Adaptation in stereoscopic depth constancy

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Stereovision is a complex process because perceived depth intervals depend not only on retinal disparity, but also on cues for distance. Because disparity decreases in proportion to the square of the object distance, a compensation process called constancy of stereoscopic depth makes the necessary correction in the perception of depth by taking object distance into account. This compensation process was altered by adaptation. Subjects were exposed to artificial conditions where disparity decreased in proportion to distance instead of distance squared. Alterations in depth perception amounting to 20% were obtained.

Stereoscopic depth perception is one of the ways in which visual perception deals with the fact that of the three dimensions of space, one, the depth dimension, is not given in the projection on the retina. Instead, the depth of solid objects and the depth intervals between objects that are not located in the same frontal plane are given indirectly by slight differences in the retinal images in the two eyes. These differences are called retinal disparities, and they occur because the two eyes view things from different vantage points. Stereoscopic depth perception uses these retinal disparities to create the third dimension of the space we perceive. Since the eyes are arranged horizontally, disparities are differences in the horizontal distances on the retinas between pairs of points that are the images of points in the environment not located in the same frontal plane. The greater the depth between the points in objective space, the greater will be the difference between these horizontal distances of their images in the two eyes, and the greater will be the perceived depth between them.

But that is not the whole story. While the magnitude of a disparity varies with the magnitude of the depth interval that produced it, it also depends on the distance of the depth interval from the eyes. In that respect, retinal disparity resembles image size, which represents objective size but also depends on the distance of the object from the eye. Because the image size, while proportional to object size, is also inversely proportional to distance, the process of size perception takes observation distance into account and compensates for the loss of image size due to observation distance. In this compensation process,

called size constancy, perceived size is proportional to image size as well as to observation distance as it is registered on the basis of the available distance cues. In the case of depth perception, however, the disparity with which an objective depth interval is given is inversely proportional to the square of the observation distance of the depth interval. To compensate for this decrease in disparity when observation distance increases, the process that connects disparity with perceived depth causes an increase of perceived depth in proportion to observation distance squared. The function that yields correct depth perception thus operates according to the equation:

perceived depth

$\equiv \text{disparity} \times \text{registered distance squared.}$

In this formula, which has been called Zuckerman's law (e.g., Welch, 1978, p. 180), registered distance is the observation distance as represented by the available distance cues. In an experiment in which adequate distance cues were provided, perceived stereoscopic depth was found to be in good agreement with objective depth up to a distance of 2 m (Fried, 1974), and this result confirmed Zuckerman's law for this distance range. Further details may be found in Ono and Comerford (1977) and in Wallach, Gillam, and Cardillo (1979).

Because we believed that stereoscopic depth constancy is learned, we made an attempt to demonstrate that it can be altered by an adaptation procedure. Such an attempt would require exposing the subject to conditions where the relation between disparity and objective depth is artificially altered, that is, where disparity is no longer reciprocal to observation distance squared. Fortunately, such a condition is

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readily available, namely, when anaglyphs are viewed. An anaglyph is obtained when pictures in different colors are made of the left-eye and the right-eye view of a real three-dimensional arrangement and are copied one on top of the other in such a way that two homologous points, one from each picture, are made to coincide. When this combined picture is viewed through color filters that cause the right-eye view to reach only the right eye and the left-eye view only the left eye, a three-dimensional scene is perceived. In the combined picture, distances between homologous points that do not coincide will be called pictorial disparities because they produce the retinal disparities that cause the depth perceived in the picture. Retinal disparities that result from such pictorial disparities vary—like all retinal images produced by the picture—in inverse proportion to the first power of the picture's distance from the eyes (Wallach, Gillam, & Cardillo, 1979). Disparities produced by real depth intervals, on the other hand, are inversely proportional to observation distance squared, and depth perception compensates for this latter decrease in disparity with observation distance, resulting in perceived depth that is proportional to registered distance squared. When this compensation is applied to the disparities caused by pictorial disparities, an overcompensation should occur; the depth perceived in the anaglyph should increase in proportion to observation distance. Wallach and Zuckerman (1963) did find changes in the depth perceived in an anaglyph that approached this prediction. Adapting stereoscopic depth perception to the anaglyph condition involves the elimination of these changes in perceived depth with changing observation distance. The process that compensates for the effect of distance on disparity would have to undergo an alteration such that depth perceived in the anaglyph would remain unchanged when observation distance was varied. The formula that describes the altered compensation process would have to read:

