The nature of adaptation in distance perception based on oculomotor cues*

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In previous work by the senior authors, brief adaptation to glasses that changed the accommodation and convergence with which objects were seen resulted in large alterations in size perception. Here, two further effects of such adaptation are reported: alterations in stereoscopic depth perception and a change when distance is represented by a response of S's arm. We believe that the three effects are manifestations of one primary effect, an alteration of the relation between accommodation and convergence on the one hand and the distance they represent in the nervous system (registered distance) on the other. This view was supported by the results of two experiments, each of which demonstrated that the alterations in stereoscopic depth perception could be obtained after adaptation periods which had provided no opportunity to use stereoscopic vision, and that the adaptation effect was larger for depth perception than for size perception when it was obtained under the same conditions; the latter finding was expected if both effects resulted from the same change in registered distance. In three of the five experiments here reported, the variety of cues that could represent veridical distance during the adaptation period was limited. In one condition of adaptation, only the pattern of growth of the retinal images of objects that S approached and the kinesthetic cues for S's locomotion served as cues to veridical distance. In two other conditions S remained immobile. In one of these, only the perspective distortion in the projection of the scene that S viewed mediated veridical distance, and in the other one familiar objects of normal size were successively illuminated in an otherwise totally dark field, conditions from which opportunities to use stereoscopic vision were again absent. After exposure to each of these adaptation conditions, adaptive changes in perceived size and larger ones in perceived stereoscopic depth were obtained. Because we found that familiar size may serve as the sole indicator of veridical distance in an adaptation process, we concluded that it can function as a perceptual as distinguished from an inferential cue to distance.

The experiments here reported answer two questions raised by previous work on adaptation in distance perception based on accommodation and convergence. Such adaptation was presumably demonstrated by Wallach and Frey (1972) by means of changes in size perception. Size estimates of abstract shapes served as tests for such changes, as did adjustments of the images of familiar objects to their true sizes, with either kind of test performed under conditions where accommodation and convergence were the only available cues for distance. Ss were given these tests before and after an adaptation period during which glasses were worn that caused an alteration of the accommodation and convergence with which objects were viewed. Adaptation to glasses that increased accommodation and convergence resulted in an increase in perceived size, and a decrease in these oculomotor adjustments during the adaptation period caused a size decrease later on. One of the issues yet to be dealt with concerns the interpretation given by Wallach and Frey to these changes in size perception. They assumed that the size changes were manifestations of changes in distance perception. The other issue is concerned with the conditions under which adaptation to such glasses can be obtained. The conditions employed by Wallach and Frey involved an active S, namely, his locomotion or his manipulation of objects. In the present work, in Experiments 4 and 5, an attempt was made to produce adaptation under conditions where S remained immobile during the adaptation period.

A. SIZE CHANGES AS MANIFESTATIONS OF CHANGES IN DISTANCE PERCEPTION

Wallach and Frey adapted Ss to eyeglasses that altered, in corresponding fashion, the accommodation and convergence with which objects were viewed. One pair of spectacles consisted of meniscus lenses that were at once prisms of 5 diopters placed with their bases in temporal position and spherical lenses of —1.5 diopters. The lens action forced the eyes to increase accommodation by 1.5 diopters at all viewing distances, and the effect of the prismatic lens component was to increase convergence by an equivalent amount. These spectacles thus caused oculomotor adjustments that corresponded to distances shorter than the true object distances by the equivalent of 1.5 lens diopters (near glasses). A second pair of spectacles (far glasses), forcing oculomotor change of the same amount but in opposite direction, were also used.[1]

The immediate effect of these glasses was to change the apparent size of the object seen through them. Under conditions where distance cues other than accommodation and convergence were largely absent, the near glasses made objects look smaller. This was due to the operation of Emmert's law, according to which the perceived size of an object is equivalent to the size of its retinal image times its registered distance. The latter is the representation of object distance in the nervous system, usually the result of the available distance cues. Since accommodation and convergence can serve as cues to distance of the viewed objects, a change in these oculomotor adjustments will have an effect on registered distance. The near glasses, for instance, caused an increase in accommodation and convergence, which meant, of course, a decrease in the distances these oculomotor adjustments implied. Hence, to the degree to which they depended on accommodation and convergence, the registered distances also decreased. This, in turn, caused perceived size to diminish.

