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1989 Phys. Scr. 39 122

(http://iopscience.iop.org/1402-4896/39/1/020)

Physica Scripta. Vol. 39, 122–127, 1989.

Spatial and Temporal Context Affects Correspondences in Apparent Motion

Stuart Anstis

Department of Psychology, York University, 4700 Keele Street, Downsview, Ontario, M3J 1P3, Canada

Received October 26, 1986; accepted February 1, 1988

Abstract

Apparent motion (AM) is seen when two patterns (such as movie frames) are exposed in succession in nearby positions. How does the visual system solve the "correspondence problem", that is, decide which item in the second frame is to be paired off with a given item in the first frame? We used a four-spot *ambiguous* AM display to reveal the influence of additional spots exposed nearby in space or in time. Spots that are close to each other tend to be paired off by proximity. AM is seen preferentially within the same hemiretina, that is within the same half of the brain, rather than across the retinal midline. AM in a straight line is strongly preferred over a bent path. Unambiguous AM drags an ambiguous nearby AM with it. An array of identical ambiguous AMs all move together, not independently.

We also describe entrained AM, and perceptual suppression of the spurious motion signals originating in static background items that are covered and uncovered by an object moving in front of them. All these phenomena demonstrate the role of parsimony and of minimum principles in motion perception.

The flashing lights on a cinema marquee give us an impression of apparent movement. The sequence of flashes draws us like moths toward the box office, where we are relieved of the entrance fee and then sit in the dark to watch a movie, which is two hours of apparent motion, because the picture on the screen is always stationary whenever the projector shutter is open. (To add insult to injury, we see only one hour's worth of pictures because the screen is actually dark for half the time.) Hochberg [1] has published an intriguing account of apparent motion at the movies.

Apparent motion (AM) was one of the first topics to attract experimental psychologists. Korte [2] measured the best spacing and timing for AM, and showed that the further apart two dots are, the longer the optimal time interval between them. It would be nice if this boiled down to a single optimal equivalent velocity for all separations, but [3] it does not.

Braddick [4] marshalled evidence that there are two separate processes for seeing AM. One is a short range process that responds only to spatial jumps of less than 1/4° and temporal intervals of less than 100 ms. This process responds only to luminance edges. Prolonged inspection of short-range AM leads to a motion aftereffect, suggesting the adaptation of neural motion detectors, of the kind first studied by Reichardt [5] in insects and by Barlow and Levick [6] in the rabbit, and subsequently found in a wide range of different animals [7].

Braddick's second process is a long range process, sensitive to large spatial jumps of anything up to tens of degrees, and to temporal intervals exceeding 100 ms. This process can respond to cyclopean edges defined only by depth or by texture even in the absence of luminance cues. It is probably an interpretative process not involving hard-wired motion detectors. In this article we shall be considering only long-range AM.

When the visual system knits together the stream of static pictures into an endless of flow of apparently continuous motion, it is ceaselessly solving what Ullman [8] has called the "correspondence problem". The problem is: How does one decide which item in one frame is to be paired off with a given item in the previous frame? If each frame contains only a single spot then the problem is easy because there are no choices to be made. But if each frame contains, say 100 spots, then each spot in the first frame has a choice of 100 candidates in the second frame, of which one is correct and the other 99 are wrong. How do we find the correct correspondences? One useful rule is: pair off each spot with its nearest neighbour. This rule works well but is not foolproof on its own. Ullman [8] has suggested a set of rules (he calls them algorithms) based upon a "minimum mapping principle" which select the alternative that carries the minimum cost. Cost is defined, very roughly, as the minimum total weighted path length.

To study solutions to the correspondence problem in AM we have used a microcomputer [9] to present a four-spot display that gives *ambiguous* AM [10]. The display is a two-frame movie that cycles repetitively; the first frame presents two spots at the opposite corners of an imaginary square, which are then replaced by the two spots at the other two corners [Fig. 1(a)]. Subjects report AM, either horizontally along the top and bottom sides, or else vertically along the left and right sides of the square. Some subjects occasionally report continuous rotation clockwise or counterclockwise.

