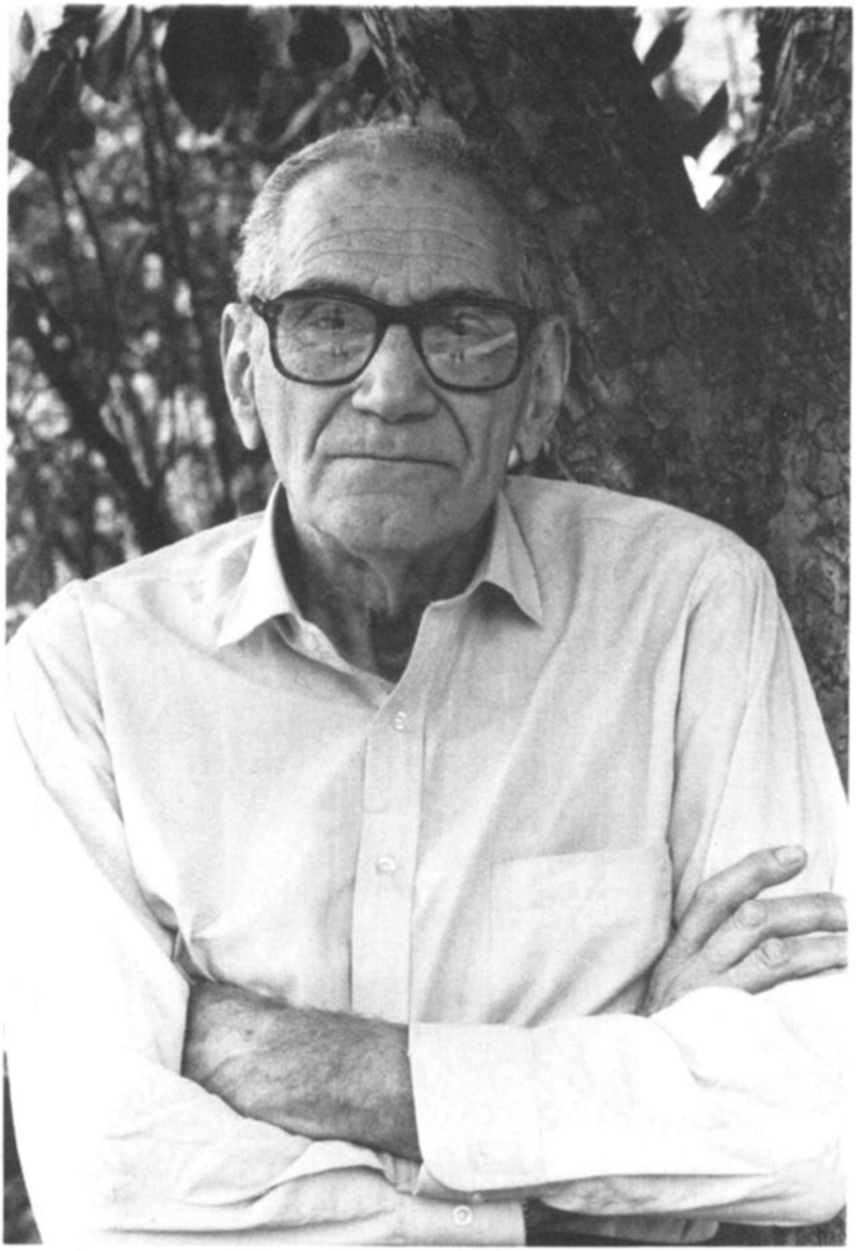

Hans Wallach

Ann. Rev. Psychol. 1987. 38:1–27

PERCEIVING A STABLE ENVIRONMENT WHEN ONE MOVES*

Hans Wallach

Department of Psychology, Swarthmore College, Swarthmore, Pennsylvania 19081

CONTENTS

VISUAL STIMULATION CAUSED BY AN OBSERVER'S MOVEMENTS

When we move we produce visual stimulation that could also be caused by motion of the environment. If that stimulation were caused by environmental motion, it would cause us to perceive motion, but when our own movements produce that stimulation, with few exceptions, no perception of motion will result. Turning or nodding head movements, for instance, cause displacements of the environment relative to the eyes that could also have been

*This is the eighth in a series of prefatory chapters written by eminent senior psychologists.

0066-4308/87/0201-0001$02.00

brought about by brief rotations of the environment about the subject. Turning the head to the right or moving the environment to the left may bring about the same relative displacement between head and environment and therefore identical visual stimulation. Yet if the environment were moving about us, we would see it move, and when we turn the head we see a stationary scene. The nervous system can distinguish between the two cases because there is sensory information that says, in one case, that the head is moving and, in the other, that it is stationary. Such proprioceptive information has an influence on the outcome of visual stimulation.

There are other circumstances where our own movements evoke from the stationary environment visual stimulation that might have been produced by objective motions, and where only proprioception provides a basis for a distinction. When we move forward, objects which we approach fill larger and larger portions of our visual field. The whole scene in front of us expands. This expansion is not perceived as such. However, if such an expansion were objectively given while we remained stationary, we would either perceive it as such or we would see the scene move toward us. Neither is seen when we cause the expansion by moving forward. Finally, there is the stimulation caused by objects or arrangements of objects that we pass when we move forward. Objects that lie to the side of one's path are successively seen from different directions. This produces the same stimulation that would be caused by turning the object through a small angle. Only rarely is such a rotation perceived. It is sometimes seen when one observes a flat landscape from the window of a rapidly moving train; the landscape seems to turn about a point near the horizon. Yet when one walks, one is mostly not aware of this rotation; the environment appears stationary. We accept this readily, while the rotating landscape seems to present a problem. The reverse should be the case since the rotation is actually given to the eye, whereas not seeing it raises one of the problems we shall have to deal with.

It is hardly surprising that the visual stimulation that results from our own movements is rarely considered. We perceive our environment as rigid and stationary, and we know that the environment in which we move is stable. When perceptual experience agrees with what is known about the physical environment, most people see no problem, but as psychologists, we have to compare perceptual experience with the pattern of stimulation. If we do that, our problem is clear: Sensory inputs that could lead to the perception of motions of the environment will not do so when they are caused by our own movements.

It would be simple if a general mechanism were responsible for the stability of the environment during our movements. Conceivably there could be an arrangement that prevents perception of any motion of the environment during bodily movement, but a series of simple observations shows that this is not so. Not all lateral displacements of the environment during head turning go unperceived. This can be seen when an inverting lens is worn during head turning. Normally, turning the head to the right will cause the environment to move to the left in relation to the head. When the inverting lens reverses this movement to the left into one to the right, one will see the environment move to the right. The environment will appear to swing with each head movement. An analogous demonstration can be made concerning the stimulation received from objects we pass as we move forward. Because it is seen successively from different directions, the scene to the side of one's path slowly rotates relative to one's eyes—counterclockwise when the scene is on one's right—and the same is true of a single object that is actually stationary. If these rotations were not perceived because no such rotations are perceived when one walks, it should not matter if the counterclockwise rotation were reversed, for instance, by looking through a reversing prism, but it does. An object on one's right that is given with clockwise instead of counterclockwise rotation as one passes it *is* perceived to turn.

Processes that Compensate for Such Stimulation

Such observations cannot be explained by a mechanism that prevents perception of environmental motion when we are moving. Rather, we deal here with several compensation processes that evaluate visual inputs by comparing them with proprioceptive data that represent our movements. For instance, when one turns one's head to the right and thereby causes the environment to move relative to the head to the left, the visual stimulus that ordinarily would cause one to perceive a motion to the left will not do so, because it occurs simultaneously with the proprioceptive stimuli that represent the head movement. Since both the visual and the proprioceptive stimulation have the same cause—a turning of the head—the two sets of stimuli stand in a fixed relation to each other. If that is the case, the compensation process prevents the visual stimulation from leading to perceived motion, and immobility results. If it is not the case, as in the two instances just cited, motion will be perceived.

