 300 ms (see, for example, Neuhaus 1930)
segregation abolished by bright uniform field in i.s.i. (Braddick 1973)	motion perceived whether i.s.i. is bright or dark
successive stimuli must be delivered to the same eye or to both eyes together (Braddick 1974), as must bright field for effective masking (Braddick 1973)	successive stimuli may be delivered to the same or different eyes (Shipley *et al.* 1945)
pattern defined by chromatic but not luminance contrast is inadequate (Ramachandran & Gregory 1978)	stimuli may be defined by chromatic contrast alone alone (Ramachandran & Gregory 1978)

The demonstration of the spatial limit (Braddick 1974) requires a slightly different stimulus from that described above. If the displacement is too large, the appearance of coherent motion of the central region breaks down, but this region is still changing from frame to frame; its elements appear to be in random, disconnected motion. It therefore still appears segregated from a static surround. However, if the elements in the surround are uncorrelated from frame to frame (figure 1), centre and surround segregate when the centre is seen to move coherently over small displacements, but they appear as a homogenous area of incoherent motion when the displacement of the centre is large. When a range of element sizes is used, the displacement at which the breakdown of segregation occurs is a constant visual angle, not a constant distance in terms of the pattern elements (figure 2). This suggests that the limit is genuinely spatial rather than a consequence of some statistical limitation in the matching of element positions between successive exposures.

Note that in this, as in the other results in the left column of table 1, the criterion was strictly one of segregation rather than of the appearance of motion. Even when segregation is abolished because of the size of displacement or the duration or luminance of the i.s.i., individual elements or clusters of elements may be observed to move appropriately. The difference between the criteria of segregation and of perceived motion or displacement may account for the differences

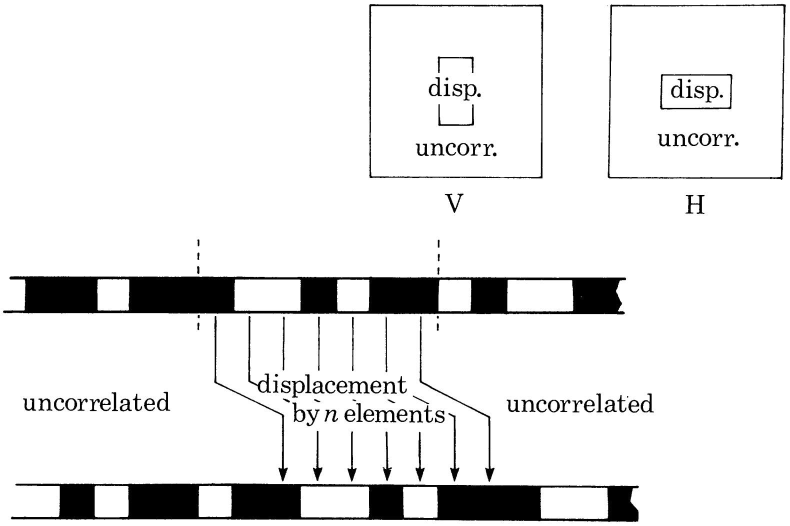

FIGURE 1. Displays used to investigate spatial limits on apparent motion in random-dot patterns. A single row of each pattern of a pair is illustrated. Outside the central rectangle (boundary indicated by dotted lines) the two patterns are uncorrelated; inside the central rectangle the dots are displaced horizontally in one pattern relative to their positions in the other. The two patterns were alternated repetitively with 75 ms exposure and 10 ms inter-stimulus interval (i.s.i.). Top right: the arrangement of the rectangular displaced region could be vertical or horizontal within the overall square 9° × 9° pattern. Subjects were required to report the rectangle's orientation. (From Braddick 1974.)