perceived depth

$$= \text{disparity} \times \text{registered distance},$$

because the retinal disparities produced by the anaglyph decrease in proportion to the first power of observation distance. Full adaptation to the anaglyph condition would mean perceiving depth according to this formula. The experiments to be reported resulted only in partial adaptation; instead of depth perceived in the anaglyph becoming the same at all observation distances, the normal change in depth perceived in the anaglyph when observation distance was altered became diminished.

We found that adapting subjects to the anaglyph condition involves having them view repeatedly an

anaglyph from different distances. Adaptation was measured by having the subjects give depth estimates from different viewing distances, either of a pictorial disparity (Experiment 1) or of a real depth interval (Experiments 2 and 3).

An anaglyph taken from p. 73 in Gregory (1970), depicting a tree branch, was used in all adaptation conditions. The left-eye picture was printed in red and the right-eye picture in green. The subjects viewed them with a green filter in front of the left eye and a red filter in front of the right eye. Depth estimates were always given for the perceived depth between the same two twigs at a point where they crossed in the picture. At this point, the horizontal distance between homologous points in the red and the green pictures, that is, the pictorial disparity, measured 2.5 mm. The subject gave estimates of the depth between the two twigs by adjusting outside calipers so that the distance between the two caliper points appeared to be equal to the depth between the twigs.

EXPERIMENT 1

Procedure

There were two copies of the anaglyph and two seats for the subject. One setup was used for the exposure, and the other for the tests. During the exposure period, the subject sat on a high stool and rocked forward and backward over a distance of about 50 cm. The anaglyph was so placed that it was 25 cm from his eyes when his head was in the forward position. The anaglyph in the setup used in the test was mounted on a carriage that moved on a track in the subject's sagittal direction, and was used in two positions 30 cm apart. The subject, who sat on a chair whose height was adjustable, assumed one of two postures, straight or leaning forward. In either posture, the position of the head was fixed by one of two teeth molds that could be moved into and out of fixed positions. There were three test conditions. In Test A, the subject leaned forward and the anaglyph was 30 cm from his or her eyes. In Test B, the anaglyph position was the same as in Test A, but the subject sat straight and the observation distance was 60 cm. In Test C, the head was again in the forward position, but the anaglyph had been moved 30 cm further out, so that the observation distance was 60 cm. The combinations of posture and observation distance that were used in Tests A and B occurred during the exposure period; the one used in Test C did not.

Subjects were first given the tests for stereovision described below. Then they were given the three tests, A, B, and C, in randomized order. The tests were given twice, with the first test given for practice only. Then the subject changed seats and sat for 10 min in front of the exposure anaglyph. He or she was asked to rock back and forth at a rate that seemed comfortable. Immediately after this exposure period, the subject moved back to the test setup and the three tests were given again, in the same order in which they were given before the exposure.

Subjects, Swarthmore College undergraduates, were selected first for adequate stereoscopic depth perception and secondly for showing the anaglyph effect. Three stereograms were used. One consisted of three vertical lines with disparities so arranged that the center line was seen behind the two outer lines. Next came a black-and-white dot-pattern stereogram designed by Julesz. The last stereogram consisted of two vertical lines. In each case, the subjects had to report the right depth relations within 30 sec. Six subjects failed this stereoscopic test. Those who passed it were admitted to the preexposure tests. Three subjects who gave depth

Table 1
Mean Estimates of Anaglyph Depth (in Centimeters)
for Two Observation Distances Before and After
Adaptation With Subject Moving

	A	B	C	B-A	C-A
Before	1.35	2.08	2.06	.73	.71
After	1.39	1.69	1.89	.30	.44
Difference				.43*	.27*

Note— $N = 11$. $A = \text{near}$, $B = \text{subject far}$, $C = \text{anaglyph far}$.
* $p < .005$.

estimates in Tests A and B that differed by less than .3 cm were also eliminated. Eleven subjects participated in the experiment.