Adaptation, consisting in a compensation for the error produced by the spectacles and causing perception to change back toward normal, would tend to do away with the loss in size that the near glasses initially produced. As long as the adaptation effect lasts, accommodation and convergence would cause larger apparent sizes than they would normally produce, and this is what Wallach and Frey found. After adaptation to the near glasses, estimates of object sizes were 50%-60% larger than before. The far glasses, by forcing the eyes to decrease accommodation by 1.5 lens diopters and to change convergence by an equivalent amount, caused oculomotor

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adjustments to correspond to distances that were larger than the object distance by the equivalent of 1.5 lens diopters. This, in turn, caused perceived sizes to increase. Adaptation to the far glasses, then, consisted in a decrease of perceived size.

Two interpretations of such effects of adaptation on perceived size are possible. Wallach and Frey believed that, in essence, adaptation consisted in an altered relation between oculomotor adjustments and registered distance. While normally a particular oculomotor adjustment, serving as cue to distance, produced one value of registered distance, after adaptation it produced another value, resulting in turn in an alteration of perceived size. This interpretation is an analogue to the manner in which the glasses affect perceived size when they are initially worn, that is, through the operation of Emmert's law. The other interpretation assumes a direct compensation for the error in size perception produced by the glasses. When, e.g., the near glasses are first worn, perceived sizes are abnormally small. Adaptation, in tending to reestablish veridical perception, causes a compensating change in size perception: perceived sizes become more veridical as the glasses are worn, that is, larger than normal; this is the effect measured by Wallach and Frey.

We resolved this issue by obtaining evidence in favor of the interpretation by Wallach and Frey. If the change in registered distance they postulated could be shown to have manifestations other than in size perception, it would be established as the primary result of adaptation, and this we were able to do. The two further manifestations of changes in registered distance we demonstrated were (1) adaptation in stereoscopic depth perception and (2) an effect of adaptation on the representations of distances by a body movement.

EXPERIMENT 1
SIMULTANEOUS ADAPTATION IN SIZE AND STEREOSCOPIC DEPTH PERCEPTION

There is a striking analogy between stereoscopic depth perception and size perception. Just as the size of the retinal image varies with the distance of the object that causes it, so retinal disparity, the condition of stimulation that produces perceived stereoscopic depth, depends on the distance from the eyes of the depth interval that causes the disparity. There is one difference: the size of the retinal image is inversely proportional to the first power of object distance, while the amount of disparity caused is inversely proportional to the square of the distance of the depth interval from the eyes.[2] Just as in the case of size, perception compensates for the decrease in retinal disparity with viewing distance: Perceived depth is roughly equivalent to the given retinal disparity times the viewing distance squared. Wallach and Zuckerman (1963) have demonstrated this in a number of ways and have shown that, just as in size perception, different kinds of cues for distance may represent the objective distance of the depth interval. They thus established the existence of a constancy of stereoscopic depth that corresponds to the constancy of size and is probably based on the same information about distance as is size constancy. To be sure, compensation for the decrease in retinal disparity with increasing distance of the corresponding depth interval is by no means as accurate as the compensation for the decrease in image size with increasing object distance that causes size constancy, and individual differences are large.[3] But there can be no doubt that compensation for the decrease in disparity is much larger than merely proportional to the first power of distance, and this fact has several easily observed consequences. One occurs in connection with displays, such as three-dimensional motion pictures that present the viewer with a left-eye picture and a right-eye picture of a three-dimensional scene. Here, apparent depth increases with the viewer's distance from the display.[4] Similarly, in demonstrations of the Pulfrich effect by means of depth perception, the apparent depth observed increases with increased distance of S from the display.[5] Finally, anyone who observes a loss in depth when viewing a scene through binoculars is witness to the fact that compensation for loss of disparity with increase in distance is greater than proportional.[6]

