
Learned Stimulation in Space and Motion Perception

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ABSTRACT: *In the perception of distance, depth, and visual motion, a single property is often represented by two or more stimuli. Two instances of such redundant stimulation are discussed: (a) the various stimuli that represent visual motion and (b) the two forms of stimulation by which binocular parallax evokes stereoscopic depth perception. In the case of visual motion, simultaneous operation of redundant stimulation has unexpected consequences and raises interesting problems. Experiments are briefly described that suggest that some redundant stimuli owe their existence to learning. Evidence is reviewed that shows that binocular parallax causes stereoscopic depth by means of two different perceptual processes.*

During the last 30 years evidence that space perception can be rapidly altered by perceptual learning has been accumulating. Adaptation to displaced visual direction involves, under certain conditions, a visual change, and there are other ways in which the relation between the position of the eyes and perceived visual direction can be altered. When subjects turn their heads from side to side while they observe a visual environment that moves left and right dependent on those head movements, an adaptation develops within minutes. It involves changes in the evaluation of eye movements that compensate for head movements and in the evaluation of eye positions as measured by pointing tests (Wallach & Bacon, 1977).

In stereoscopic depth perception, the relation between retinal disparity and the extent of perceived depth can be rapidly changed. In such experiments, tridimensional shapes are viewed through a mirror arrangement that enhances the disparities with which their depth is given so that they are perceived with greater than normal depth. When these shapes are rotated, information about their true depth is provided, which disagrees with the enhanced stereoscopic depth that the mirror arrangement causes. Exposure to this conflict between two different kinds of stimulation that both represented the depth of the same object resulted in adaptation; stereoscopic depth perception was temporarily altered so that it partly compensated for the enhanced depth that the mirror

arrangement provided (Wallach, Moore, & Davidson, 1963; see also Wallach & Barton, 1975).

Convergence and accommodation function as cues for viewing distance for a great majority of observers. The relation between these oculomotor cues and perceived distance can be greatly changed in 20 minutes by having subjects wear spectacles that force the eye to view objects with oculomotor adjustments that normally represent, for instance, smaller distances. The presence of other distance cues that are not affected by the spectacles results in a rapid change in the perceived distances that result from the oculomotor cues. What happens in this case is easily explained. The distance cues that are not affected by the spectacles result in veridical perceived distances, and the altered oculomotor cues caused by the spectacles become contiguous with these correctly perceived distances and become connected with them. These new connections and the normal evaluations of oculomotor adjustments that the subject brings to the experiment add up to partial adaptation (Wallach, Frey, & Bode, 1972; see also Wallach & Halperin, 1977).

Demonstrations of such rapid adaptations do not prove that the evaluation of eye position, of retinal disparity, or of oculomotor adjustments is originally learned, but they make it likely. Moreover, original learning may resemble what goes on in adaptation. Convergence and accommodation are being adjusted for distance whether they function as distance cues or not, because they are necessary for single vision and optimal acuity. Therefore, they are present when other distance cues result in perceived distance, and they may thus become connected to the perceived distances. Forming such connections may be favored when we move and when viewing distances change. Oculomotor adjustments and perceived distances will then vary together, and this covariance may provide the signal that brings such heterogeneous matters as oculomotor adjustment and distance perception in contact with each other.

Redundant Stimulation in Motion Perception

Learned stimulation also seems to play a large role in motion perception, and it raises interesting prob-

lems. It has been known for more than 50 years that three major conditions of stimulation mediate the motion of objects in the environment. Two of them represent the change in the visual direction of the moving object, a subject-relative change. A subject-relative change is either given by pursuit movements when the eyes track the object or by displacement of the object's image on the retina when the eyes are fixed on a stationary point. A third stimulus condition represents the changing configuration in the vicinity of the moving object, caused by its changing position relative to other field contents. This changing configuration is given as such, as a change in the pattern of images on the retina. This so-called object-relative stimulus condition is redundant; the information it carries does not add to the information that either one of the subject-relative stimuli provides. Because it is redundant, the function of configurational change as a stimulus in motion perception can be demonstrated only because it operates in a peculiar manner. Primarily it registers only the relative displacement between the moving object and its stationary surround, and it becomes veridical only through the operation of an additional rule that says that in such a relative displacement the surrounded object is seen to move. This rule transforms the relative displacement that is actually given into absolute motion and was first formulated by Duncker (1929). We know about configurational change only because the relativity of object-relative stimulation and Duncker's rule can lead to a misperception that will occur when the surrounded object is actually at rest and the surround moves. The stationary surrounded object will then often be seen to move, although subject-relative conditions of stimulation represent it as stationary. This experience is called induced motion, and it is used when the effect of configurational change in motion perception is being investigated. Such investigations have shown that configurational change is a potent stimulus condition, about as potent as image displacement and much more effective than ocular pursuit (Wallach, O'Leary, & McMahan, 1982).