Results

The results are given in Table 1. The mean pre-exposure depth estimates A and B measured the normal effect of the anaglyph. They can be compared with the results of a similar measurement made by Wallach and Zuckerman (1963), who obtained estimates for a depth interval in an anaglyph at the observation distances of 45 and 90 cm. The ratio of the two mean estimates was found to be .6, while the complete anaglyph effect would have produced a ratio of .5. The corresponding ratio for our mean estimates in Tests A and B was 1.35/2.08, or .65. Adaptation to the anaglyph conditions caused the difference between the depth estimates obtained in these tests to become smaller. After adaptation, the ratio between the mean depth estimate at the 30-cm distance and the mean estimate at the 60-cm distance, Test B, was 1.39/1.69, or .82. In the case of Tests A and C, the corresponding ratios were .65 before adaptation and .74 after adaptation. Complete adaptation to the anaglyph condition would have made these postadaptation ratios 1.3.

In Table 1, the same results are presented in a different form. The mean depth estimate obtained before adaptation at the near distance (A) is subtracted from the mean obtained at the far distance (B), and the result is compared with the difference between these mean estimates obtained after adaptation (see column B-A). The second difference is smaller as a result of adaptation, and the difference between these differences, amounting to .43 cm, also measures the adaptation effect. In fact, we used this difference to compute the significance of the adaptation effect. Each subject's estimates were treated as were the mean estimates in Table 1. A score was obtained that consisted of the difference between the estimate differences computed from his pre- and postexposure estimates. The mean of these scores is listed in the third row of Table 1 in the column headed B-A and a corresponding mean is listed under C-A. For the B-A mean, $t(10)$ was 3.85, and for the C-A mean, it was 3.51. The difference between the B-A mean and the C-A mean failed to be significant. No such differences were found in the subsequent experiments.

EXPERIMENT 2

Procedure

Experiment 2 differed from Experiment 1 in two ways. The tests were not done with the anaglyph but with a real three-dimensional object, an exact reproduction in metal of the branch depicted in the anaglyph.¹ The particular pictorial disparity for which the depth estimates were given before was here a real depth interval of 1.1 cm. There was also a control condition where the real three-dimensional object replaced the anaglyph in the exposure period, and where no adaptation was expected to develop. Different subjects were used in the experimental and in the control condition, but the same selection criteria were used on both groups.

The same stereograms were used as in Experiment 1. Of the subjects who were to serve in the experimental condition, four failed the stereoscopic test and one was eliminated because his pre-exposure estimates differed by more than .3 cm. Because here a real depth interval was used in the test, selecting subjects for good constancy meant choosing those who gave similar depth estimates at different observation distances. Of the subjects who were to serve in the control condition, undergraduates of the University of Pennsylvania, seven failed the stereoscope test and another nine were eliminated because their preexposure depth estimates differed by more than .3 cm. Twelve subjects participated in the experimental condition and 12 participated in the control condition.

Results

Because a real three-dimensional object was used in the tests, estimates of the depth interval made from different distances should be nearly equal if stereoscopic depth constancy operates well. Partly because the subject selection eliminated those whose estimates at the two observation distances differed greatly, mean depth estimates before exposure, which are presented in the first row in Table 2, were hardly smaller at the large distances than at the small distance. The mean depth estimate obtained in the far position was 1.10 and at the near position, 1.18. The ratio of .93 denotes almost complete constancy.

Adaptation to the anaglyph condition causes the difference between the depth estimates obtained at different observation distances to be diminished, and this change manifested itself in Experiment 1 by depth estimates becoming smaller at the far distance. In the tests of Experiment 2, where a real object was used, the mean depth estimates at the two test dis-

Table 2
Mean Estimates of Real Depth Intervals (in Centimeters) at Two
Observation Distances Before and After Exposures to an Anaglyph
or to a Three-Dimensional Object With Subject Moving