1. Proximity

The brain tends to link up nearest neighbours in AM. The equally spaced spots in Fig. 1(a) give ambiguous AM, but if

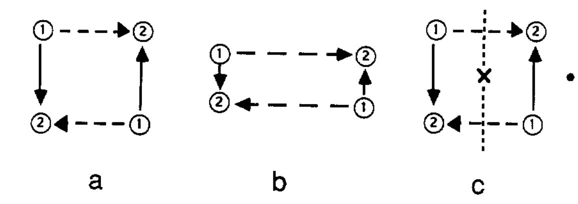

Fig. 1. In all the Figures the number inside each spot represents the order of presentation. (a) Ambiguous four-spot display shows apparent motion (AM), either vertically (solid arrows) or horizontally (dashed arrows). (b) Proximity. Vertical motion is shorter, hence far more probable, than horizontal motion. (c) Retinal midline. When central cross is fixated the display straddles the retinal midline and horizontal motion is rarely seen. When the black spot is fixated the entire display falls in same half of retina and horizontal and vertical motion are equiprobable [11].

the horizontal distances between successive spots are made much shorter than the vertical, as in Fig. 1(b), then horizontal AM will invariably be seen. Physiologically there are likely to be many motion sensors with small receptive fields. Statistically, most motions between frames are likely to be small. Linking up nearest neighbours tend to give a minimum total path length over the whole moving display.

In what follows we use proximity as a tool to measure the strength of other influences upon AM.

2. Same half of brain

Owing to an anatomical quirk of the visual system one prefers to see motion within one visual half-field rather than across the retinal midline. In Fig. 1, if one fixates on the stationary cross in the centre of the square, vertical motion is seen much more often than horizontal. Fixation off to one side abolishes this vertical bias. The explanation is that the visual system prefers not to see motion across the retinal midline, because the two halves of the visual field go to opposite halves of the brain. Correspondences are easier to establish between the neural representations of two spots that lie in the same half of the brain [11]. Thus, the visual system selects correspondences which yield AM paths of minimum cortical distance.

The preference for seeing vertical AM within one hemiretina, rather than horizontal AM across the retinal midline, can be nulled out by gradually increasing the horizontal separation and decreasing the vertical, until the horizontal and vertical motions are equiprobable. The ratio of horizontal to vertical at this point gives a measure of the strength of the preference.

3. Spatiotemporal context: visual inertia

In what follows the four spots are arranged in a diamond instead of a square to avoid the midline problem (Fig. 2a). Now the top and bottom spots appear at time 1 and the left and right spots appear at time 2. The AM is still ambiguous, and the top spot is equally likely to jump diagonally downwards to the left as to the right.

The direction of seen motion can be strongly biassed by means of a preceeding pair of priming spots at time 0, respectively northwest of the top spot and southeast of the bottom spot [Fig. 2(b)]. We find there is a strong tendency to see motion in a straight line, so the top spot appears to move down to the right from t0 to t1 and continue moving down to the right from t1 to t2. The motion down to the left from t1 to t2, which without the priming spots was seen about half the time, is now completely inhibited [12, 13]. The visual system strongly prefers straight line motion to an L-shaped motion path. We have called this effect visual inertia, which suggests that in some sense the visual system is acquainted with Newton's First Law of Motion.

The strength of visual inertia can readily be measured by nulling it out with proximity. Whereas the visual system prefers to see motion from the upper spot 1 in a southeasterly direction (to the right-hand spot 2), this preference is experimentally opposed by lengthening the southeasterly path k and shortening the southwesterly path j, in order to encourage it to jump southwest. The spot position at which motion to the left and right again become equiprobable gives an index of the strength of visual inertia. With this nulling procedure we have shown that inertia is strongest when the priming spot lines up with one side of the diamond, and falls off progressively as the angle between priming spot path and the side of the square is increased [Fig. 2(c)]. Figure 2(d) shows this as a polar diagram in which the angle of each radius represents the direction of the priming spot and the length of the radius shows the strength of the visual inertia.