The operation of redundant stimuli in motion perception raises interesting questions. When we see an object move in a well-lit scene, and its motion is

given simultaneously by configurational change and perhaps by ocular pursuit, what is the object's experienced motion based on? It could be based either on ocular pursuit or on the configurational change, or it might be based on both. In the latter case, the different processes that result from the different stimuli would have to combine at some level of perceptual processing, although they start out quite differently, one with an evaluation of an eye movement and the other as a matter of form perception.

We know several instances in which the different processes clearly combine. In one such instance, a pattern of long vertical lines moved horizontally in reciprocating motion and caused horizontal induced motion in a dot located near its center. The dot moved up and down, reversing its motion at the same moments when the line pattern reversed its motion. Because the lines presented no landmarks for the vertical motion of the dot, the dot's real motion was given only subject relatively. But it also moved horizontally, an induced motion, that resulted from the configurational change in the dot-line arrangement. But neither one of the two motions was perceived as such. The two motion processes, one due to subject-relative stimulation and the other due to configurational change combined into a single unified motion. The dot was always seen to move on an oblique path. In an experiment where the extent of the vertical motion of the dot and of the horizontal motion of the lines were equal, this oblique path formed a mean angle of 45° with the vertical, when the vertical motion of the dot was given by ocular pursuit. The mean motion path was steeper, 23° , when the dot motion was given as image displacement. Apparently, when it was in conflict with the vertical dot motion that was given as image displacement, induction was not fully effective (Wallach et al., 1982).

A straight motion path that is the resultant of two simultaneous motions in different directions is the simplest instance of a Lissajous figure. (Lissajous figures are the resultants of two simultaneous simple harmonic motions.) But in the Wallach et al. (1982) experiment, the path was not an ordinary Lissajous figure, and was not a physical resultant. It was the combination of two nervous processes; it might be called a psychological Lissajous figure. We found that we could produce more complex psychological Lissajous figures by changing the phase relation between the motions of the dot and of the line pattern. When, for instance, one motion reversed when the other was at its midpoint, a circular or oval path was seen, as normally happens when physical motions combine in this manner. O'Leary and I had subjects reproduce more complex Lissajous paths, those with 2:1 and 3:2 ratios, either when

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they were actually presented or when they existed only by virtue of process combination. Reproductions of the psychological Lissajous paths were not worse than reproductions made after the corresponding real Lissajous paths had been viewed. This was the case, although the subjects had never before encountered conditions for process combination where a single object's motion resulted from two conditions of stimulation that represented two motions in different directions. Forming such combined motion paths were novel psychological events for our subjects, but that may not be true of all process combinations. Process combination may take place under ordinary conditions, when an object in motion is seen among other, stationary objects or against a patterned background. Its motion will then be given as configurational change, whereas the displacement of its image on the retina will evoke another motion process. Because different motion processes combine when they represent motions in different directions, they are likely to combine also when they represent motion in one direction.

What seemed for 30 years to be the result of a psychological vector analysis also follows from the existence of redundant stimulation in motion perception. Gunnar Johansson had discovered several patterns of moving dots in which each dot was often seen to undergo two simultaneous motions (Johansson, 1950). Such events appeared to be products of an organizing activity of the nervous system, but we found that they occur because a single objective motion, by virtue of the rules of kinematics, results in two different proximal stimulation conditions, which then produce simultaneous motion processes, one process that represents configurational change and another that represents subject-relative stimulation. We also found that the two motion processes sometimes combine and produce a single motion of each dot, and we found out under what circumstances they combine and what sometimes keeps them separate so that the two simultaneous motions are perceived. The latter had previously been ascribed to vector analysis (Wallach, Becklen, & Nitzberg, 1985).

How does the redundant stimulation that mediates motion perception come about? I believe that it is the result of simple associative learning and plan to show now that this belief is reasonable.