	A	B	C	B-A	C-A
Exposure to Anaglyph ($N = 12$)					
Before	1.18	1.10	1.09	-.08	-.09
After	1.45	1.06	1.07	-.39	-.38
Difference				.31*	.29*
Exposure to Object ($N = 12$)					
Before	1.15	1.20	1.10	.05	-.05
After	1.22	1.21	1.22	-.01	.00
Difference				.06	-.05

Note— $A = \text{near}$, $B = \text{subject far}$, $C = \text{object far}$. * $p < .001$.

tances were nearly equal before the exposure, and the changes produced by adaptation should make them less equal. Comparing the first and second row of Table 2 shows that this is, indeed, what happened. The difference between the mean estimates obtained at the near and far distance was greater after exposure than before in both the B-A and the C-A column. The mean difference scores listed in the third row of Table 2 were highly significant, with $t(11)$ equal to 4.64 and 4.45, respectively. There was no corresponding change in the control experiment, and the differences between corresponding results in the experimental and in the control condition were highly significant [$t(22)=3.32$, $p < .01$, and $t(22)=4.89$, $p < .001$]. In the experimental condition, the ratio of the mean depth estimates at the two distances was .93 before exposure and .73 after exposure. Thus, adaptation had changed depth perception by more than 20%.

EXPERIMENT 3

Our last experiment was concerned with the question of whether movements by the subject were necessary or whether simultaneous changes of disparity and of observation distance were sufficient to bring about adaptation. Here the anaglyph was moved during exposure, and the subject remained immobile. While the subject's head was on the teeth mold, the experimenter caused the anaglyph to move toward and away from the subject at the rate of approximately 10 sec/cycle between the distances of 25 and 65 cm. Immobilizing the subject eliminated some of the distance cues, namely, those connected with the subject's forward and backward movement. But oculomotor cues for distance and perspective distance cues were still operating, and the experiment did provide an answer to the question of whether movements by the subject were essential in altering stereoscopic depth constancy.

The test setup of the previous experiments was used for the exposure as well as for the test, during which the subject was immobile also and sat straight. There were only two test conditions. In Test A, the real object was 30 cm from the subject's eyes; in Test B, that distance was 60 cm.

Undergraduates of the University of Pennsylvania served as subjects. Six failed the stereoscopic test, and five were eliminated because their preadaptation depth estimates differed by more than .3 cm. Fourteen subjects finished the experiment.

The results, presented in Table 3, show a change between the mean pre- and postexposure estimates that was analogous to the one obtained in Experiment 2. The mean of the difference scores between the pre- and postexposure estimate difference of .19 cm was significant [$t(13)=3.06$, $p < .01$]. This

Table 3
Mean Estimates of Real Depth Intervals (in Centimeters) at Two Observation Distances Before and After Exposure to Anaglyph With Subject Stationary

	A	B	B-A
Before	1.09	1.01	-.08
After	1.27	1.01	-.26
Difference			.18*

Note—A = object near, B = object far. * $p < .01$.

adaptation effect was smaller than the .29 cm effect that was obtained in Experiment 2 under corresponding conditions. This difference, which was not significant [$t(24)=1.25$], may have been due to the fact that fewer distance cues operated during exposure when the subject was immobile.

DISCUSSION

The experiments here reported were not the first in which the relation between retinal disparity and perceived depth was altered by adaptation. Wallach, Moore, and Davidson (1963) caused such changes by adapting subjects to telestereoscopes that altered the effective interocular distance. Enhanced binocular parallax increased the disparities with which the depth in a wire form was given and, with it, perceived depth. Adaptation partially compensated for this effect of the telestereoscope in such a way that diminished perceived depth resulted from given disparities. This adaptation required the presence of nonstereoscopic veridical depth cues. In most of the experiments, rotation provided the cues for veridical depth, with which the enhanced disparities caused by the telestereoscope were then in conflict. The immediate perceptual effect of this cue discrepancy was that the subject saw the wire form change shape as it rotated. This deformation gradually diminished as stereoscopic depth perception adapted. Thus, adaptation to the telestereoscope resulted from exposure to the discrepancy between different kinds of depth cues at a single observation distance, whereas, in our experiments, exposure to the anaglyph provided only stereoscopic depth cues and changing observation distances were essential.