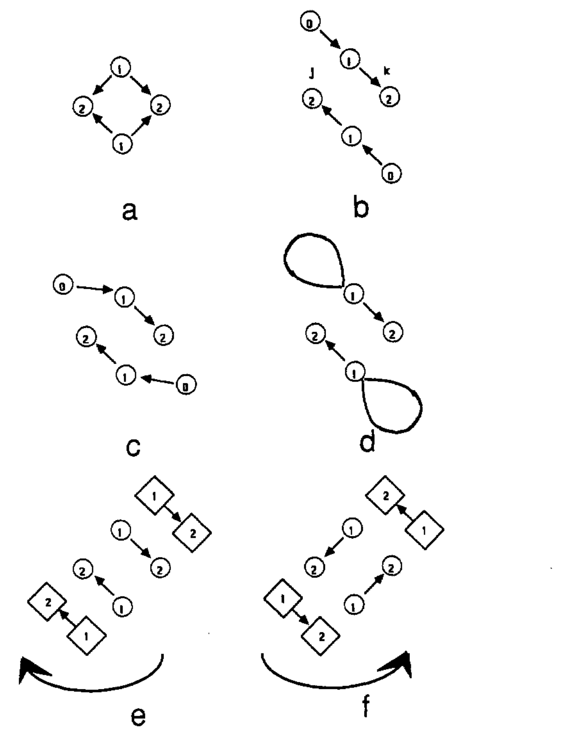

Fig. 2. (a) Ambiguous four-spot display arranged in a diamond. Top spot is equally likely to jump down to the left or the right. (b) Visual inertia [12, 31]. When priming spots at time t0 precede the ambiguous four-spot quartet the top spot always appears to continue in a straight line, down to the left. Visual inertia can be nulled out by shortening the path j and lengthening the path k. The two directions of AM become equiprobable when k exceeds j by about 35%. (c) Changing the angle of the priming path reduces the strength of visual inertia. (d) Inertia as a function of the priming angle. Angle of any radius within the curve indicates angle of priming path, and length of radius indicates amount of visual inertia measured by anulling method. (e) Spatial context influences AM. The unambiguous motion of the priming diamonds carries the AM of the four spots clockwise with them. (f) Reversing the presentation order of the diamonds makes the ambiguous AM go counterclockwise.

Thus, one's judgment of apparent motion is strongly influenced by the direction of motion that just preceded it.

4–6. Spatial contexts

Visual inertia shows that spots seen in the immediate past can influence the perceived direction of apparent motion, becoming linked with it in series. We shall now describe how neighbouring spots seen simultaneously can also become linked with the test motion in parallel when neighbouring motions interact. Demonstration 4 shows that an unambiguous apparent motion draws an ambiguous motion with it, whilst Demonstration 5 shows that ambiguous motions affect each other, pulling each other into synchrony. Demonstration 6 shows that one apparent motion can alter the perceived path of another.

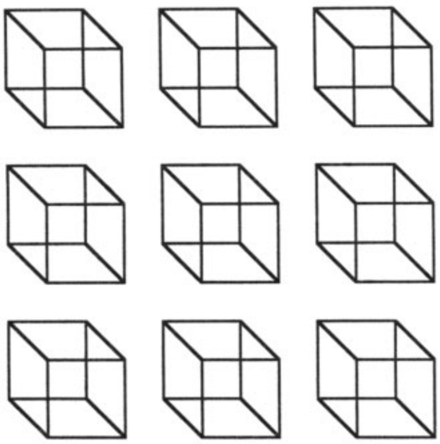

Fig. 3. Spatial context and ambiguous perspective. Each Necker cube viewed on its own periodically fluctuates, being seen with first one then the other face apparently nearer. Look at these cubes and see whether they all fluctuate independently or in step. Compare with Fig. 4.

4. Unambiguous apparent motion drags ambiguous motion with it

Figure 2(e) shows an ambiguous spot quartet surrounded by a quartet of diamonds. When the diamonds on their own are flashed in sequence their AM is unambiguously clockwise because the two upper right diamonds are close to each other so are paired off by proximity, and the same is true for the two lower left diamonds. However, if the spots on their own are flashed in sequence their AM is ambiguous because they are equally spaced. We have found that whenever the spots and diamonds are flashed on together the unambiguous AM of the diamonds drags the ambiguous AM of the spots along with it, so that the spots always move clockwise with the diamonds [curved arrow in Fig. 2(e)]. If the temporal order of the diamonds is reversed [Fig. 2(f)] the spots appear to jump in the other direction, southwest instead of southeast. Thus rotating the path of the diamonds' AM by 180° has the effect of rotating the path of the spots' AM by 90°. This is because the whole display now appears to rotate counterclockwise around the centre of the whole display.