In these instances the given motions are grossly different from the relative motion that the subject's movements produce. We now turn to the question of what happens when the given motions are not as different from the relative motions that are caused by the subject's movements. Are the motions then also perceived? Or more precisely, how much must the given motions be different from the movement-produced motions for some motion to be perceived? This is an important question for it amounts to asking: how accurate are the compensation processes that result in environmental immobility during the subject's movements?

The Accuracy of Compensation

COMPENSATION FOR THE EFFECT OF HEAD TURNING OR NODDING Turning the head to the right by 20° will result in the environment moving 20° to the left in relation to the head, but what would happen if the environment turned by 25°? This would require an arrangement where the environment can be made to move dependent on the head movement. To achieve the 25° turning of the environment to the left when the head turns right by 20°, the environment must be made to move 5° to the left simultaneously with the head movement. This is done by coupling environmental motion to the head movement so that the environment shifts during every head movement by 5/20 of the head rotation. The total relative displacement is then 25° when the head turns 20°. In such an arrangement, *all* subjects perceive environmental motion. Motion of the surround is also perceived when the environment shifts by 1° during a 20° head turn. In fact, young and healthy subjects regularly detect environmental motions during head turning that amount to 3% of the head movement, whether it is against the head rotation or in the direction with it, that is, whether it is in effect added to or subtracted from the relative motion of the stationary environment. The value of 3% is the result of measurements that determine the range of relative environmental displacements that result in perception of the environment as stationary. We shall call this the *immobility range*. The unit of measurement is the *displacement ratio,* the angle of the real environmental displacement divided by the angle of the head rotation. The range of displacement ratios at which immobility is experienced was found to be between .04 and .06 displacement ratios wide, that is, 2% or 3% on either side of objective immobility. This implies a remarkable precision of the sensory processes that represent the relative environmental displacement and the head movement, and of the compensating process that makes use of them.

A fairly simple apparatus was used to make these measurements. The subject wore a helmet to which a vertical shaft was so attached that it coincided with the head's rotation axis. This shaft was connected to the input shaft of a variable ratio transmission located above the subject's head. The transmission's output shaft, turned vertical, supported a mirror that reflected the beam of a projector on a screen in front of the subject. The beam came to a focus on the screen, and the projected pattern would shift left and right when the subject's head turned and made the mirror turn back and forth. In some experiments the output shaft supported a cylindrical cage of vertical rods with a point source of light in its center. The shadows of the rods fell on a large cylindrical screen that surrounded the subject, and the shadow pattern could be made to rotate to the left or to the right when the subject turned his head from side to side. The variable ratio transmission made it possible to vary the displacement ratio, that is, to vary the extent of the environmental motion that resulted from a particular head rotation. A dial on the transmission provided accurate readings of the displacement ratio for which the transmission was set at a given time (for an illustration see Wallach 1985a, p. 120).

The range of immobility was measured in the following way. The transmission was set so that the pattern seen by the subject moved so much in the direction with each head turn that it was clearly perceived to move. After the displacement ratio had been made smaller by half a percentage point, the subject again sampled the pattern motion by turning his or her head back and forth. If the pattern appeared to move, the transmission setting was changed by another half percentage point and so on until no motion was seen during head turning. At that point one limit of the immobility range was reached. Then the same procedure was used to find the other limit by starting with pattern motion in the direction opposite to the head movement. As mentioned, these limits were 2 or 3% on either side of objective immobility.

COMPENSATION FOR THE RELATIVE ROTATIONS CAUSED BY MOVING FORWARD The immobility of the scene that we pass when we move forward has hardly ever been understood to be the result of a compensation process. The exception is the work of Wallach et al (1974). It was spurred by rather simple observations that strongly argue for compensation. It is often noticed that the scene in a large painting appears to rotate as we pass by it, or that the head of a portrait seems to turn as if to keep looking at the passing viewer, but this happens only if the painting renders perspective depth realistically. The operation of the compensation process in connection with passing the painting explains this observation. If the scene were real instead of painted, passing it, for instance, on the left would cause it to rotate counterclockwise relative to one's eyes, and compensation would cause this counterclockwise rotation of the scene not to be perceived. Seeing no rotation instead of counterclockwise rotation amounts to perceiving a change in the clockwise direction. In the painting, when the counterclockwise rotation is absent and compensation nevertheless causes the change in the clockwise direction, the nonrotating content of the painting should rotate clockwise. Compensation apparently does operate because the painted scene seems indeed to turn clockwise as we pass it on the left.

The immobility range for the objects that we pass and thereby cause to turn relative to the eyes was measured in a manner analogous to our method of measuring the accuracy of the compensation for the effect of head movements. A variable ratio transmission was suspended from the ceiling; below it and attached to its extended output shaft was the three-dimensional test object. The observer moved back and forth past the object, guided by a handrail. His movement resulted in the object's relative rotation. The changing angle of the observer's position relative to the test object was transmitted to the variable ratio transmission, which in turn could make the test object rotate in either direction and in any proportion of the relative rotation caused by the observer's changing position. It would thereby cause that relative rotation to increase or decrease (for an illustration see Wallach 1985a, p. 121).

The measurements performed with this arrangement showed that the accuracy of the compensation for the relative rotation of objects caused by forward movements is quite low. The mean limits of the range of immobility amounted to about .4 rotation ratios in either direction—that is, the test object had to rotate actually by 40% of its relative rotation before an actual rotation was perceived. Although large, this range of immobility is still compatible with the apparent rotation in paintings of three-dimensional objects or scenes. The paintings present the observer with a failure to rotate that amounts to a rotation ratio of 1.0, well outside the measured .4 limits of the range of immobility.

COMPENSATION FOR DISPLACEMENT OF RETINAL IMAGES DURING EYE MOVEMENT The compensation process that takes head turning into account and results in immobility of the environment has an analogue that deals with eye movement. A moving object causes displacement of its retinal image in the stationary eye, and this displacement causes perceived motion of the object, but when image displacements are caused by eye movements, they do not lead to perceived motion of the environment. In this compensation process image displacements and registered eye movements are matched up. It has been called position constancy. To differentiate environmental immobility during head movement from it, I have called the latter *constancy of visual direction*.

Mack (1970) did the first experiments that amounted to measuring the range of immobility for image displacements caused by eye movements. She induced saccadic eye movements with light flashes and had them monitored. A visual target, a point of light, moved with varying displacement ratios in the same plane as the eye movement and simultaneously with it. Motions of the target were correctly perceived when they amounted to .2 of the eye movements. Later, William R. Whipple (Whipple & Wallach 1978) made analogous measurements, using a circle subtending 7° of visual angle as a target. Whipple asked his subjects to look from one side of the circle to the other. Again the eye movement was monitored, and the circle was displaced in various amounts as the eye movement took place. He found that target motions amounting to .08 of the simultaneous eye movements were correctly called 80% of the time. When eye movements were vertical a similar threshold for the detection of vertical target motions had a displacement ratio of .09. But even these smaller values are large compared to the .03 displacement ratio at which target motions during head turning are perceived.