If adaptation to our glasses produces a change in size perception because it alters the relation between accommodation and convergency on the one hand and registered distance on the other, it may also have an effect on stereoscopic depth perception. But in that case, the effect of our adaptation on depth perception should be larger than its effect on size perception. This is so because, according to Emmert's law, perceived size depends on the first power of registered distance, whereas, according to the rule stated above (Zuckerman's law), perceived depth should be equivalent to the square of objective distance as represented by distance cues. Unlike the increase in perceived size due to adaptation to the near glasses, which is proportional to the increase in registered distance that results from its changed relation to accommodation and convergence, perceived depth should increase by an amount in keeping with Zuckerman's law. This means that adaptation to our glasses should produce a larger effect on perceived stereoscopic depth than on size. Such a result would favor the interpretation of Wallach and Frey that adaptation to our glasses consists in the first place in an alteration of registered distance. Registered distance, in turn, would affect both perceived size and depth.

PROCEDURE

We demonstrated an effect of adaptation to near glasses on depth perception that was larger than the corresponding effect on size perception by obtaining size and depth estimates before and after the same adaptation period. As in the size estimation test used by Wallach and Frey, Ss gave size and depth estimates using the sense of touch only and under conditions where only accommodation and convergence operated as distance cues. Test objects were two regular four-sided wire pyramids, their bases placed in S's frontal parallel plane and their apexes pointing away from S. Size estimates were given by reproducing the length of one of the diagonals of the base with one of a series of small brass rods which S could select and whose length could be adjusted by him, and depth estimates were made by reproducing in the same manner the apparent distance between base and apex. Pyramids were presented at only two distances from S, one of the reasons being that in the present experiments two estimates were given for every test object, one of size and the other of depth. The two distances were 33.3 and 66.7 cm. They were chosen because they fell, in terms of the diopter scale, in the middle, between the 25- and 50-cm distances and the 50- and 100-cm distances, respectively, which had been used by Wallach and Frey, and because the difference between the 33.3-cm and the 66.7-cm distance was equivalent to 1.5 lens diopters. Inasmuch as, according to our hypothesis, complete adaptation would involve a change in registered distance amounting to 1.5 diopters, preadaptation estimates made at a 66.7-cm distance could serve as norms for the effects of complete adaptation on a test object at 33.3 cm distance. This was possible because the size of the bases of our pyramids were so chosen that they produced equal retinal images, although they were placed at different distances from S. Also, the distances between apex and base of the two pyramids were such that they produced equal retinal disparities. To achieve this, the pyramid that was twice as far from S had to be four times as deep as the nearer pyramid. Then, if complete adaptation to the near glasses were achieved, with accommodation and convergence evaluated by the nervous system as 1.5 diopters less than normal, the perceived size and depth of the pyramid at 33.3 cm should be the same as the size and depth measured prior to adaptation for our properly transposed pyramid at 66.7 cm distance.

Specifically, the diagonals of the square pyramid bases measured 5.5 and 11.0 cm, and the distances between apex and base amounted to 2.5 and 10 cm, respectively. The diagonals of the bases, which, incidentally, were in the diamond position, were represented by thin wires. This was done because Wallach and Frey had found that the presence in test objects of thin lines improved size perception when only accommodation and convergence served as cues for distance. The thickness of the wires of which the pyramids were made was also properly transposed. These wires were 1/16 and 1/8 in. in diam, and the thickness of the diagonal wires was .3 and .6 mm, respectively.