5. Ambiguous motions in a large array lock together

Suppose you look at a 3 × 3 array of the ambiguous spot quartets (Fig. 4). Fix your gaze on any one of them and notice which way it seems to move, say horizontally. Now make the following observation: are the other quartets all moving horizontally, locked to the one you are looking at, or are some quartets moving horizontally and others vertically? The situation is rather like looking at an array of ambiguous Necker cubes (Fig. 3), each of which can be seen with either its left or its right face nearer to you in depth. See whether they all have the same handedness in depth at any given time, and whether they all flip in depth at the same instant.

The result with the jumping spot quartets is very clear [14]. All the spots keep in step, and all change simultaneously, from time to time, from horizontal to vertical apparent motion or vice versa [Fig. 4(a, b)].

In Fig. 4(c, d) the display is modified so that the central columns is a left-to-right mirror image of the outer columns. Because of this, during horizontal AM spots in the central column jump to the right when the spots in the outer columns

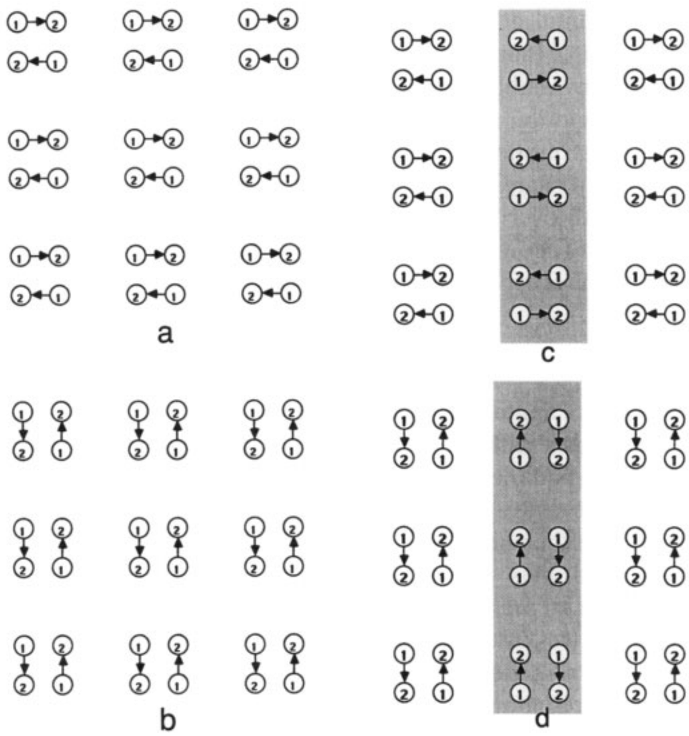

Fig. 4. Spatial context affects AM in a synchronous array of ambiguous four-spot quartets. Result: all quartets move together. If one quartet shows horizontal AM, they all do (a). If one quartet switches to vertical AM, they all do (b). (c, d) The central row is now mirror-reversed (shaded). Result: the quartets still move together. If the outer columns show horizontal AM to the left, the central column shows horizontal AM to the right. If the outer columns show vertical AM downwards, the central column shows vertical AM upwards. (Shading is for emphasis and was not present in the actual stimulus.)

jump to the left, and during vertical AM spots in the central column jump upwards when the spots in the outer column jump downwards. We have found that this makes little difference; the entire array of spot quartets still remained locked in synchrony, all jumping horizontally together or all jumping vertically together. In other words spots in neighbouring columns are always perceived as jumping along the same axis (vertical vs. horizontal) even though they are jumping in opposite directions (left vs. right, or up vs. down).

This concludes our studies on the ambiguous four-spot display.

6. Entrained motion

The path of AM can be apparently entrained or deflected to conform with the paths of inducing AMs in the spatial neighbourhood [15, 16]. Five spots were displayed on a computer-controlled TV screen, arranged like the five spots on a die [Fig. 5(a)]. The four entraining spots lay at the four corners of an imaginary square of side 4° and the entrained spot lay at the centre. The five spots were flashed successively at four positions, like a movie which was four frames long. The four outer spots were visible in all four frames, but the central spot was visible only on frames 1 and 3 and was electronically erased in frames 2 and 4.