The Meaning of the Range of Immobility

These differences in the width of the ranges of immobility are of no consequence where perceiving a stable environment is concerned. It does not matter how wide an immobility range is as long as objective immobility is part of it. On the other hand, a narrow range of immobility favors correct perception of real motions that occur during eye or head movements. Because head movements take more time than saccadic eye movements, it makes sense that compensation for the effect of head movement is more accurate than compensation for the image displacement caused by rapid eye movements; more real motion can take place during head movements. Two conditions transmit to the eyes that an object moves: the direction in which an object is seen gradually changes, and the position of the object changes relative to its background. The first condition is called *subject-relative displacement* and the second *object-relative displacement*. The latter is given to the eye as a changing configuration, and the resulting perceptual process is different in nature from the processes that result from subject-relative displacements (Wallach et al 1982, Wallach 1985b). Our compensation process deals only with the latter, with motion perception that results from displacements relative to the observer. Motion perception that results from object-relative displacement is not subject to the compensation process. Motions of objects that take place during head movements can be correctly perceived because of their displacement in relation to their background, which is perceived as immobile no matter how wide the range of immobility is.

These considerations raise an interesting problem. The motions of most objects are given object-relatively as well as subject-relatively. Only objects that are moving in a homogeneous surround are given solely subject-relatively, and only the perception of their motions is favored by accurate compensation for the effects of head movements. Do we have to assume that accurate compensation develops for the sake of perceiving motions in homogeneous surrounds? If object-relative displacement becomes a stimulus for motion through associative learning (Wallach et al 1978, Wallach 1985b), object-relatively perceived motion may not guide motor responses, and accurate subject-relative motion perception then is needed to guide them.

Dealing with Expansion of a Scene One Approaches

Finally, we come to the perceived stability of a scene that one approaches. The scene appears stable although retinal projection of it expands as it is approached. This case presents a complex problem. Not to see objects grow when their retinal images increase in size as we approach them may not require registering of one's movements and a compensation process. Rather, ordinary size perception may be responsible. The size of an object is correctly perceived even while the size of its retinal image differs greatly because the distance of the object from the eye changes. Under these circumstances, perceived size actually corresponds to the product of the object's image size and its distance as registered by the nervous system. Quite a variety of cues provide the information on which registered distance is based, and under favorable conditions size perception is very accurate. Correct size perception can therefore occur at any point in one's approach to an object, and perceived size may be stable because it is at every instant correctly perceived. A number of distance cues rather than proprioception of one's moving forward would be responsible for the stable size of the objects we approach.

The perceived stability of an approached scene turns out to be not primarily a matter of size perception. Expanding retinal images are stimuli for motion perception also, and compensation for the effect of such stimulation accounts for the stability of the approached scene. This can be shown by a simple experiment in which one's movements do not fit the simultaneously given visual changes. The expansion of the scene in front is here replaced by a contraction, namely, by viewing through a mirror the scene at one's back while taking a few steps forward. The mirror is held at the level of one's head in such a way that one looks backward over one's shoulder. As one walks forward, the scene in the mirror seems to shrink or to recede rapidly. This is in striking contrast to what one sees when the mirror is lowered and one views the scene in front. It will neither appear to expand nor to approach. The nervous system treats the expansion that is normally associated with moving forward differently from a contraction of equal amount, and that suggests that there is a specific effect of moving forward on the perception of expansion. But that does not mean that not seeing objects grow that we approach is entirely the result of a compensation process. Size perception may be involved also. What is needed is a method of testing that is unmistakably a matter of motion perception.

When one looks at a pattern that moves continuously in the same direction for more than 30 sec, two effects of such prolonged exposure can be observed. The apparent speed of the motion becomes slower, and when the motion is stopped, one sees in an objectively stationary pattern a creeping motion in the direction opposite to the motion that had been observed just before. The two effects are manifestations of a quasi-sensory adaptation that developed during the prolonged exposure to the continuous motion.

Flaherty (Wallach & Flaherty 1975) used these quasi-sensory adaptation effects to demonstrate that one's forward movement stops the perception of the expanding motion that is caused by one's forward movement. If the proprioception of forward movement stops the perception of an expanding motion that is associated with such movement, it may also block the motion process caused by a real expansion that is added to the movement-caused expansion, provided that there is room for the added expansion in the immobility range of the compensation process that is here involved. If, during repeated forward movements, the motion perception of a real expansion, along with the expansion caused by the forward movement, were to some degree stopped, the quasi-sensory adaptation effects might be lessened. This was indeed the case and was demonstrated by two experiments.

In one of the experiments, the expanding motion was provided by a spiral that rotated so that the windings appeared to move outward at a standard velocity of 2.25 cm/sec. The perceived speed of expansion of this spiral could be measured by having a subject adjust the rotation velocity of a second spiral until the speed of the two spirals appeared equal. The subjects made such speed matches before and immediately after the exposure period. There were two different exposure conditions, each lasting 10 minutes. In one, the "movement" exposure, the seated subject rocked forward and backward, with the expanding spiral visible only during his forward movements. In the other, the "stationary" exposure, the subject sat still, but here, too, the spiral was alternately visible and invisible. In spite of such intermittent presentation, an effect of prolonged exposure accumulated in the "stationary" condition; after exposure, the average matching speed of expansion was 37% smaller than it had been initially. No such effect was measured after the movement exposure; the mean apparent speed of expansion was exactly the same as it had been before the exposure period. Exposing the expanding spiral only during the subject's forward movements resulted in no accumulation of an effect on perceived speed.

The other experiment made use of the aftereffect of motion; the criterion for the effectiveness of exposure to an expanding spiral was the frequency with which a motion aftereffect, an apparent contraction of a stationary spiral, was reported. The critical exposure conditions were the same as in the previous experiment except that the exposure period was briefer. The result confirmed that of the previous experiment; when the expanding spiral was visible only during forward movements, the frequency of aftereffect reports was strongly diminished. It was also found that backward movements during exposure to contracting motions have no similar effect. Contracting motion paired with backward movements did not diminish the frequency of aftereffect reports. Thus, the combination of moving backwards with contracting retinal images does not initiate compensation, but moving forward does. The reason for this discrepancy may well be that backward movements while one looks forward occur only rarely. Such an influence of frequency would suggest that the compensation operating here is learned.

Limits of the Effect of Compensation

Being unaware of a motion that corresponds to stimulation produced by our own movements does not mean that such stimulation is totally ineffective. The relative rotation of objects we pass is a case in point. The deformations of the retinal images with which objects in relative rotation are given almost certainly give rise to kinetic depth effects, one of the ways by which veridical perception of tridimensional shapes takes place. In fact, the relative rotation of objects we pass during locomotion is the only occasion where the kinetic depth effect comes into play under ordinary circumstances. In experimental demonstrations of the kinetic depth effect (Wallach & O'Connell 1953), the deformations of the retinal images of rotating shapes result in perception of tridimensional objects that rotate. When the image deformations result from the relative rotation of objects that one passes, compensation stops the awareness of rotation but tridimensional form perception is not affected.

Another case where stimulation evoked by our movements has a perceptual effect, although it may not result in awareness of environmental motion, is the expansion of the visual scene when we move forward. Gibson discovered that the center of this expansion serves as visual cue for the direction of one's locomotion (see Gibson 1950, p. 128). The expansion is effective even when it results from walking and is not perceived as such. This was demonstrated by Wallach & Huntington (1973), who obtained adaptation to a laterally displacing wedge prism when the subject, led by the experimenter, was made to walk straight ahead while his or her visual field was laterally displaced. Such an exposure resulted in both visual and proprioceptive adaptation. Proprioceptive adaptation manifested itself in a changed walking direction when after the adaptation period the subject was asked to walk forward in total darkness. Visual adaptation was measured, also in total darkness, by requiring the subject to set a light point in the straight-ahead direction. Since the subject while wearing the prism was, apart from walking, only in visual contact with the environment, discrepancy between the visual and the proprioceptive walking direction caused the adaptation. The visual walking direction, however, was derived from the center of the expansion pattern. Here, too, stimulation evoked by locomotion had an effect, but the subjects were not aware of the motion that resulted from stimulation, although it was effective in another way.