The pyramids were placed inside wooden lightboxes whose black front panels measured 18 x 18 in. A diamond-shaped aperture was cut in the center of each panel and framed the pyramid's base, which was centered in the aperture and whose sides were parallel to its edges. These apertures measured 2.5 and 5 in. square, respectively. Beyond the apex inside each box was a translucent white plastic sheet that evenly diffused the dim light of four 7.5-W bulbs lit by a 40-V current and located in the rear of the box. Against this bright background, the wires comprising the pyramid appeared clearly outlined. The purpose of the box was to prevent the light needed to make the pyramid visible from illuminating the rest of S's field of vision. Black cloth drapes were used to block excess light escaping from the apertures. The boxes weryplaced one behind the other on a platform that brought the apertures to the level of the eyes of S who was seated before them on an adjustable chair. The box with the nearer pyramid was hinged to the platform. By tilting it out of the way, E could expose the distant pyramid to S's view. A biteboard was used to keep S's head in a fixed position at the proper height and proper distance from the pyramids. Built into its mounting was a microswitch which operated the light bulbs in both boxes. By lightly pressing the biteboard forward with his teeth, S could turn on the box lights and make the exposed pyramid visible. Ss thus made their estimates from a constant position and never saw a pyramid while moving their heads. The order in which the two pyramids were exposed for testing varied from S to S, but was the same in the postadaptation test as before the adaptation period. Both the size and the depth estimates, always in that order, were given for one pyramid before the other pyramid was presented.

Since Wallach and Frey had already demonstrated that adaptation could be obtained in opposite directions using near as well as far glasses, and since, with the shorter test distances that were also employed in the present work, the near glasses had produced stronger adaptation effects, only the near glasses were used in the first four experiments here reported. In all experiments the adaptation period lasted 20 min. In Experiment 1, E led S on a walk through a college building—the halls, lecture rooms, laboratories, a library, and up and down stairs. On the way, S saw many familiar objects, watched people approach and recede from view, and was exposed to scenes providing good perspective cues for depth.

Sixteen Ss, paid undergraduates, completed Experiment 1. They were selected for good size perception based on accommodation and convergence and for good stereoscopic depth perception. The following selection criteria were applied: When Ss were tested without glasses, the size estimate given for the 66.6-cm-distant pyramid had to be at least 1.4 times as great as that for the nearer pyramid, and the corresponding ratio of depth estimates had to be at least 1.7. A total of 29 Ss had to be tested to yield the 16 experimental Ss.

Results

The means of the preadaptation estimates for size and depth are given in the columns headed "Experiment 1" of Table 1 in Row 3, and the mean estimates after the adaptation period, in Row 4. The differences between corresponding mean estimates, which measure the adaptation effects, are found in Row 5, and the proportional size and depth increases after adaptation, in Row 6. All mean postadaptation estimates were changed in the direction of the expected adaptation effect: both mean size estimates and both mean depth estimates were larger after the adaptation period than before. Moreover, there was not one individual pair of estimates by any S that did not change in this direction. At both test distances, the increases in the depth estimates were considerably higher than the increases in the size estimates. The differences between these increments were highly significant; for the test distance at 33.3 cm, the depth increase was larger than the size increase for all Ss except one, and for the 66.7-cm distance 14 out of 16 Ss gave this result. That the effects of adaptation on perceived size and depth differed in amount showed the effect on depth to be independent of the effect on size, and the fact that the effect on depth was larger supported the hypothesis that both resulted from a change on registered distance.

To be sure, the effect on depth is not as much larger as the difference between Emmert's law and Zuckerman's law would predict. The depth increases amounted to 103% and 101%, while, theoretically, based on the size increases actually obtained, they could be expected to be 134% and 186%. This discrepancy is, however, easily explained. A comparison of our preadaptation estimates for size and depth shows that stereoscopic depth constancy does not hold as well as size constancy under the conditions of our test. Whereas the ratio of the objective sizes of the pyramid bases at the two test distances amounted to 2.0, the corresponding ratio of the mean size estimates was 1.7 (while the ratio of the retinal image sizes was 1.0). The ratio of the actual depth of the two pyramids, on the other hand, was 4.0 and the corresponding ratio of the mean depth estimates amounted to 2.32 (with the ratio of retinal disparities 1.0). Made comparable to the ratio of size estimates of 1.7 by taking the square root, the ratio of depth estimates amounted to 1.52 only.