The four positions for each spot were arranged at the north, east, south and west corners of a tiny diamond. Thus on frame 1 (west) all five spots were flashed on, then they were switched off and replaced in frame 2 (north) by the same spots shifted slightly up and to the right. However, only the four outer spots were visible; the centre spot was erased. On frame

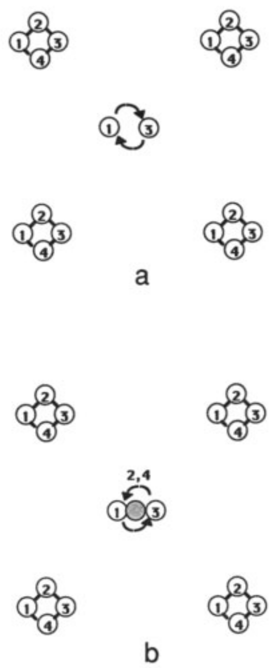

Fig. 5. Five spots are displayed. Each of the four outer spots jumps clockwise round a diamond-shaped path. (a) The central spot is visible in frames 1 and 3 but is erased in frames 2 and 4 so that it jumps back and forth horizontally. However, its AM is entrained by the surrounding spots so that it also seems to follow a clockwise trajectory (arrows). (b) The central spot still jumps back and forth horizontally, but it is now visible on frames 2 and 4 in the central position (shaded). Simultaneous contrast with the motion of the surrounding spots now causes it to appear to move counterclockwise (arrows).

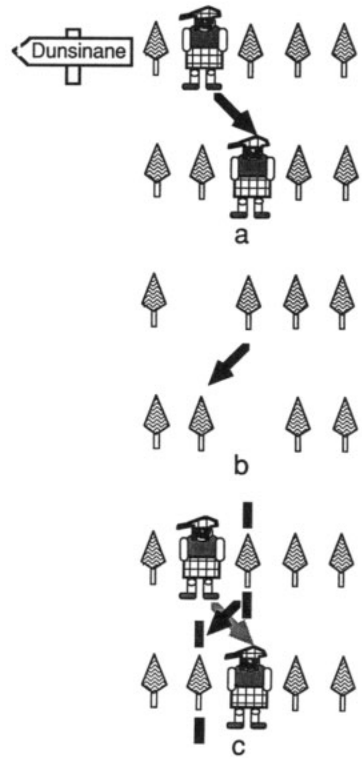

Fig. 6. Covering and uncovering [17, 19]. (a) When Macbeth jumps from left to right (arrow) he successively uncovers trees # 3 and # 2, but the trees are perceived as stationary. (b) When Macbeth is made invisible, tree # 3 is seen as jumping to the left to position # 2 (arrow). (c) When Macbeth jumps to the right (light arrow) a tree enhanced by rectangular pointers above and below it appears to jump to the left (dark arrow).

3 (east) all five spots were visible again, flashed on in a third position that was shifted down and further to the right of frame 2. On frame 4 (south) only the four outer spots were visible, shifted down and to the left of frame 3; the centre spot was again erased. This four-frame cycle repeated endlessly.

Note that the four outer spots each circled clockwise endlessly around parallel diamond-shaped paths, whereas the centre spot oscillated back and forth horizontally, being visible only on frames 1 and 3. In particular, the path of the centre spot had no vertical component. However, it showed a striking illusion of apparently moving clockwise along the same diamond-shaped path as the entraining spots. When the entraining spots jumped upwards on frame 2 and downwards on frame 4, the centre spot appeared to jump with them, although it was erased and not even visible during those frames. So a spot that was not there showed an apparent motion that was not there! If the entraining spots were made to reverse and go anticlockwise, the centre spot appeared to do so as well.