ADAPTATION

Compensation for the Effect of Head Turning or Nodding

The compensation process that keeps the environment stable during head rotation, also called constancy of visual direction, can be altered by perceptual adaptation.[1] The adaptation resembles prismatic adaptation that corrects for the displacement of visual direction caused by wearing wedge prisms. Prismatic adaptation alters the relation between the given and the perceived visual directions so that perception compensates for the displacement of the given directions caused by the prism. Adaptation in the constancy of visual direction corrects for the effect of devices that cause the stationary environment to move optically during head movements so that the environment no longer undergoes the normal relative displacements that are caused by the head movements. Such devices cause the relative displacements of the environment to be larger or smaller than normal relative displacements so that the environment appears to move during each head movement. Such motion will, of course, be perceived only if the added displacement is large enough for the total displacement to fall outside the range of immobility. As adaptation develops, the motion of the environment perceived during every head movement subsides, and the environment becomes again immobile. Such adaptation had been discovered by Stratton (1897), who wore an inverting lens and over days adapted to its effects. Among other effects, such a lens causes a reversal of the motion between the environment and the turning head. While normally a turn of the head to the right causes a relative displacement of the environment to the left, the lens causes the relative displacement to be to the right. Since the compensation process causes the normal displacement in the direction *against* the movement of the head not to be seen, the displacement in the direction *with* the head is perceived as a swinging of the environment with every head movement, with an excursion of roughly twice the angle of the head rotation. Over a period of two days Stratton observed this motion of the environment to subside gradually until the environment remained immobile during head turning. When he took the inverting lens off, he observed still another manifestation of adaptation. He saw a displacement of the environment in the direction opposite to the turning of the head. It had the same direction as the normal relative displacement that results from the head movement but was stronger because adaptation had established an immobility range such that the environment was actually moving in the direction *with* the head movement. This apparent motion subsided rapidly as normal compensation became reestablished.

Stratton's observations were more recently confirmed under conditions where a right-angle prism provided the left-right reversal, but the underlying adaptation process was not investigated in any detail. Only after I designed the method of measuring the immobility range did it become possible to measure partial adaptation instead of having the subject wear the lens or the

[1]Perceptual adaptation must be distinguished from sensory adaptation; the latter alters sensitivity to stimulation, while perceptual adaptation alters perceptual processes.

prism until the perceived environment had become stable. This method made it possible to shorten the exposure period from days to hours and eventually to minutes, since partial adaptation of small amounts could be measured accurately. A subject's immobility range, for instance, was measured before the adaptation period and again immediately after it. Ascertaining the adaptation effect then took the form of computing the difference between the midpoints of the two immobility ranges on the displacement ratio scale (DR scale for short).

In our early work on adaptation (Wallach & Kravitz 1965a), no inverting lens or reversing prisms were used because when they are worn an inadvertent tilting of the head causes a tilting of the visual field that nauseates the subject. Instead we used telescopic spectacles of low power. A two-power telescope, for instance, doubles all visual angles and therefore the angle by which a moving object is displaced, and this applies also to the angle of the relative environmental motions caused by head rotation. When this motion is doubled, the environment moves optically with a displacement ratio of 1 in the direction *against* the head rotation. Wallach & Kravitz (1965a) actually used spectacles of .66 power[2] that caused the environment to shift optically with a displacement ratio of .34 in the direction *with* the head rotation. In our first adaptation experiment, 12 subjects wore these spectacles for 6 hr. Their immobility ranges were measured before they put the spectacles on and again immediately after they took them off. All subjects showed adaptation. Since they all saw the environment stationary when it moved to some degree in the direction *with* the head turns, all saw the stationary environment move in the direction *against* the head rotation when they turned their head. What motion of the environment each subject saw as stationary was determined by measuring his or her immobility range after the adaptation period. There were large individual differences in the amount of adaptation achieved. The changes in the midpoint of the immobility ranges after adaptation varied between .10 DR and .345 DR. A change in the displacement ratio of .34 DR meant, of course, that the subject had completely adapted to the spectacles that caused the environment to shift in the amount of .34 DR during each head turn. The mean adaptation measured for all 12 subjects amounted to .175 DR, or one-half of full adaptation.[3]

Adaptation to environmental displacements during head movements could be speeded up by having the subject turn his head continuously during the adaptation period. Since it is the exposure to instances of abnormal dis-

[2]These spectacles were constructed in our shop at Swarthmore College according to the scheme of the Galilean telescope.

[3]For a more detailed explication of these experiments, see Wallach & Kravitz 1968, pp. 299–301.

placements of the field content during head movements that causes adaptation, the more frequently such instances occur the faster adaptation should proceed. Such rapid adaptation can be produced by using the same apparatus that serves to measure the immobility range. The apparatus is simply set to some suitable displacement ratio, and the subject keeps turning his head and observes the shifting environment. When the shifting pattern subtended an angle of 16° and the displacement amounted to 1.5 DR in the direction *against* the head movement, 10 min of continuous head turning yielded an adaptation effect of .137 DR (Wallach & Kravitz 1965b). Much of our subsequent research employed brief periods of continuous head turning.

We have seen that one manifestation of adaptation to objective horizontal displacement during head turning consists in an apparent horizontal motion of the stationary environment during head turning. This motion turned out not to be merely a matter of experience. Rather, it functions like an objective displacement. After adaptation to horizontal displacement during head turning, the subjects of Wallach & Frey (1969) pursued a target dot that moved upward when a subject's head turned to the right and downward during a head movement to the left. In such a test, the vertical target motion was perceived to be oblique, the kinematic resultant of the horizontal motion that was the result of adaptation and the given vertical motion of the target. The authors obtained estimates of the angle of the sloping motion of the paths and used them as a measure of adaptation. This slope estimation method of measuring adaptation had the advantage of requiring only a single trial after adaptation. It was eventually abandoned, because Bacon (Wallach & Bacon 1977) developed a more accurate method.

In Bacon's method, estimates of the extent of the apparent motion of a stationary spot were obtained, with the extent of the head movement fixed. Subjects gave their estimates by marking a distance corresponding to the extent of the adaptation-caused motion on a paper pad. Before the adaptation exposure, each subject had given similar estimates for a series of real displacements during head movements of the same fixed extent. This series of estimates was used to evaluate the subject's postadaptation estimate. This estimation test was sometimes used along with the test that measured the shift of the immobility range. The latter was called a compensation test because those objective environmental motions that after adaptation result in perceived immobility compensate for the apparent motion of the stationary environment.

The Nature of Adaptation

As stated above, the compensation process that keeps the environment stable during head movements matches up the stimulation that represents the relative motion of the environment with proprioceptive stimulation that represents the head movement. When it comes to explaining adaptation that alters the outcome of this process, three changes may be considered: the outcome of the visual stimulation may be changed; proprioception of the head movement may be changed; or the compensation process itself may be altered.

Wallach & Kravitz (1968) did an experiment that tested whether adaptation consisted of a change in the proprioceptive process that represented the head movement. They demonstrated an auditory analogue to the constancy of visual direction and asked whether adaptation to visual motion during head turning would manifest itself in a shift in the auditory immobility range. If adaptation consists of a change in the representation of the head movement, it should make the auditory immobility range shift in the same direction as it shifts the visual immobility range. The apparatus for measuring the constancy of auditory direction resembled the one for measuring the visual immobility range. The subject's head was attached to a variable ratio transmission whose output shaft turned a rotary switch with 30 contacts that shifted the auditory signal through a row of 30 small speakers in front of the subject. The auditory immobility range was measured before and after an adaptation period lasting an hour, during which the subject wore 1.8 power magnifiers, which caused the visual target to move with a displacement ratio of .8, turned the head frequently, and watched television. While an identical adaptation exposure caused the mean visual range of immobility to shift by .132 DR to target displacements in the direction *against* the head movement, no significant shift of the auditory immobility range was found, and the difference between the two results was significant at the .02 level.[4] This result showed that proprioceptive change does not account for our adaptation.[5]

Wallach & Canal (1976) asked a different question about adaptation. They noted that turning the head to look at another point in the environment involves two kinds of eye movements, a saccade in the direction of the head turn and compensatory eye movements that for moments keep the eyes fixed on a point that together with the whole environment undergoes the relative displacement caused by the head turn. They asked whether perhaps adaptation

[4]Adaptation in the direction *against* the head turning was here deliberately chosen so that a shift in the auditory immobility range would have been in that direction had it occurred. Having the auditory direction move in the direction *with* the head movement to test for an opposite adaptation effect might not have resulted in immobility. A sound direction that moves in the direction *with* the head turn provides the condition of stimulation for perceiving an elevated sound direction (Wallach 1940), and such sound localization would have interfered with our experiment.