It seems that image displacement is the primary stimulus in motion perception. This is suggested by a comparison of image displacement with configurational change with which it is redundant. Configurational change consists of changes within the patterns of retinal images. It causes perceptual changes of which we would be aware even if there were no motion perception. An image displacement, on the other hand, is experienced *only* as motion,

as a temporary state of the perceived object that results from that image. Another reason for assuming that image displacement is the primary stimulus in motion perception is the fact that image displacements produce motion aftereffects most reliably.

Opportunities for configurational change to become a stimulus condition for motion through learning are ample. When an object moves with its stationary surround visible, its motion may be given as image displacement, but configurational change is also visible. If configurational change has not yet become a stimulus for motion, the displacement of the object's image will cause the object's perceived motion, and configurational change will be simultaneously present. A connection will be established between configurational change and perceived motion. The connection need not be solely the result of contiguity accounting. Image displacement, perceived motion, and configurational change start and stop simultaneously, and this covariance may well put configurational change and perceived motion in contact with each other. (The role of covariance in perceptual learning was first discussed in Wallach, Stanton, & Becker, 1974, p. 343.)

If this is the manner in which configurational change becomes a stimulus for motion perception, Duncker's rule is also accounted for. If the occasions at which configurational change becomes a stimulus for motion consist of seeing objects move whose stationary surrounds are visible, the surrounded object will later be perceived to move when configurational change is given.

That configurational change becomes a stimulus condition for motion through learning is supported by the fact that its relation to perceived motion can be altered by adaptation. Perceptual adaptation is often obtained by exposure to cue conflict. Normally, when two stimuli evoke the same perceptual property, they both operate veridically. Altering one stimulus artificially, perhaps by means of some kind of spectacles, causes the two stimuli to disagree, and the resulting perceptual processes will have different outcomes. At this point, one or both of these processes will gradually change in such a way that the discrepancy is diminished (Wallach, 1968; Wallach & Huntington, 1973). In the case of configurational change no artificial intervention is necessary. An arrangement that results in induced motion represents a cue conflict in itself: Configurational change causes the surrounded object to move, although the subject-relative conditions of stimulation represent it as stationary. A 10-minute exposure to such an arrangement diminished the induced motion by 15% (Wallach, Bacon, & Schulman, 1978).

Ocular pursuit also is likely to be a learned stimulus condition for motion. It would take place even if it did not function as a stimulus. If a moving

object is of interest, tracking takes place to keep its image near the fovea. As a result, ocular pursuit of an object would frequently occur at the time when other stimulation caused the object to be perceived in motion. To be specific, ocular pursuit may become a stimulus for motion perception in the following way. When an object we are looking at begins to move, the eyes remain still for a brief time before they start to track it. Thus, pursuit is typically preceded by image displacement. When the motion is straight, image displacement and subsequent pursuit have the same direction. There is no reason why the same sequence should not have taken place before pursuit had become a stimulus for perceived motion, because the image displacement probably serves as the signal to start tracking. This sequence may well be the occasion where the connection between ocular pursuit and perceived motion becomes established. Image displacement causes perceived motion and is immediately followed by pursuit. Eventually, the contiguity between pursuit and perceived motion establishes a connection between them, and pursuit evokes perceived motion (Wallach, 1976, pp. 98-99).¹

If this is the way ocular pursuit becomes a stimulus for motion perception, it might be possible to alter the relationship between pursuit and perceived motion by an adaptation procedure that involves altering the sequence of image displacement and pursuit. Suppose reality were such that motion was always horizontal but changed to oblique at the moment when the eyes took up pursuit. Horizontal image displacement would then always be followed by oblique pursuit. If the hypothesis about the manner in which ocular pursuit becomes a stimulus for motion is correct and ocular pursuit eventually comes to evoke the sort of perceived motion that is produced by the preceding image displacement, the oblique pursuit should cause perceived horizontal motion when it becomes a stimulus for motion. If such a learning process can take place in adults, in whom the normal relation between ocular pursuit and perceived motion is well established, it would manifest itself in partial adaptation. That is what Bacon found in an adaptation experiment modeled after this scheme (Bacon & Wallach, 1982a). In the adaptation period, over 75 trials, the subject saw a dot start to move horizontally and change the direction of its motion upward as soon as the subject's eyes started to move. After some adaptation has taken place, sloping dot motions that are given by

ocular pursuit but follow horizontal motions that are given as image displacement should look more horizontal than they really are, and that is what Bacon found. These changes were large; mean estimates of two different slopes were more horizontal by 38% and by 57% of the normal slope estimates. These adaptation experiments support the view that the conjunction between image displacement and pursuit provides the condition in which pursuit becomes a stimulus for motion.