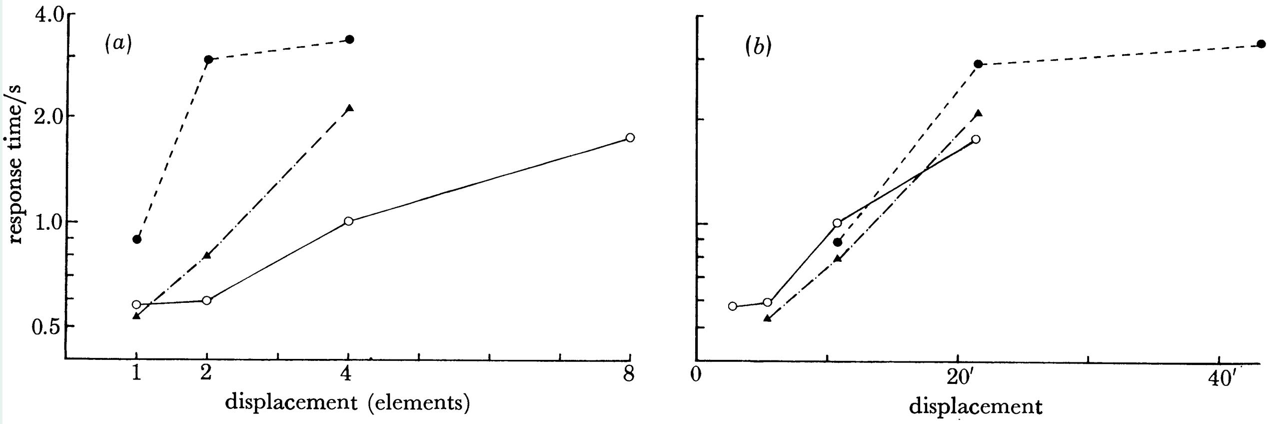

FIGURE 2. Response time for the report of orientation of the displaced rectangle in displays of the type shown in figure 1. The three plots are for different element sizes: ○, 2.7′; ▲, 5.4′; ●, 10.8′. Data are the mean of the logarithm of the response time for five subjects. The same data are plotted (*a*) in terms of displacement expressed in units of the pattern element width, and (*b*) in terms of displacement expressed as a visual angle. Long response times indicated poor segregation, evidenced also by high variability of response times, low rated clarity of the rectangle's boundaries, and frequent errors in the reported orientation. These measures, like the plots of response time shown here, coincided for different element sizes if displacements were expressed as visual angles rather than as multiples of the element dimension. (From Braddick 1974.)

between the results of Braddick (1974) and those of Bell & Lappin (1973) using random-dot patterns.

Two-process theory of apparent motion

I have proposed (Braddick 1974) that the differences listed in table 1 arise because the two perceptual criteria depend on two distinct processes that extract information about visual displacement. The segregation effect seems to characterize the process that, of the two, occurs at an earlier stage in the visual system. Evidence for this is: the relatively short spatial and temporal range over which it can combine information; its vulnerability to interference from a stimulus (bright uniform field) that is likely to have little effect on high-level pattern processing mechanisms; and its failure to operate dichoptically. This low-level 'short-range' process may tentatively be identified with the response of directionally selective neurons in the visual pathway to discontinuous stimulation. The more interpretive phenomena of apparent motion may then be associated with the higher-level process that determines the criterion of smooth perceived motion.

If there are two distinct processes, it is unlikely that the operation of each one would be restricted to the specific types of stimulus which is used to characterize it in table 1. Presumably the higher-level process can be activated by the elements of random-dot kinematograms, although its activity does not lead to perceptual segregation. Similarly, the classic type of display consisting of isolated elements would be expected to activate the short-range, low-level process if the various constraints in the left column of table 1 were satisfied. It would be surprising if its action was not reflected in some way in the perception of these stimuli.

Reversal of short-range apparent motion

For example, experiments currently in progress in my laboratory indicate that the interfering effect of a bright i.s.i. can be demonstrated with stimuli other than random dot patterns. Figure 3 illustrates the type of display. An annulus divided into bright and dark sectors is exposed in a succession of positions, each one rotated anticlockwise with respect to the one before. The rotation is always in steps of one-fifth of a period of the annular grating. Of course, this can equally well be described as a clockwise shift through four-fifths of a period. The absolute size of the step can be varied by varying the number of sectors in the circle, but this 1:4 ratio is kept constant. The subject's task is to fixate the centre of the display for 30 s and to record the periods in which the apparent rotation is clockwise. If the 35 ms interval between successive exposures is dark, clockwise rotation is almost never reported in any of the conditions used: the apparent motion follows the shorter, anticlockwise steps. However, if during the interval the annular region is bright (equal in luminance to the bright sectors) clockwise apparent reversal occurs and may even predominate. Figure 4 shows some preliminary results obtained with a single subject. The effect depends strongly on the rate at which the stimuli are exposed. Here the i.s.i. is kept constant at 35 ms, and the duration of the exposures varied: the abcissa in figure 4 is the onset–onset time, which is the sum of exposure time and i.s.i. Each curve is obtained with a particular sector size, and the parameters on the figure are the sizes of the anticlockwise steps, expressed as visual angles. For small steps, the amount of reversed motion perceived increases steeply with increasing onset–onset time, and in the range used approaches 100% reversal. As the step size increases, this rise occurs at longer onset–onset times. However,