[5]This result contradicts a view of Gauthier & Robinson (1975), who studied compensatory eye movements after adaptation to 2.1 power magnifying spectacles lasting 5 days. They attributed the adaptation effects they obtained to a changed evaluation of semicircular canal signals. They found no changes in eye movements when the head was stationary and did not consider changes in the evaluation of eye movements such as Wallach & Bacon (1977) found.

consists in a changed evaluation of these compensatory eye movements. If adaptation is, for instance, to an actual motion of the environment in the direction *with* the head turns, then compensatory eye movements that keep the eyes fixed on a point are diminished, because the point actually moves somewhat in the direction of the head turn. If adaptation takes place and the environment that partially moves with the turns of the head is perceived as stationary, then either one of two changes must have taken place. Either the compensation process had changed so that now a diminished compensatory eye movement results in immobility of the environment, or compensation remained unaltered and the eye movements had become overrated.[6] Fortunately, Wallach & Canal considered, at this point, only the changed evaluation of eye movements, and that turned out to be what happens.

If adaptation consists in changed evaluation of compensatory eye movements, it should not matter how the visual environment moves during the adaptation period so long as the eyes track a mark that undergoes the appropriate head movement–dependent displacements. Wallach & Canal obtained adaptation even when the moving mark was surrounded by a stationary pattern. The latter's immobility indeed did not prevent some adaptation. They also did what seemed to them a control experiment in which motion and rest were reversed. A large pattern representing the visual environment was made to move dependent on head turning while the subject had to fixate a stationary mark, which, because it was stationary, underwent the normal relative displacements caused by the head movements and evoked normal compensatory eye movements. Surprisingly, this condition, too, resulted in some adaptation. It was apparent that the two exposure conditions evoked adaptation processes that were different in nature. The adaptation that resulted from tracking a mark that actually moved during head turning was called "eye movement adaptation," because it presumably consisted in a changed evaluation of compensatory eye movements, and the adaptation that resulted from head movement–dependent motions of a large pattern representing the environment while the eyes performed normal compensatory movements was called "field adaptation."

Wallach & Bacon (1977) compared the two kinds of adaptation with each other. Normal adaptation conditions where the subject looked at the moving pattern freely as in our earlier experiments were included in the comparison. The visual environment was represented by the shadow pattern cast by the cylindrical cage on the curved screen that surrounded the subject and filled his or her visual field. To obtain the conditions for eye movement adaptation, the cage was made immobile and a mirror, connected to the transmission's output

[6]For the sake of simplicity, the discussion assumes here complete adaptation, but the consideration fits also partial adaptation.

shaft, reflected the moving mark to the region of the screen in front of the subject. For conditions of normal adaptation and for field adaptation, the output shaft turned the cage so that the movement of the shadow pattern was dependent on the head turns. When conditions for field adaptation were presented, a stationary mark was provided by another lantern. The motion of the shadow pattern or of the mark when it was used for eye movement adaptation amounted to .4 DR and was in the direction *with* the head turns for all adaptation conditions. Exposure lasted always 10 min. Both adaptation tests were used in connection with each of the three adaptation conditions. In the compensation test, the immobility range was measured before and after the adaptation exposure, and in the estimation test, the apparent extent of the motion of the stationary mark was measured as described above.

The results are given in the first two rows of Table 1, which also lists the number of subjects used in each of the experiments. All six adaptation effects listed were significant at the .001 level.

Wallach & Bacon (1977) obtained evidence for Wallach & Canal's proposition that eye movement adaptation consists in a changed evaluation of compensatory eye movements, an overrating when adaptation is to environmental motion in the direction *with* the head turns. There are two ways to show that an overrating of compensatory eye movement can account for this adaptation. In the compensation test, when, after adaptation, actual motion of the test mark in the direction *with* the head turns results in the mark's immobility, compensatory movements that keep the eyes on that mark are shorter than normal. They must be overrated so that the registered extent of the eye movements matches the extent of the head turns and perceived immobility of the mark results, because the compensation process itself is assumed to remain unaltered. Or when, in the estimation test, a stationary mark appears to move in the direction *against* the head turns, the normal

Table 1 Mean adaptation effects of 10 min exposure to three adaptation conditions, in displacement ratio (DR) units and number of subjects (N)

Test	Adaptation Conditions: Normal		Eye movement		Field		Field with saccades	
	DR	N	DR	N	DR	N	DR	N
Estimation	.131	16	.055	16	.053	16		
Shift of immobility	.098	12	.072	28	.056	28		
Pointing I	.126	12	.133	12	.002	12		
Pointing II			.106	18				
Forward direction	−.004	12	−.013	12	.087	12	.172	12

extent of the eye movements necessary to keep the eye on the stationary mark must be overrated so that the mark appears to undergo this motion.

Wallach & Bacon demonstrated such an overrating of the extent of the eye movements with a simple pointing test (Pointing Test I). In total darkness the subject turned the head to the left by 18°, controlled by a stop. When the stop was reached, a vertical line straight in front of subject's body lit up. The subject had to look at it and point at it. Immediately, the pointing direction was recorded. The subject made three such pointings, and their average direction was computed. The test was repeated after the adaptation exposure. The difference between the two averages became the subject's pointing effect. This test was given in connection with each of the three adaptation conditions.

After eye movement adaptation as well as after normal adaptation, subjects pointed too far to the right, showing that the eye movement to the right that was needed to look at the vertical line was overrated. The mean pointing errors after adaptation were 2.4° and 2.27° respectively and were highly significant. Transformed into DR measures, the pointing effects are listed in the third row of Table 1. No such pointing effect was obtained after field adaptation where the eyes fixated a stationary mark and made normal compensatory movements; and the difference between this result and the results of eye movement and of normal adaptation was also significant ($p < .02$).

Normal and eye movement adaptation resulted in quite similar pointing effects. Table 1 shows that they were as large as normal adaptation measured with the estimation test. It seems that changed evaluation of eye movements as measured with the pointing test accounts for the normal adaptation that had been obtained. That the adaptation measured after eye movement adaptation conditions was somewhat smaller than the corresponding pointing effect probably resulted from the shadow pattern being stationary during the adaptation exposure. Its normal relative motion provided conflicting information for adaptation, while the result of the pointing test reflected only the abnormal motion of the tracked mark.

We were also able to show that the change in the overrating of eye movements after adaptation did not take place only after the head had just been turned. Eye movement adaptation apparently consists in a changed evaluation of all kinds of eye movements as Pointing Test II showed. This test started with the subject's head locked in normal position and the eyes fixed on a luminous mark straight in front of head and body. When the mark was extinguished, another spot 18° to the right of the mark lit up. The subject had to look at the spot as soon as it appeared and then point at it. The pointing direction was immediately recorded. There were again three such tests before and three after eye movement adaptation. After adaptation, 18 subjects pointed on the average 1.9° farther to the right, a change that was significant at the .001 level. This overrating of the eye movement was equivalent to .106 DR and was not significantly smaller than the result of Pointing Test I.