7. Suppression of the spurious motion that results from covering and uncovering

When an object glides over a stationary textured background, the object's leading edge progressively covers up parts of the background, which then reappear as they are uncovered by the object's trailing edge. The same is true for apparent motion [17]. In Fig. 6, when Macbeth jumps from left to right, he successively covers and uncovers two stationary background trees in Birnam Wood, exposing first tree # 3 on the right, then tree # 2 on the left. Result: when one sees Macbeth jumping to right one does not see a tree jumping to the left. However, if Macbeth is made invisible (Fig. 6b) then the background tree is seen as jumping from right to left. We conclude that when the visual system accepts the motion signals from Macbeth it suppresses the spurious motion signals from the tree. The motion is assigned to Macbeth and not to the tree because he covers the tree, and the *foreground* object, nearest in depth, is favoured as moving. If Macbeth and the trees are presented stereoscopically, the binocular disparity can be manipulated so that Macbeth lies in a depth plane either in front of or behind the trees (Fig. 7). Result: when he jumps back and forth in front of a background of trees the trees look stationary [Fig. 7(a)], as in real life. But if he jumps back and forth in a depth plane behind the trees [Fig. 7(b)], then the tree that he previously covered and uncovered is still visible in two positions alternately, but the suspicious coincidence of its appearance and disappearance can no longer be exlained by its being hidden and revealed by Macbeth, because the trees are now nearer than he is. Therefore as Macbeth jumps to the right in the background plane the tree appears to jump to the left in the foreground plane.

Instead of favouring the tree by putting it nearer than Macbeth, we can also favour it with a moving context, by adding pointers above and below it that move in step with the tree [Fig. 6(c)]. These pointers entrain the motion of the tree, as in Demonstration 4 above, and once again the tree jumps to the left as Macbeth jumps to the right. The tree and Macbeth move in opposite directions along approximately the same path.

In our studies of covering and uncovering we made an outline square jump back and forth in front of a static back-

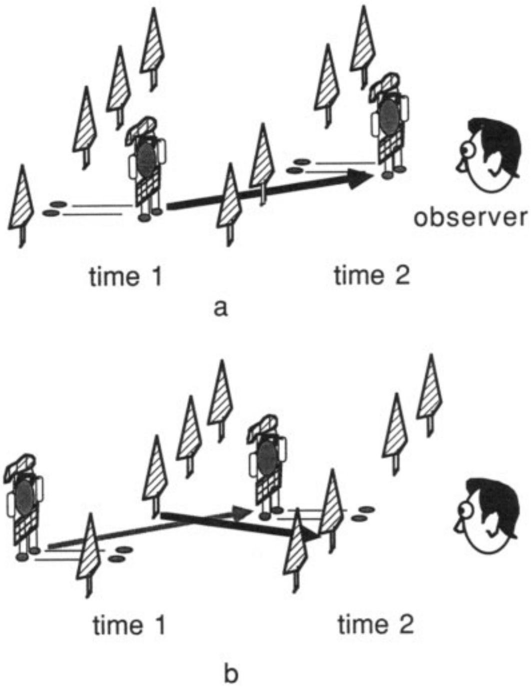

Fig. 7. (a) Macbeth is placed stereoscopically in front of the trees. When he jumps to the right (arrow), the trees that he covers and uncovers are perceived as stationary. (b) Macbeth is now placed stereoscopically behind the trees. When he jumps to the right (light arrow), the trees that he replaces appear to jump to the left (dark arrow).

ground of sparse random dots [18, 19] [Fig. 8(a)]. We used two conditions. First, the square appeared to jump over a motionless background. Second, the outline square was erased, leaving only an empty region jumping back and forth [Fig. 8(b)]. The perceived motion changed radically; one no longer saw a square-shaped blob jumping back and forth. Instead, the two parts of the stationary background that were previously perceived as being passively covered and uncovered were now perceptually combined into a single cluster jumping between two "holes", in the opposite direction from before. Thus what was previously seen as two unrelated portions of static background was now perceived as a single figure in motion. The two clusters differ in their fine structure, but were seen as a single unitary cluster in motion. This reinforces our view that apparent motion is perceptually assigned only to objects that are interpreted as figure rather than as ground.