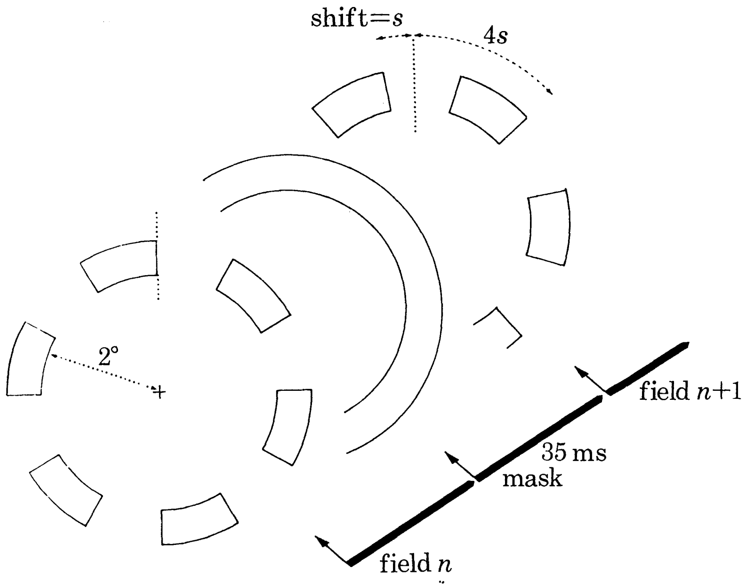

FIGURE 3. Display showing reversal of apparent motion with a bright i.s.i. The three fields shown were exposed superimposed in space and successively in time. The outlined areas were bright on a dark background. Successive exposures of the sectored annulus were rotated anticlockwise by one-fifth of period (i.e. a sector pair). The period shown here is one-sixth of the circle; values used varied from one-third to one-thirtieth of the circle.

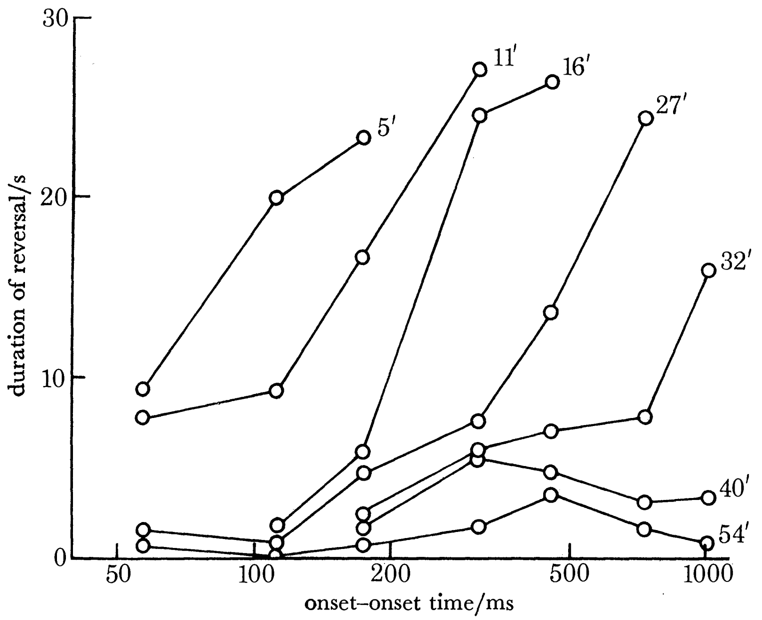

FIGURE 4. Duration of reversed motion (in seconds) seen in 30 s periods of viewing displays of the type shown in figure 3 (each point is the mean of 5–9 observations by one subject). Onset–onset time (plotted logarithmically on the abcissa) is the i.s.i. duration (always 35 ms) plus the exposure of a single field. The parameter on each curve is the shift s between successive exposures of the annulus, expressed as the visual angle subtended at the viewing distance of 2 m. Different values of s were obtained by the use of annuli with different numbers of sectors. Note that with a 35 ms dark i.s.i. all of these points would be below 1 s.

if the steps are greater than about 30′ of visual angle, this rise does not occur: clockwise motion remains at around 10 % or less of the viewing period. One might argue that, following the trend for the smaller displacements, this rise does occur but at onset–onset times longer than those used in the experiment. Figure 5 shows, however, that there is a real difference between the small and large displacements. This figure plots a particular point on the rising curves: the onset–onset time at which reversed motion was seen one-third of the time. For the small shifts,

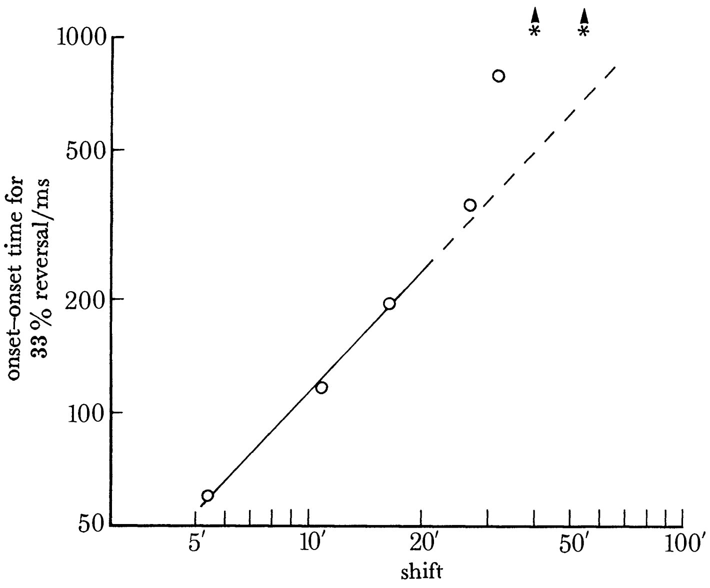

FIGURE 5. Onset–onset time (in milliseconds) producing 10 s reversal of motion in a 30 s viewing period, obtained by interpolation from data in figure 4, as a function of the shift between successive exposures of the sectored annulus. Shifts are expressed as visual angles subtended. Note that both axes are logarithmic. The line drawn has a slope of 1.06. The asterisks indicate large shifts for which 10 s reversal was not obtained in the range of onset–onset time used.