EXPERIMENT 2
ADAPTATION UNDER CONDITIONS THAT DO NOT PRODUCE RETINAL DISPARITY

There is still another way in which one can show that the effects of adaptation on size and depth perception are due to a changed relation of registered distance to accommodation and convergence: by eliminating stereoscopic depth perception entirely from the adaptation period. If postadaptation depth estimates are again higher than before adaptation, this cannot be ascribed to adaptation of stereoscopic vision itself. It rather must be the result of a change of an antecedent of perceived depth, i.e., of registered distance.

We created conditions of adaptation that were free of disparity-producing depth intervals, having S walk back andforth between two flat luminous surfaces, located at either end of a darkened room and the only objects visible to him. One of the surfaces was the screen of a TV set adjusted to a low brightness, and the other the translucent surface of a lightbox that was covered with ¼-in. wire screening. S's glasses were equipped with blinders that prevented him from seeing the dim reflections of the two bright objects from floor and ceiling. Under these conditions, the only possible information about distance besides that supplied by accommodation and convergence, derived from the growth of the retinal images of the luminous surfaces during S's appraoch and from Ss' walking toward these objects.

There are several ways in which such information may be effective in causing adaptation. (1) Kinesthetic information about walking cannot serve as cues for distance, but it can mediate distance change. Because accommodation and convergence are inversely proportional to distance, there is, when the glasses are worn, an alteration in the relation between these oculomotor adjustments and distance change provided by kinesthetic information. Normally, for instance, a change in oculomotor adjustment from an equivalent of 1.5 lens diopters to one of 2.5 lens diopters corresponds to a distance change from 66.7 to 40 cm and would be produced by a small step forward. When the near glasses are worn, however, about the same change in the oculomotor adjustments is produced when S walks from the far end of the room to within 1 m of the TV set.[7] (2) In conjunction with information about distance change, image size change may serve as a distance cue. Because the size of its image is inversely proportional to the distance of the object from S, the rate of image growth varies with the distance at which a certain change in distance is made. The larger the distance of the object from S, the smaller will be the change in image size that one step taken toward the object will produce. (3) Finally, there is, when the glasses are worn, an alteration in the normal association between the changes in image size and oculomotor adjustments. With both, image size changes and oculomotor adjustments, in an inverse relationship to distance, such an alteration should produce a striking discrepancy.

During S's 20-min walk back and forth between the TV set and the light box, he was entertained by the TV broadcast. The pre- and postadaptation tests were identical with the tests in Experiment 1; 16 Ss, of whom 14 had participated in Experiment 1, took part.

The results are presented in Table 1 under the heading "Experiment 2." Here, the mean changes in size and depth estimates were only half as large as those we obtained in Experiment 1. This is not surprising given the comparative paucity of veridical distance cues that were available during the adaptation period. Nevertheless, there was a highly significant increase in the depth estimates due to adaptation. At both test distances, every S gave a larger depth estimate after adaptation than in the preadaptation test. This is the answer to the main issue of this experiment. It happened although no practice of stereoscopic depth perception was possible during the adaptation period. Again, mean increases in depth estimates were greater than the mean changes in size, and these differences were, proportionally, equal to or larger than those obtained in Experiment 1. (They were also significant, with $p < .005$ for the pyramid at 33.3 cm and $p < .02$ for the 66.7 cm distance.)

EXPERIMENT 3
ADAPTATION MEASURED BY A MOVEMENT RESPONSE

Up to this point, adaptation to glasses that alter oculomotor adjustments had been demonstrated only by effects on size and depth perception. When these effects had been shown to be indirect, mediated by alterations of registered distance, an attempt to demonstrate an effect of our adaptation on visual *distance* seemed appropriate. Because experienced distances of objects often do not only seem to depend on the given cues for distance, but also on the objects' perceived sizes, no test consisting in distance estimation appeared likely to succeed. We therefore used a bodily response to express the distance at which a target appeared to be located.