Redundant Stimulation in Stereoscopic Vision

It is relatively easy to deal with redundant stimulation in motion perception, because motion provides different distal stimulus conditions, subject-relative and object-relative displacement, and because the two subject-relative stimuli involve different behaviors of the eyes. Redundant stimulation also operates in stereoscopic vision, but it took me 20 years to arrive at a clear view of it, because here the redundant stimulation consists in a single proximal stimulus condition giving rise to two different perceptual processes, one resulting from local stimulation and the other a configurational one. Let me explain.

Retinal disparity, the stimulus for stereoscopic depth, results from the two eyes viewing a tridimensional scene or object from slightly different directions. As a result the image patterns on the two retinas differ slightly. The nervous system uses these differences to build a tridimensional experienced scene or object shape. When the eyes converge on a particular point in the tridimensional array, other points, nearer or farther than this converged-for point, have images on retinal locations in the two eyes that represent different visual directions. These so-called noncorresponding locations feed the mechanism that constructs the experienced tridimensional array. Thus, stimulation by a particular environmental point at corresponding or noncorresponding locations is the stimulus condition for its perceived location in the depth dimension. The stimulus provided by noncorresponding location is the retinal disparity.

The immediate antecedents of retinal disparities are the different image patterns in the two eyes. If we were directly sensitive to these differences, they would provide exactly the same information about depth as the disparities. There is now evidence that such a sensitivity exists and provides redundant stimulation. Because this differential stimulation is based on pattern differences, I call it *binocular configurational difference*.

Because binocular configurational difference exactly duplicates retinal disparity, its operation as a stimulus was hard to discover. It was discovered only because one of the two basic forms of binocular

¹ The following articles for which the original sources are cited in the text were reprinted in Wallach's 1976 book *On Perception*: Wallach (1968); Wallach, Frey, and Bode (1972); Wallach and Huntington (1973); Wallach and Lindauer (1962); Wallach, Moore, and Davidson (1963); and Wallach, Stanton, and Becker (1974).

configurational differences is more effective in causing stereoscopic depth than the other. When two points, one of which is farther from the eyes than the other, are in the plane of the eyes, the distance between their retinal images, which are, of course, horizontally arranged, is shorter in one eye than in the other. The configurational difference consists here in a distance difference. This distance difference is one basic form of binocular configurational difference. When, on the other hand, the two points are in the median plane, the pair is given on the two retinas with slightly different tilts. The configurational difference consists in different vertical alignments of the points. (If the two points are obliquely arranged, they are given in the two eyes with both these basic forms of configurational difference.) It turned out that different stimulation patterns in the two eyes are more effective when they involve vertical alignment differences than when they consist mainly of horizontal distance differences. We found that the latency with which subjects report depth are shorter when the patterns on the stereoscopic charts contain vertical alignment differences than when they do not. The greater effectiveness of vertical alignment differences has still another manifestation. In arrangements in which stereoscopic depth is in conflict with other cues for location in the depth dimension, binocular pattern differences prevail more readily when they incorporate vertical alignment differences than when they do not (Bacon & Wallach, 1982b).

The two forms of binocular configurational differences can be so chosen that they produce the same disparities, and that was, of course, the way the experiments just mentioned were done. Thus, only the different forms of the binocular configurational difference could have been responsible for the different results in these experiments (Wallach & Bacon, 1976).

Fortunately this is not the only evidence that binocular configurational differences play a role in stereoscopic depth perception. My colleagues and I have done three experiments that show that they can have a direct effect on perceived depth.

1. A difference in the horizontal distance between the images of two points in the two eyes produces a disparity that is equal to the distance difference. Therefore, the perceived depth that this disparity produces is independent of the absolute distance between the images. But a particular distance difference is configurationally more conspicuous when the absolute distance between the images is short rather than long. Lindauer and I (Wallach & Lindauer, 1962) found that identical disparities resulted in larger perceived depth when they were associated with shorter absolute distances than with larger absolute distances. The more conspicuous configurational differences produced greater depth.