there is a regular relation between this time and the size of the shift. The line drawn has a slope of 1.06 on the log–log plot. This is close to the slope of 1 that would result if a constant reversal fraction occurred at a constant velocity. At a shift of about 30′, the data break away from this straight-line relation. For the two largest shifts, a reversal rate of 33 % is never attained in the range of onset–onset times employed, which it clearly should be if the straight-line relation was followed. Recall that these data show the effect of the bright field in the i.s.i., since with a dark i.s.i. the reversal rate was uniformly approximately zero for all the shifts and onset–onset times. Thus the outcome is that the bright field has a specific effect for small displacements. This is in accord with the idea that bright i.s.is act specifically on the short-range, low-level process responsible for apparent motion. In comparing the 30′ breakpoint in this experiment with the smaller value implied by the random-dot experiments, the position in the visual field should be taken into account: the annular stimulus was 2° from the fixation point. It is plausible that the range of the short-range process, like most other spatial parameters of vision, should increase with retinal eccentricity, although this requires direct confirmation in both types of experiment.

Unfortunately, I cannot yet offer any adequate theory of *why* the bright field in the i.s.i. should induce a reversal of apparent motion from the short-range process. This lack prevents any fully satisfying account of the experiment in terms of the two-process theory of apparent motion.

Two processes in a multistable motion display

A perceptual difference that appears to relate to the dichotomy between the two postulated processes has been studied by Petersik (1975) and Pantle & Picciano (1976). They used a display first described by Ternus (1926), similar to that shown in figure 6*a*. In this display a set of three elements is shown alternately in two positions, so arranged that the positions of the two rightmost elements in one exposure coincide with the position of the leftmost elements in the alternating exposure. Ternus reported that, even though two of the three elements remain individually in constant positions, the group of three was seen to move to and fro as a whole. He regarded this as a Gestalt phenomenon; i.e. the perception was determined by the overall organization of the stimulus rather than by its local properties. Petersik and Pantle & Picciano showed that this 'group movement' depended on the temporal parameters of the sequence: it was observed if the i.s.i. was relatively long (80 ms or greater), but for short i.s.is, such as 20 ms the dominant appearance was of 'element motion' in which the central two elements remained static and the outer element jumped to and fro across or around them. Pantle & Picciano (1976) suggest that the two percepts result from two distinct mechanisms and explicitly identify the mechanism yielding element motion with that involved in the segregation of random-dot kinematograms.

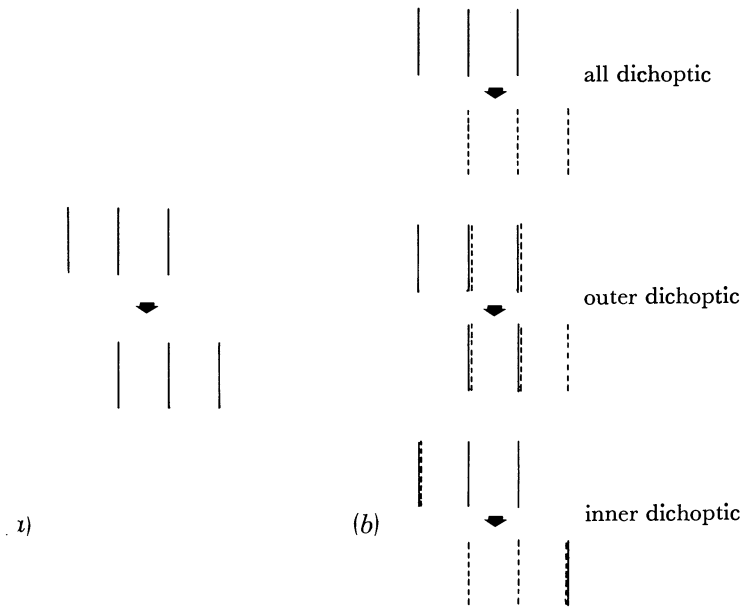

Figure 6 (*a*) The basic display giving group-motion and element-motion percepts. Vertical separation in the diagram is solely to indicate temporal sequence; there was no vertical separation in the display. A complete display sequence consisted of the upper pattern initially visible, followed by a (variable) i.s.i., followed by 200 ms exposure of the lower, with the upper then reappearing after the same i.s.i. (*b*) Three dichoptic conditions of presentation. Lines presented to the left eye are shown as solid, those presented to the right eye as broken. In the actual displays all lines were solid. Versions of these displays in which left-eye and right-eye images were interchanged were used in half the trials. (From Braddick & Adlard, 1978.)