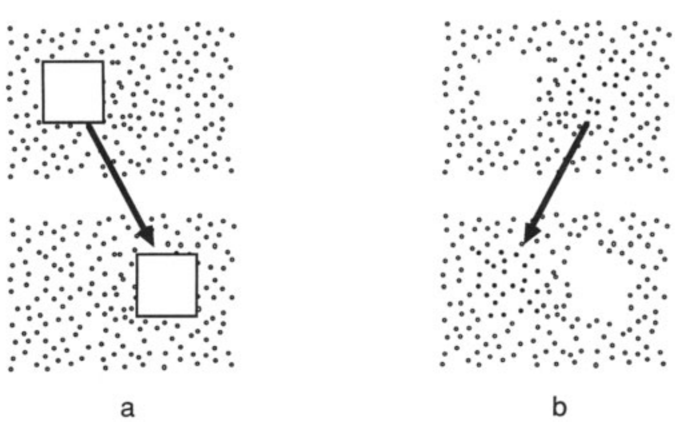

Fig. 8. More covering and uncovering. (a) An outline square jumping across a stationary background of sparse random dots is seen as jumping (arrow) whereas background appears stationary. (b) the outline square is now deleted. Result: the square-shaped blob is not seen jumping along the same path as before. Instead the region of background dots covered and uncovered by the square (shaded) is now seen as a single cluster jumping back and forth (arrow) between two stationary holes. Shading is added to these dots for explanatory purposes and was not present in stimulus.

Yet how are the two dot clusters perceptually segregated as figures in the first place? Clearly they are literally invisble while they are at rest, because they are embedded in, and indistinguishable from, the rest of the random dot background, from which they differ in no way save for being periodically switched on and off. This intermittent extinction and restoration of the two dot clusters in antiphase labels them as moving, and the motion itself labels them as figures. The cluster has no visible shape until it is first defined by the motion.

8. Why do we see apparent motion?

Why has the ability to perceive motion in a stroboscopic stimulus evolved, since "there are no stroboscopes in nature" [20]? How would an organism be handicapped that possessed no capacity for AM?

First, a red herring. Actually, we do have a built-in natural stroboscope. I refer to blinks, which keep the eyeball clean but do disrupt vision for a surprisingly long time. A blink, together with the associated rolling up of the eyeball, can last for 600 ms, yet we do not usually notice when we blink. Do we actively compensate for our own blinks? Perhaps not; if you look up at a featureless summer sky and attempt to blink, while holding the eyelids open by grasping the eyelashes between finger and thumb, you might expect to see some kind of bright flash representing an internal compensation for the darkening that usually occurs during every blink. But I cannot see any such bright flash. Then perhaps AM evolved as a way of bridging the gap during blinks while viewing a moving object? Certainly not in the case of fishes, which are very good at responding to stroboscopic AM, even at birth before any visual learning can have occurred [21]. For it is certain that fish never blink because they have no eyelids! So I doubt whether blinking has any connection with AM.

Now, the truth. Every tree is a natural stroboscope. When a man walks behind a tree and comes out the other side, the visual system does not see one object disappear and a different object come into being nearby a moment later. Instead it adopts the parsimonious hypothesis of a single object momentarily disappearing and reappearing, namely moving behind an obstruction. This is probably the origin of our ability to see long range AM. Our ability to knit together the small, fast jumps of short range AM has a different explanation. Here the stimulus, such as a movie or a TV program, is close enough to real movement to stimulate the neural motion detectors, rather as a key can operate a lock even it is not an absolutely precise fit.

9. Further reading

The theme of this article is extended in [18, 19] and review articles on apparent motion are available by Anstis [22, 23]. Koler's book [3] reviews the older literature on apparent motion. The Handbook of Perception (Vol. 1), edited by Boff, Kaufman and Thomas [24], contains articles on various aspects of motion perception by Anstis [20], Hockberg [1], Howard [25], Mack [26], and Regan, Kaufman and Lincoln [27]. Two books of readings on motion perception, based on conference proceedings, have been edited by Leibowitz, Osaka and Oyama [28] and by Wertheim, Wagenaar and Leibowitz [29]. Finally, two books from the computational school of MIT have changed the ways in which we think about motion perception. These books are by Ullman [8] and Hildreth [30].

10. Acknowledgments

This work was supported by Grant A 0260 from the Natural Science and Engineering Research Council of Canada (NSERC). I thank V. S. Ramachandran who collaborated with me on this research.

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