2. A similar result was obtained when we compared perceived depth in two stereograms (Wallach & Bacon, 1976, Experiment 3). One of them consisted of concentric circles where the inner circle was given with disparity. The other stereogram consisted of two pairs of vertical lines, an inner pair and outer pair, that were arranged as an analogue of the concentric circles: The inner pair was given with the same disparity as the inner circle. Nevertheless, the perceived depth between the circles was found to be larger than the depth between the line pairs. Much more conspicuous configurational differences produced the disparities in the circle charts than the disparities in the line charts.

3. In our most recent experiment, (Bacon & Wallach, 1982b) we measured more depth between two vertical lines of unequal length when we made one of the lines slightly longer for one eye than in the other. This did not change retinal disparity where only different location in the horizontal dimension matters, but it increased vertical alignment differences in the two eyes. We found that this increase in the vertical alignment difference increased perceived depth. Here too, a configurational difference was effective in stereoscopic depth perception that was not accompanied by a change in disparity.

In summary, because the eyes view a tridimensional array from slightly different vantage points, the array is given with slightly different patterns in the two eyes. These pattern differences are effective in two ways, as differences in local stimulation, with the images of individual environmental points falling on corresponding or on disparate points on the two retinas. Or the pattern differences as such cause perceived depth, with the result that configurational properties of these differences can influence the amount of depth that these pattern differences produce.

It turned out that one of the two basic forms of binocular configurational difference is more effective, and this played a large role in the discovery that it operates in stereoscopic depth perception. But why should one basic form, the vertical alignment difference, be more effective than the other basic form, the horizontal distance difference? I believe that this is a consequence of the particular occasions at which binocular configurational differences are acquired as stimuli for stereoscopic depth.

There are two reasons to believe that stereoscopic depth perception based on retinal disparity is innate. One is that the phylogenetic changes in the visual cortex that accompany the shift of the eyes from the side to the front and the concomitant overlapping of their visual fields bring the cortical representation of corresponding points into proximity. Secondly, when Erismann's subjects wore left-right reversing spectacles, there was no adaptation

to the inverted depth that such glasses produce, although the glasses were worn continuously for 37 or 24 days (reported in Kohler, 1964, p. 143). Binocular configurational difference, on the other hand, probably becomes a stimulus for depth by means of learning. Binocular configurational differences occur while disparities and perhaps other depth cues (those provided by the perspective distortions with which projections of tridimensional scenes are given) cause perceived depth, and the contiguity between them and perceived depth causes them to become connected. Covariance may also be a factor in such learning. When we move forward, binocular configurational differences increase, and the disparities they cause do too. Of its two basic forms, vertical alignment differences occur more frequently than horizontal distance differences under the circumstances of our daily lives. Vertical alignment differences occur when the ground in front of us is projected on the retinas of the two eyes, whereas horizontal distance differences occur between points on one's side. Because we look much more often at the ground in front of us than to the side, there are many more occasions where vertical alignment differences between points are given than horizontal distance differences. These vertical alignment differences then become associated with the perceived depth that the disparities produce.

The difference in the effectiveness of the two basic forms of binocular configurational differences is, at present, our only argument that this redundant stimulation is acquired, and no adaptation experiment that could provide support is in sight. The reason is that it is impossible to separate binocular configurational difference from disparity, because they are two aspects of the same proximal stimulus condition, and because there is no analogue in stereovision to the role that induced motion plays in motion perception.

Conclusion

The situation in motion perception is quite different from that in stereovision. Adaptation succeeded in altering the effect of two kinds of redundant stimulation. The rapidity with which these adaptations took effect suggests that the learning that originally makes ocular pursuit and configurational change stimuli for motion perception also takes place easily. This suggests in turn that similar learning processes may operate in the context of other stimulation and that further redundant stimuli are yet to be discovered. Any sensory condition that is covariant with a known stimulus condition is likely to have become, in a person's past, a stimulus that functions in a way similar to the stimulus it duplicates. The slope

of regard with which a point on the ground in front is viewed is such a condition. It varies with viewing distance and hence with other distance cues. O'Leary and I were able to show that it indeed functions as a distance cue (Wallach & O'Leary, 1982). One wonders how many more duplicating stimuli are yet to be discovered.

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