This identification is supported by the dependence on i.s.i. (compare the temporal limit on segregation in Table 1) and also by the finding that element motion, like segregation, did not occur when the successive stimuli were presented to different eyes (Pantle & Picciano 1976). The effects of luminance in the i.s.i. provide a further analogy. Figure 7 (Braddick & Adlard 1978) shows data from a display like figure 6*a*. The i.s.i., which could be either dark or a uniform bright field equal to the background luminance of the patterns, was varied. The subject saw a single displacement and its reversal in a rapid sequence, and had to report whether he perceived group or element movement. (Other responses were permitted but were rarely used.) With dark i.s.is of increasing durations, there is a steady transition from element to group motion as reported by Petersik (1975). With the bright i.s.i. element movement is always more predominant than with dark, and except for the shortest i.s.i. it is close to 100%. (Braddick (1973) found that bright i.s.is had to be greater than 20 ms to abolish segregation in random-dot kinematograms also.) Thus the i.s.i. conditions that are supposed to suppress the short-range process also strongly favour element motion. A similar result has recently been reported by Petersik & Pantle (1979).

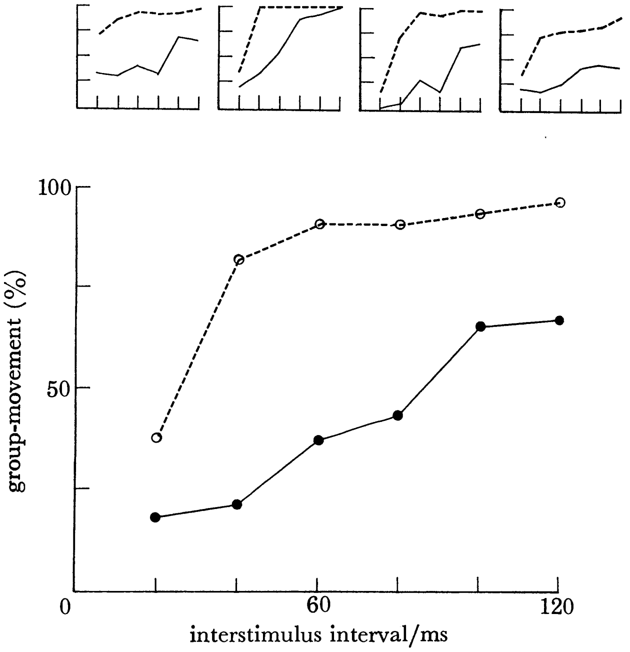

FIGURE 7. Proportion of group-movement responses as a function of i.s.i. duration for the display sequence of figure 6*a*. The i.s.i. could be either dark (●) or a uniform field of luminance equal to the background of the patterns (○). The main graph shows mean data for four subjects (20 trials each per point); individual data appear in the insets at top. (From Braddick & Adlard 1978.)

There remains a major obstacle to asserting that the short-range process is responsible for element motion in this display. The spatial displacement of the element that is perceived to move is not over a short range. It is three times the inter-element separation, hence three times larger than the displacement in group motion which is presumably to be ascribed to the higher-level, longer-range process, and in our display it is over 3° – at least ten times greater than the limit implied by the segregation experiments (Braddick 1974).

THE SHORT-RANGE PROCESS SIGNALS NULL MOTION

However, the outermost element is not the only one involved in the difference between group and element movement. The two inner elements appear stationary in the element movement percept, while in group movement they are seen to move with the group. Perhaps, then, the specific contribution of the short-range process is not to signal the motion of the outer element, but to signal that the inner elements remain stationary. Any system of directionally selective detectors must have a characteristic null response when no movement occurs (Barlow & Hill 1963).

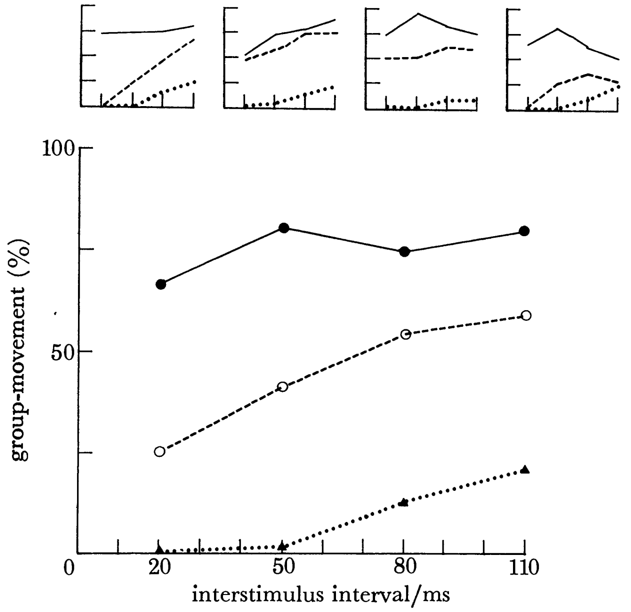

FIGURE 8. Proportion of group-movement responses as a function of i.s.i. for the three dichoptic display sequences of figure 6*b*. ●, All dichoptic; ○, inner dichoptic; ▲, outer dichoptic. The main graph shows mean data for four subjects (20 trials each per point); individual data appear in the insets at top. (From Braddick & Adlard 1978.)