This difference in the nature of the two adaptation processes is reflected in their results. In the experiments where adaptation resulted from exposure to a cue discrepancy, its effect compensated for the effect of the telestereoscopes. When adaptation was to a device that increased disparities, it resulted in diminished depth, and when the device diminished disparities, the effect of adaptation made perceived depth larger. In our experiments, adaptation made the *difference* between the depth perceived at the greater distance and the depth perceived at the shorter distance smaller, and this change in the depth difference

could manifest itself in a decrease in depth at the greater distance or in an increase in depth at the shorter distance. That is, in fact, what happened. In Experiment 1, the mean depth estimate decreased significantly at the greater distance [$t(10)=3.44$, $p < .01$], and in Experiment 2, mean depth increased significantly at the smaller distance [$t(11)=3.98$, $p < .01$].

In recent years, the term "constancy" has undergone a change in meaning. In addition to the original constancies of size and shape, the term has been applied also to the processes that aid in perceiving a stable environment when we move, the position constancies.² The reason for this usage is that all of these processes are compensatory. It seems, however, useful to distinguish between the position constancies and the original constancies. In the position constancies, the compensatory processes *prevent* those stimulations that are caused by our movements from developing into perceptions. In the original constancies, to which the more recently discovered stereoscopic depth constancy and the constancy of object orientation (Ebenholtz & Paap, 1973) must be added, the compensation process deals with stimulus variables that do lead to perceptions and involves their evaluation: Perceived size varies with image size, perceived depth with amount of disparity, and perceived shape with image shape. Here, the compensatory process influences how these perceptual variables are related to the pertinent conditions of stimulation; it corrects for the effect that extraneous conditions, such as distance and slant, have on the stimulus variables.³ Since these constancies protect the perceived variables from the effects of these extraneous conditions, they might be called invariance constancies. They cause perceptual variables to be veridical, whereas the position constancies achieve a specific state, immobility of the environment. Although adaptation has been obtained in two of the five known position constancies, the constancy of stereoscopic depth is the first invariance constancy that has been altered by adaptation.

It has been found that some adaptations to spectacles that distort shape take effect only when, through movements by the subject, the distortions are transformed into deformation (Wallach & Barton, 1975; Wallach & Flaherty, 1976). In addition, it has been found—and this is here important—that causing the deformation by external means does not suffice; they have to be produced by the subject's own movements. These findings suggested to Wallach and Flaherty that covariance between the deformations and the body movements initiates the adaptation process. They saw this as a sound principle of perceptual learning, because any change in sensory input that is covariant with the subject's movements is most likely caused by them and does not represent a genuine environmental event.

It seemed quite possible that the covariance principle plays a role also in the acquisition of the invariance constancies. Moving toward an object changes the size of its retinal image and the disparities with which its depth is given along with the cues for observation distance, and changing one's vantage point causes changes in the shape of the retinal images of a surface along with cues for its slant. If these concomitant changes constitute the conditions under which the invariance constancies are learned, covariance of the stimuli with the body movements that cause these changes may well be a factor. In that case, that covariance may also be a factor in adaptation. For this reason, we made our subjects move to bring about the distance changes during the exposures in Experiments 1 and 2, and we expected that the exposure conditions of Experiment 3, where subjects remained immobile, would not yield an adaptation. The fact that we did obtain adaptation in Experiment 3 shows that the concomitance of disparity changes with changing cues for observation distance is sufficient to alter stereoscopic depth constancy.

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NOTES

1. We are grateful to Mr. Harry Smith for making this accurate reproduction.
2. The following position constancies have so far been measured: the constancy of visual direction (Wallach & Kravitz, 1965), the constancy of auditory direction (Wallach & Kravitz, 1968), the

compensation for eye movements (Mack, 1970), the compensation for movement-produced changes in object orientation (Wallach, Stanton, & Becker, 1974), and the constancy of orientation of the visual field (Wallach & Bacon, 1976).

3. It has often been questioned whether shape perception takes slant into account or whether the conditions of stimulation have parallel effects on perceived slant and perceived shape. In an article by Wallach and Moore (1962), which is usually overlooked, strong evidence is presented that cues for slant are causally related to perceived shape.

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