Another test of visual direction, the forward direction test, that had been used to measure adaptation to a wedge prism (Wallach & Huntington 1973) turned out to show an effect after field adaptation. In that context, the subject, with his head turned to the side by 18°, had to set a luminous mark in the dark to appear to be straight in front of his or her body. The mean settings after the standard field adaptation exposure were 1.6° to the right of the mean pre-adaptation settings, a significant difference at $p < .01$. This effect was equivalent to .087 DR. No such effect was obtained after eye movement adaptation and after normal adaptation. The latter finding suggests that normal adaptation that was produced by 10 min of continuous head movements of moderate extent consisted in eye movement adaptation.

These findings—that the pointing test measured only eye movement adaptation but not field adaptation, and that the forward direction test registered a change only after field adaptation and not after eye movement adaptation—suggests that field adaptation takes place at a level of processing different from the one where eye movement adaptation operates. In field adaptation the eyes fixate a stationary mark and the head movement–dependent actual motions of the environment are given as image displacements. With eye movements corresponding to the normal environmental displacements associated with the head movements, these image displacements are effective at a level of processing where eye positions have been taken into account and where the environment is represented as it is located relative to the head. This higher representation then registers the displacement of the environment relative to the head. When the head is turned under normal conditions, the constancy of visual direction causes this registered displacement to result in environmental immobility. Field adaptation presumably alters the evaluation of displacements represented at this higher level, and the forward direction test that registered only field adaptation is connected with the representation of the environment at this level.

During field adaptation, when the environment is made to move dependent on head turning, the representation of the environment at this higher level registers displacements larger than normal, and the environment is seen to move *with* each head turn. After partial adaptation, displacements somewhat larger than normal are accepted as normal and result in immobility of the environment, while an actually stationary target is perceived to move in the direction *against* the head movements.

The experiment by Wallach & Kravitz (1968), which demonstrated that adaptation in the constancy of visual direction did not transfer to the constancy of auditory direction, eliminated one possible explanation of that adaptation: change in proprioception of the head movement does not account for it. Whether adaptation consists in a changed outcome of visual stimulation or whether the compensation process itself is altered remained an open question. We can now conclude that at least the rapid adaptations that Wallach & Bacon (1977) investigated consist in a changed evaluation of visual stimulation. After eye movement adaptation the pointing tests showed as large an effect of eye movement adaptation as direct measurements. This meant that such adaptation consists in a changed evaluation of eye movements. Similarly, the forward direction test fully measured field adaptation, as the results in Table 1 show, and this made it clear that field adaptation consists in changed evaluation of image displacements.

As stated earlier, compensatory eye movements are not the only eye movements that ordinarily take place during head turning. Saccades in the direction of the head movements also take place. Wallach & Bacon (1977) did an experiment in which such saccades were included in the adaptation conditions. As in their other experiments, a pattern moved during head turns at .4 DR *with* the head turns, but it consisted here of seven columns of groups of three letters. During each head movement to the right the subject had to read a group of three letters in each of two neighboring columns, and that required making a saccade to the right during each right turn of the head. After the 10-min-long adaptation exposure, the forward direction test registered a change of .172 DR. A look at Table 1 shows that this was by far the largest adaptation effect that was obtained under the standard conditions that Wallach & Bacon (1977) employed. If the finding applies, that the forward direction test measures only field adaptation, then the present experiment produces strong field adaptation—a changed evaluation of the representation of the environment after eye position has been taken into account. That the presence of saccades causes adaptation at this level may be an indication that saccades are steered from this level of processing. Inasmuch as the adaptation conditions also evoked compensatory eye movement, eye movement adaptation may also have taken place, and the experiment was likely to have produced adaptation of both kinds. Whether that is the case is worth exploring. It would throw some light on the relationship between the two kinds of compensations involved in the constancy of visual direction.

The two kinds of adaptation strongly suggest that the constancy of visual direction operates at two levels of visual processing. At one, in connection with the operation of compensatory eye movements, eye movements are evaluated; at the other, after eye movements have been taken into account, the visual environment is represented as it is related to the head. It is hard to imagine how one could arrive at this view without knowing about eye movement and field adaptation. Adaptation is an important tool in the investigation of visual processing, and that is an important reason for studying it.

The Secondary Displacement

As Wallach & Kravitz (1965a) pointed out, the relative motion of a visual target depends not only on the head rotation but also on the distance of the target. If that distance is relatively small, the target's displacement is larger than the angle of the rotation of the head would warrant, because the eyes, being located forward of the rotation axis of the head, are laterally shifted during the head rotation. The displacement that depends on this lateral shift of the eyes is additional to the relative target motion caused by the head rotation and has a measurable effect on the target motion up to a distance of two or three meters. Since the distance between the midpoint between the eyes and the head's rotation axis averages 10 cm, the additional displacement of a stationary target caused by head movements amounts to .25 DR when the target distance is 40 cm from the eyes. It amounts to .1 DR when that distance is 1 m, and it is .05 DR when the target is 2 m away. (For the derivation of the formula with which these values were computed see Wallach et al 1972.) This additional displacement caused by the lateral shifting of the eyes will be called secondary displacement.

In our measurements of the immobility range, we used target or pattern distances of 200 cm and 120 cm and found that the midpoint of the immobility range coincided accurately with objective target immobility. At a distance of 120 cm, the average secondary displacement amounts to .083 DR, and compensation for this additional displacement was found to take place. On the other hand, a stationary target 43 cm from the eye was seen to move in the direction against the head turning by half of our subjects. For a group of 10 subjects, the mean midpoint of the immobility range was found to be at .06 DR. Thus, compensation for the secondary displacement was incomplete by this amount. At a distance of 43 cm, the average secondary displacement amounts to .23 DR, but the average compensation amounted only to .17 DR (Wallach et al 1972). Hay & Sawyer (1969), however, measured the immobility range for a target distance of 40 cm using a nodding rather than a turning motion of the head and found that its mean midpoint coincided with objective immobility. We later confirmed their result. Because nodding of the head alters the head position with respect to the gravitational direction, such head movements are probably more sharply represented; this may account for the more accurate compensation during head nodding.

The effect of viewing distance on the constancy of visual direction is best demonstrated by using deceptive distance cues. In the conditions under which the immobility range was measured, only convergence and accommodation served as distance cues. Thus, Wallach et al (1972) had subjects wear spectacles that diminished accommodation by 1.5 diopters and convergence by 5 prism diopters.[7] These spectacles thus caused a target at a distance of 40 cm from the eyes to be viewed with accommodation and convergence for a distance of 1 m.[8] As stated above, the secondary displacement of a stationary target at the distance of 1 m amounts to .1 DR. When the constancy of visual direction takes that distance of 1 m into account, it compensates for a secondary displacement amounting to .1 DR. At the actual target distance of 40 cm, secondary displacement amounts to .25 DR. Since, with the spectacles in place, compensation amounts to .1 DR only, the 40-cm-distant target should be seen to move by .1 DR less than .25 DR. It should therefore appear to move at .15 DR in the direction *with* the head turns. Measurements confirmed this prediction; the mean midpoint of the immobility range for the 40-cm-distant target viewed through the spectacles was found to be .158 DR. The deceptive target distance that the spectacles provided proved fully effective in the compensation process that takes the effect of head movements and the secondary displacements into account.