To test this possibility, we have taken some of the variables that are presumed to affect the low-level and high-level processes differentially, and applied them selectively to different elements in the pattern (Braddick & Adlard 1978). Figure 6*b* illustrates one way of doing this. Presenting the whole display dichoptically (top) is known to favour group movement (Pantle & Picciano 1976). We could also restrict dichoptic presentation to the outer elements (middle) or the inner elements (lower), with the remaining elements being seen by both eyes together.

Figure 8 presents the results. As Pantle & Picciano found, complete dichoptic presentation produces a uniformly high proportion of group-movement reports. There is also a substantial amount of group movement seen when the inner lines are dichoptic, but there is almost complete element movement, particularly at short i.s.is, when the outer lines are dichoptic. Thus the effect of dichoptic presentation in reducing element movement seems to depend not on dichoptic presentation of the element that apparently moves, but of the elements that appear stationary.

An analogous result comes from the manipulation of the i.s.i. In display sequence *a* illustrated in figure 9, 120 ms (most of which is bright) elapses between the disappearance of the outer line on the left and its reappearance on the right, while only a 20 ms (dark) interval occurs between disappearance and reappearance of the inner lines in their fixed positions. In sequence *b*, the time relations are reversed. Figure 10 shows the proportions of group-movement and element-movement reports obtained with these displays. Recall that for the basic display of figure 6*a*, long, bright i.s.is favour group movement. In this experiment, group movement was seen almost invariably in sequence *b*, when a long, bright i.s.i. intervenes between exposures of the *inner* lines. In sequence *a*, where the outer lines have such an i.s.i. but the inner lines have a short, dark i.s.i., perception of element movement is the rule.

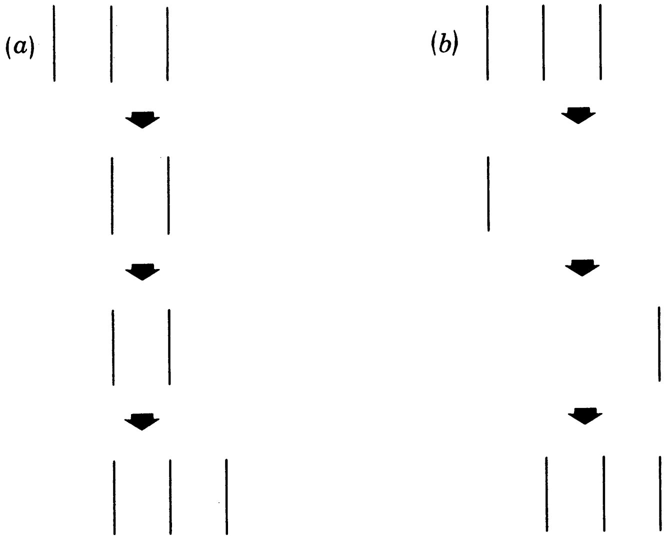

FIGURE 9. Two displays dissociating i.s.i. for the 'inner' and 'outer' elements of the display. Vertical separation was not present in the displays and is solely to indicate temporal sequence. In each case, the top row was visible at the onset of the trial, the second row was exposed for 50 ms, then 20 ms i.s.i., then the third row was exposed for 5 ms, then the fourth row was exposed for 200 ms. The reverse sequence then followed immediately. (From Braddick & Adlard 1978.)

My interpretation of these results is that, when conditions are right for the inner lines to activate the short-range process, element motion of the outer element is perceived; but if the short-range process is not activated, group movement occurs. Now short, dark i.s.is in binocular presentation, while required for the short-range process, do not exclude the higher-level process. This process, I have suggested, is more interpretive in nature. That is, the perceived motion may be selected among alternatives on the basis of complex information derived from the overall configuration, past experience, and so on. However, if the lower-level process – hypothetically, activity of directional detectors quite early in the visual pathway – is signalling that the inner two lines have *not* moved, this signal constrains the interpretations that the higher-level process can select. If those lines are stationary, then the only option is to see the third line as moving between the two outer positions. If because of long, bright i.s.i. or dichoptic presentation of the inner lines, the short-range process is silent, then there is no such constraint and the high-level process can freely operate its own selection rules: these generally favour group movement. Ullman (1979) has provided an elegant analysis of how such selection rules might operate to optimize the perceived motion paths.

Petersik *et al.* (1978) have recently reported an ingenious experiment that fits this account nicely (although it was not conceived with this in mind). They used random-dot kinematograms to create a two-bar display; that is, each bar was seen as a block of dots which remained static while its surround was in random motion, or *vice versa*. This pattern was then switched to a similar one in which the bars were displaced so that the left-hand bar now occupied the former position of the right-hand bar, a two-bar analogue to the sequence of figure 6*a*. The effect was that subjective figures, themselves generated by the segregation effects of the short-range movement process, were seen to move. This perceived movement is presumably a consequence of the longer-range process. The observation therefore implies that figures formed by the short-range process can serve as an input to the longer-range process, and thus supports the assertion that the short-range process operates earlier in the visual pathway. Further, they compared two alternative versions of this display. In one, the detailed pattern of dots making up the central bar remained the same before and after the switch. In the other, while this bar was created in the same position in the successive kinematograms, the detailed dot structures before and after the switch were uncorrelated. In the former case, the short-range process will yield a signal of 'no movement' for the central bar throughout the whole sequence. In the latter case, the dots change when the switch occurs, so such a signal is not sustained. The account given here would therefore predict that in the former case the short-range process would constrain the perception to element motion, while in the latter case group motion of the bars would be the preferred perception. This is exactly what Petersik *et al.* found.

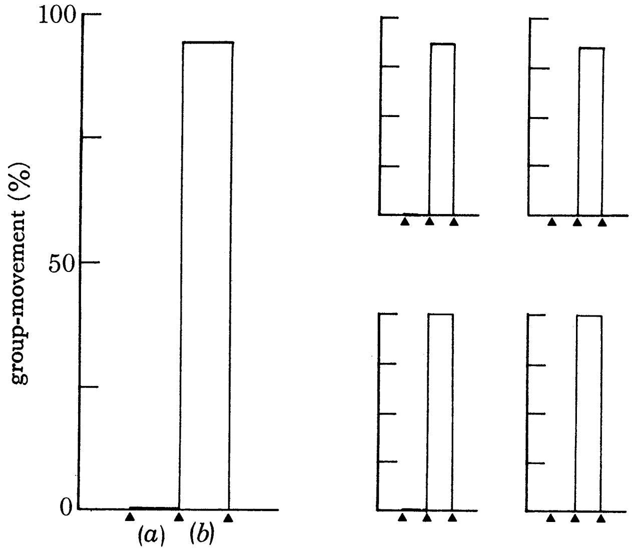

FIGURE 10. Proportion of group-movement responses for the two display sequences illustrated in figure 9. The left diagram shows mean data for four subjects (20 trials per display); individual data appear in the insets on the right. (From Braddick & Adlard 1978.)

INTERACTION OF LOW-LEVEL AND HIGH-LEVEL PROCESSES

I believe that this account of the interplay of low-level and high-level processes in the perception of apparent movement may make some general points that are illuminating in considering how specific-detector and interpretive processes contribute to perception. First, even when we know, or believe we know, what information a low-level physiological analyser is transmitting, we should not be too facile in jumping to conclusions about how that information is used in perception. In the Ternus display, I have argued that motion detectors are activated under certain conditions. However, the effect of that activation is not to produce the perception of movement, but the perception of no movement.

Secondly, it is characteristic of the higher-level processes that they operate with a good deal of freedom: all the phenomena of multistable or reversible figures are examples where a variety of perceptions are possible with the same input. The action of lower-level mechanisms wired into the visual pathway is likely to be more closely determined by the stimulus, and this determinate response has the effect of constraining the freedom available to the higher-level 'interpretive' processes. I have argued for a similar constraining role of low-level feature detection in the quite different context of binocular single vision (Braddick 1979).

Those confronting the problems of computer vision have contrasted 'top-down' and 'bottom-up' processes in arriving at an internal representation from the external stimulus (Boden 1977). Undoubtedly both sorts of process are involved in effective human perception. Interpretive processes are likely to have 'top-down' properties, at least in part: the problem of such processes is that their very autonomy makes them inefficient at converging on a correct solution; they have too many options. Low-level processes, such as the short-range motion detector, can constrain the interpretations so as to make the selection of appropriate perceptual hypotheses feasible.

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Discussion

K. H. Ruddock (*Biophysics Section, Physics Department, Imperial College, London SW7 2BZ, U.K.*).

(i) Dr Braddick describes the temporal and spatial response characteristics of two mechanisms involved in the detection of apparent motion. In view of the extensive evidence for directionally selective resonses in cortical neurons, would Dr Braddick please explain why he proposes that the central of your two mechanisms is of the 'perceptual hypothesis' forming kind?