Wallach et al (1972) also demonstrated an effect of experimentally altered distance perception on the constancy of visual direction. Previously, Wallach & Frey (1972) had found that distance perception based on convergence and accommodation can be altered rapidly when subjects adapt to spectacles like the ones just described. When, for instance, spectacles are worn that have the opposite effect and cause the eyes to be adjusted for distances shorter than the actual distances of the objects viewed, an adaptation develops that partially compensates for the effect of these "near" spectacles. When these spectacles are removed and while this adaptation effect lasts, convergence and accommodation will denote distances larger than normal and target points will appear to be farther away than they really are. Such an adaptation effect, then, changes distance perception in the same direction as wearing the spectacles that were used in the experiment just reported. Therefore, it should change the immobility range in the same direction as did these spectacles. This expectation was confirmed when the immobility range of a target at 40-cm distance was measured twice, once before and again after subjects had adapted to the "near" spectacles for 90 min. It was found that after adaptation the immobility

[7]Such spectacles were much used by Wallach & Frey (1972). They consisted of positive lenses of 1.5 diopters which diminished by that amount the accommodation with which the eye viewed objects at distances of 67 cm or less. The lenses were combined with wedge prisms that diminished the need for convergence of the eyes in corresponding fashion.

[8]Viewing a target at 40 cm distance requires an accommodation amounting to 2.5 diopters. With the spectacles diminishing accommodation by 1.5 diopters and convergence in equivalent amounts, the eyes viewed the target with oculomotor adjustment that corresponded to an accommodation of 1 diopter and to a viewing distance of 1 m.

range had shifted, on the average, by .11 DR. This effect corresponds to 70% of complete adaptation to the "near" spectacles.

These demonstrations of the compensation for the secondary displacement that nearby objects undergo during head movements give a good idea of the complexity of the processes that keep the perceived environment stable during head movements and of the ease with which adaptation can alter them.

Adaptation Unrelated to Existing Compensation

So far I have reported adaptation that altered the constancy of visual direction. Subjects were exposed to objective displacements that either diminished or increased the relative displacements of the stationary environment that are the direct consequence of head turning. The adaptations that developed were modifications of the process that compensates for such relative displacements. Now I am reporting experiments where the head turning–dependent objective displacements were vertical and orthogonal to the relative displacement of the stationary environment that accompanies every head turn. The orthogonal displacements were unrelated to these relative displacements, and any adaptation that developed was unrelated to the constancy of visual directions.

Wallach et al (1969) obtained such adaptation after an exposure period of one hour, during which each of 12 subjects watched a television broadcast through a mirror arrangement that was coupled to their head turning. As the subjects turned their heads back and forth, they saw the TV screen move up and down at .5 DR, that is, at half the angle of their head turns. After the exposure period, a stationary target spot appeared to move down and up. When this effect was measured, it was found that the target spot had to move up and down with a mean displacement ratio of .087 in order to compensate for the apparent motion of the stationary target and to be seen as stationary. A shift of the immobility range amounting to .087 DR means that the exposure resulted in 17.4 percent of complete adaptation.

This kind of adaptation, which was also obtained by Hay (1968), shows that a compensation process can develop from scratch and under completely artificial conditions. Repeated environmental displacement orthogonal to the plane of the head rotation never occurs naturally. If compensation can develop in this case, it follows that the constancy of visual direction can also develop as an adaptation to the relative environmental displacements caused by head movements. But while the constancy of visual direction contributes to the stability of the perceived environment, adaptation to orthogonal displacements occurs only in an artificial situation and is of no advantage. Why does it develop at all? I believe that the central nervous system responds to covariance between proprioceptive information about movements of oneself and stimulation representing environmental motion as a means for identifying those stimuli that represent motions caused by such movements. Since such motion stimuli do not represent genuine environmental events, perceived motion that resulted from such stimulation would have to be disregarded. Instead, the covariance between the representation of our own movements and the stimuli that these movements cause instigates the development of a compensation process. It frees perceptual experience of such uninformative contents. Compensation develops to the point where such covariant visual stimulation no longer results in perception, and that means that the environment becomes stable.

Adaptation to Form Distortions

This interpretation of compensation is supported by two experiments where adaptation developed only when a form distortion caused by spectacles resulted in deformations produced by head movements. In the compensations just discussed, head movements were the causes of the stimulation to which subjects adapted. Whether the head movements caused the stimulation naturally or by means of a mirror arrangement does not matter here. In the experiments to be reported, either the motion that changed the form distortion into deformation could result from head movements and thus be covariant with them, or the motion responsible for deformation could be artificially produced and no head movements made. In the latter case, adaptation did not develop.

Wallach & Barton (1975) adapted subjects to spectacles that caused retinal disparities which in turn caused plane frontal patterns to appear concave instead of flat.[9] The apparent curvature was like an inside view of part of a large cylinder with horizontal axis. During an adaptation period that lasted 20 min, the subjects sat in front of a plane random dot pattern, which they viewed through the spectacles while nodding their heads up and down. When the spectacles were later removed, the pattern appeared to bulge. This adaptation effect was measured by using a test surface with a similar pattern fixed to a flexible metal sheet that could be made to curve. Twice the subject made settings of the flexible surface so that it appeared flat, once before and again after the adaptation period. Because a plane pattern seemed to bulge after adaptation, the flexible surface had to be concave to appear flat. Such measurements made it possible to explore the specific conditions that produce this adaptation. First we demonstrated the need for having the subject see the flat pattern deform: 12 subjects looked at the pattern with the head in a

[9]Viewing a vertical line through a wedge prism with base vertical will cause perception of a small optical curvature of the line. Such a wedge in front of each eye with base toward the temples will cause opposite curvature of the lines in each eye and retinal disparities that make plane patterns concave.

headrest; they saw the pattern as a fixed concave shape.[10] Another group of 12 subjects nodded their heads continuously; the concave shape shifted up and down with the moving heads and caused the pattern to deform. Adaptation occurred only under the latter condition. It caused a curvature that formed a 90-cm-long arc, with a mean height of 2.35 cm ($p < .005$). At this point the question arose whether the deformation was the only condition necessary for adaptation to develop or whether the head movement was also a necessary condition. In a third adaptation condition, the heads of 16 subjects were stationary and the pattern was made to move up and down continuously. This condition also caused the concave shape produced by the spectacles to shift in relation to the pattern and deform it. No adaptation was here obtained, and this result was significantly different (at the .01 level) from the one obtained with head nodding.

Wallach & Flaherty (1976) did a similar experiment using a different form distortion. It was produced by placing a 30-diopter wedge prism in front of the subject's right eye, with the left eye occluded. The base of the prism was horizontal and downward. In this orientation it caused a distortion in a pattern of evenly spaced horizontal stripes such that the lower part of the pattern looked narrower and its upper part seemed expanded. When the subject nodded his or her head, the prism tilted with the head, and this tilting of the prism caused the distortion to travel up and down with the head movement. After a 10-min adaptation period during which the subject nodded his or her head incessantly, the prism was removed. The stripe pattern then appeared mildly distorted in the opposite manner. This adaptation effect was measured by compensation. A weak wedge prism was selected from a graduated series that would cause the striped pattern to look regular when it was put in front of the eye with base down. For a group of 21 subjects who nodded their heads in the tests, the mean strength of the compensating prism was 2.76 diopters after an adaptation period of 10 min ($p < .005$).

A further experiment was analogous to the experiments by Wallach & Barton (1975). During the adaptation period the subject either nodded his head or kept it on a biteboard. In that case the pattern was made to deform in the same way as it does during head nodding. The prism that the subject wore during nodding was mounted in front of the subject's eye and was made to undergo the same tilting motions that it underwent when it moved with the nodding head. During the tests, the subject's head was kept immobile by a biteboard. A single group of 16 subjects served in both adaptation conditions, with an interval of 5 days between the two parts of the experiment. Whereas the mean strength of the compensating prism after a 20-min adaptation period

[10]No figural aftereffect (Köhler & Emery 1946) developed, because the subjects did not fixate a stationary point.

of head nodding was 1.91 diopters, there was no adaptation after the subjects observed, for 20 min, the same pattern deformations with the head stationary. The difference between the results was significant at the .01 level.

In both experiments rapid adaptation took place only when the subjects' head movements changed the form distortions caused by the spectacles into deformations of the patterns on which the distortion were visible. But the deformations alone were not sufficient; they had to be caused by head movements, a condition that manifested itself as covariance between the proprioception that represented the head movements and the motions of the distortions visible on the pattern. This covariance is a requisite for the adaptations that were found, and it may be their cause. Because it serves as an indication that the perceived deformations are not genuine environmental facts, the resulting adaptations free perceptual experience of immaterial contents. Covariance, thus, may serve as a general cause for adaptation and may make the existence of a variety of normative tendencies and of specific capacities for developing various compensation processes unnecessary.

APPENDIX: COMPENSATION FOR FIELD ROTATION CAUSED BY HEAD TILTING

So far we have considered the stimulation caused by turning and nodding of the head, horizontal or vertical translatory motions of the environment. A sideways tilting of the head, which amounts to a rotation of the head about a front-back axis, causes rotation of the environment, a change in its orientation relative to the head. The compensation that deals with this relative orientation change was investigated by Wallach & Bacon (1976). The accuracy of this compensation was measured in the same manner as the accuracy of the constancy of visual direction. An apparatus that made it possible to have a tilting of the head cause a pattern in front of the subject to rotate in either direction at a variable ratio to the head rotation was constructed, and the immobility range was measured as before. It turned out to be almost as narrow as the one for the constancy of visual direction—on the average .05 rotation-ratios wide. There was one difference: While, in the case of head turning, the range of immobility was symmetrically located about the point of objective immobility, in the case of head tilting the immobility range comprised, in addition to the point of objective immobility, only objective rotation in the direction *with* the head tilting.

The circular pattern in front of the subject that yielded these results consisted of radial lines that originated from a point in the center of the subjects' visual field. The pattern subtended a visual angle of 40°. Measurements of the range of immobility were taken also for a central portion of the pattern that subtended a visual angle of 5° and for a peripheral region. To obtain the latter, a central portion of the pattern subtending 10° of visual angle was obscured so that only a ring 15° wide was visible. In the latter case, a small lightspot, which the subject had to fixate, marked the invisible center of the radial pattern.

For this ring-shaped peripheral region the range of immobility was somewhat larger than that for the whole pattern; it was .09 rotation-ratios wide. It, too, was asymmetrically located in the *with* direction. A surprising result was obtained for the central region. Its mean immobility range extended from .06 to .184 in the direction *with* the head tilting on the rotation ratio scale. This result means that when the central region was actually stationary, it appeared to turn slightly in the direction *against* the head tilting. Of the 35 subjects who observed the central region 31 saw this motion. Many readers will be able to duplicate this observation when they look through a tube that causes the visible field to subtend only 5° of visual angle or less. When they look at a vertical or horizontal edge through the tube and tilt their heads from side to side, they will see the edge tilt in the direction *against* their head tilting. It appears that in central vision, compensation for field rotation during head tilting is incomplete.

The compensation for field rotation caused by head tilting could be altered by adaptation. Ten minutes of continuous tilting of the head from side to side while the radial pattern in front of the subject turned at a rotation ratio (RR) of .4, either in the direction *with* or *against* the head tilting, yielded measurable adaptation. For the peripheral ring-shaped region it amounted to .064 RR, and for the central region it was .085 RR.

ACKNOWLEDGMENT

This report is an expanded version of the second James J. Gibson Memorial Lecture, which the author delivered at Cornell University in 1982.

Literature Cited

Gauthie, G. M., Robinson, D. A. 1975. Adaptation of the human vestibulo-ocular reflex to magnifying lenses. *Brain Res.* 92:331–35

Gibson, J. J. 1950. *The Perception of the Visual World*. Boston: Houghton Mifflin

Hay, J. C. 1968. Visual adaptation to an altered correlation between eye movement and head movement. *Science* 160:429–30

Hay, J. C., Sawyer, S. 1969. Position constancy and binocular convergence. *Percept. Psychophys.* 5:310–12

Köhler, W., Emery, D. A. 1946. Figural aftereffects in the third dimension of visual space. *Am. J. Psychol.* 40:159–201

Mack, A. 1970. An investigation of the relationship between eye and retinal image movement in the perception of movement. *Percept. Psychophys.* 8:291–97

Stratton, G. M. 1897. Vision without inversion of the retinal image. *Psychol. Rev.* 4:341–60, 463–81

Wallach, H. 1940. The role of head movements and vestibular and visual cues in sound localization. *J. Exp. Psychol.* 27: 339–68

Wallach, H. 1985a. Perceiving a stable environment. *Sci. Am.* 252(5):118–24

Wallach, H. 1985b. Learned stimulation in space and motion perception. *Am. Psychol.* 40:399–404

Wallach, H., Bacon, J. 1976. The constancy of the orientation of the visual field. *Percept. Psychophys.* 19:492–98

Wallach, H., Bacon, J. 1977. Two kinds of adaptation in the constancy of visual direction and their different effects on the perception of shape and visual direction. *Percept. Psychophys.* 21:227–41

Wallach, H., Bacon, J., Schulman, P. 1978. Adaptation in motion perception: Alteration of induced motion. *Percept. Psychophys.* 24:509–14

Wallach, H., Barton, W. 1975. Adaptation to optically produced curvature of frontal planes. *Percept. Psychophys.* 18:21–25

Wallach, H., Canal, T. 1976. Two kinds of adaptation in the constancy of visual direction. *Percept. Psychophys.* 19:445–49

Wallach, H., Flaherty, E. W. 1975. A compensation for field expansion caused by moving forward. *Percept. Psychophys.* 17:445–49

Wallach, H., Flaherty, E. W. 1976. Rapid adaptation to a prismatic distortion. *Percept. Psychophys.* 19:261–66

Wallach, H., Frey, K. J. 1969. Adaptation in the constancy of visual direction measured by a one-trial method. *Percept. Psychophys.* 5:249–52

Wallach, H., Frey, K. J. 1972. Adaptation in distance perception based on oculomotor cues. *Percept. Psychophys.* 11:77–83

Wallach, H., Frey, K. J., Rommey, G. 1969. Adaptation to field displacement during head movement unrelated to the constancy of visual direction. *Percept. Psychophys.* 5:253–56

Wallach, H., Huntington, D. 1973. Counteradaptation after exposure to displaced visual direction. *Percept. Psychophys.* 13:519–24

Wallach, H., Kravitz, J. 1965a. The measurement of the constancy of visual direction and of its adaptation. *Psychon. Sci.* 2:217–18

Wallach, H., Kravitz, J. 1965b. Rapid adaptation in the constancy of visual direction with active and passive rotation. *Psychon. Sci.* 3:165–66

Wallach, H., Kravitz, J. 1968. Adaptation in the constancy of visual direction tested by measuring the constancy of auditory direction. *Percept. Psychophys.* 4:299–303

Wallach, H., O'Connell, D. N. 1953. The kinetic depth effect. *J. Exp. Psychol.* 45: 205–17

Wallach, H., O'Leary, A., McMahon, M. L. 1982. Three stimuli for visual motion perception compared. *Percept. Psychophys.* 32:1–6

Wallach, H., Stanton, L., Becker, D. 1974. The compensation for movement-produced changes in object orientation. *Percept. Psychophys.* 15:339–43

Wallach, H., Yablick, G. S., Smith, A. 1972. Target distance and adaptation in distance perception in the constancy of visual direction. *Percept. Psychophys.* 12:139–45

Whipple, W. R., Wallach, H. 1978. Direction-specific motion thresholds for abnormal image shifts during saccadic eye movement. *Percept. Psychophys.* 24:349–55