(ii) We have found that a hemianopic subject, with severed left optic radiation, is able to detect apparent motion between two bars presented in his 'blind hemifield'. The bars were each 5.5° × 0.2°, orientated with long sides parallel and separated by some 3°, a configuration that should selectively stimulate the central mechanism of Dr Braddick's analysis. The subject reported only the appearance of a dark shadow when the stimulus lines were presented separately, yet he unfailingly identified correctly the direction of apparent motion. How would Dr Braddick interpret this observation?

O. J. Braddick. (i) Tentatively, I would associate the directional selectivity of striate cortical cells with the short-range rather than the higher-level process. Note that many such cells are monocularly driven. The 'more central' mechanism is, I would conjecture, well beyond area 17. I have proposed that it is of a 'hypothesis forming' nature simply because, in the classical kind of display, the perception of apparent notion can be affected by what may be called 'semantic' aspects of the display and by the observer's biases and experience.

(ii) Presumably Dr Ruddock's hemianopic patient is receiving information from his 'blind' hemifield only by a subcortical pathway. Weiskrantz has found that a similar patient can localize stimuli by forced choice although he denies 'seeing' them. I would probably have to interpret Dr Ruddock's observation in terms of such subcortical localization being available to the higher-level motion process I have proposed. (Although conceivably a 3° shift might activate the short-range process in peripheral vision.) It is interesting if motion is more directly apparent to the subject than location: this is not entirely clear from the question.

If such a patient showed clear evidence of the *short-range* process in the hemianopic field, that would constrain quite heavily the locus of that process and raise some interesting problems.

M. J. Morgan (*University of Durham, Department of Psychology, Durham DH*1 3*LE, U.K.*). I am wondering what the relation might be between Dr Braddick's short-range process and the interpolation effects that I described in my paper. We seem to be in agreement that the classical kind of apparent motion seen with long i.s.is in the order of 200 ms differs markedly from continuous motion. I think that the only reason why apparent motion with long i.s.is was ever called 'continuous' is that this was assessed by verbal report rather than by 'class A' psychophysical procedures. In reality, it is not continuous at all, if it is assessed by the interpolation effect, or by Dr Braddick's perceptual segration phenomenon.

It is interesting that in all the experiments that I have reported on the interpolation effect, the spatial separation corresponding to the i.s.i. at which there was a significant degree of interpolation i.s.is of 32 ms or less) was no greater than 0.2°. When a 64 ms staircase had its interstep jump reduced from 0.4° to 0.2°, the motion continuity index rose markedly, although this was not true when the jump size of the 128 ms staircase was reduced. In a separate experiment P. Mather showed that the stroboscopic Pulfrich effect broke down entirely when the jump size exceeded 1°. I wonder if Dr Braddick could comment on the relevance of these findings to his short range process? In particular, what role does he think that visual persistence and spatial averaging might play?

O. J. Braddick. In speaking of 'smooth apparent motion' over relatively long temporal and spatial intervals, I was referring to succession or alternation of just two stimuli. I was not asserting that smooth *continuous* motion can be perceived from a succession of stimuli such as Professor Morgan uses. Kolers (1972, p. 37) reports that, while a single displacement over $7\frac{1}{2}°$ looks smooth, a succession of displacements appears jerky unless they are 14′ or smaller, which indeed does suggest that only the short-range process can yield continuous perceived motion.

Even with a single jump, Professor Morgan may well be right that displacements with long i.s.is are never perceptually identical to real continuous motion. But apparent motion over large i.s.is and displacements is a real phenomenon, not just a consequence of sloppy criteria: subjects can clearly distinguish alternative organizations of motion, for instance.

It is interesting that the limiting jump size that Professor Morgan mentions for the interpolation effect is comparable with the spatial limit that I have suggested for the short-range process. I presume that he would explain his figure as the range of a spatial averaging process. Spatial and temporal averaging may account for intermediate position judgements in discontinuous displays. However, I do not think that such averaging can explain motion perception, since it would lose information about the temporal ordering of spatial positions. Hence, averaging or summation provides no basis for perceiving the direction of motion: information must be combined over space and time in a more complex (if you like, more nonlinear) way. I do not know whether it is more than coincidence that the spatial ranges of averaging for interpolation and of directional motion detection are so similar.

D. Marr (*The Artificial Intelligence Laboratory, M.I.T., Cambridge, Massachusetts* 02139, *U.S.A.*).
Computationally, there are two kinds of task associated with motion, which Marr & Ullman (1979) have called tasks of separation and tasks of integration. Tasks of separation are those that can in principle be solved by using only instantaneous measurements, like position and its time

derivatives in the image. They include tasks like the separation of differently moving objects from one another and from the background. Tasks of integration, on the other hand, are those that cannot be solved using only instantaneous measurements, but require the combination of information over time. Ullman (1979, §4) has shown that the recovery of three-dimensional structure from motion is a task of this kind. It seems likely that these two types of task are served by the two mechanisms that Dr Braddick describes. See Marr & Ullman (1979) for a computational account of mechanisms of the first kind, and Ullman (1979), of the second.

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