The target was a vertical black wire, .6 mm thick. It was made visible by a dimly luminous area, 30 cm high and 1 cm wide, just behind it. Otherwise, the room was completely dark. The wire was located 33.3 cm from S's eyes and in his median plane, with S's head kept in position by a head- and chinrest. S's task was to make the index finger of his right hand point to the left and, by moving it to the apparent distance of the wire, make it point at the wire from the side. Then S was to move the finger leftward toward the wire. A vertical board, parallel to S's median plane and 3 in. to the right of the wire prevented S's finger from actually reaching the wire. S, who could see neither his hand nor the board, was instructed to point at the wire from the side and to move his hand toward it until his finger made contact with the board and to keep it there until E had marked its position. For each S a fresh piece of paper was clipped to the board on which to make these marks.

Ss made three such depth pointings before and three after the 20-min-long adaptation period. Unlike the tests in all our other experiments, this one was made with S wearing the glasses. That is ordinarily the preferred procedure. The reasons our other tests were made without glasses were set forth by Wallach and Frey. The conditions of adaptation were the same as in Experiment 1. Care was taken that S keep his hands in his trouser pockets or on his back throughout the adaptation period. This was done to prevent S from seeing his hands move while he wore the glasses and from perhaps developing an adaptation of motor processes related to the arm that was later employed in pointing. Twenty-five selected Ss participated,[8] all except two of whom were new to our adaptation experiments.

Results

The mean distances to which Ss were pointing before the adaptation period amounted to 27.6 cm. This was significantly larger than the distance for which S's eyes were actually accommodated and converged behind the glasses, which amounted to 22.2 cm.[9] The preadaptation pointings made by individual Ss varied only moderately; the mean difference between the shortest and largest among the three individual pointing distances was only 1.96 cm. The variability among Ss of the preadaptation pointing distances was larger; its standard deviation amounted to 3.67.

The pointing distances after adaptation had a mean of 38.9 cm. For every one of our 25 Ss all his postadaptation pointing distances were larger than any of his preadaptation pointing distances. The mean proportional increase in pointing distance amounted to 40.9%.[10] It may be compared with a result obtained at a similar test distance by Wallach and Frey. They found after an adaptation period of similar length, that is, 15 min as against our 20 min, a size increase of 41.8% for a test object at 25 cm distance. This test distance was nearly the same as the distance of 22.2 cm for which, behind the glasses, the eyes of our Ss were adjusted. Since, according to Emmert's law, changes in perceived size are proportional to changes in registered distance, our proportional increase in pointing distance should be comparable to proportional size increases. The obtained values, 40.9% by us and 41.8% by Wallach and Frey are in good agreement.

Table 1
Mean Size and Depth Estimates (20 Min Adaptation)

			Experiment 1 (N = 16)		Experiment 2 (N = 16)		Experiment 4 (N = 20)	
1	Test distance		33.3 cm	66.7 cm	33.3 cm	66.7 cm	33.3 cm	66.7 cm
2	Objective size and depth of pyramids (in cm)	S	5.5	11.0	5.5	11.0	5.5	11.0
		D	2.5	10.0	2.5	10.0	2.5	10.0
3	Preadaptation size and depth estimates (in cm)	S	6.29	10.72	6.82	11.58	6.40	10.03
		D	5.03	11.69	6.02	12.71	5.46	11.00
4	Postadaptation size and depth estimates (in cm)	S	9.61	17.72	8.62	14.52	7.51	11.44
		D	9.93	23.16	9.10	18.10	7.10	14.49
5	Difference between pre- and postadaptation estimates (in cm)	S	3.32	7.00	1.80	2.94	1.11	1.41
		D	4.90	11.47	3.08	5.39	1.64	3.49
6	Adaptation effect as increase in size and depth	S	53.35%	68.59%	27.17%	25.44%	17.84%	14.76%
		D	102.88%	100.79%	52.89%	43.95%	32.22%	31.19%

Since Ss neither moved their arms nor saw them during the adaptation period, we conclude that the increase in pointing distance after the adaptation period was not the result of an adaptation in kinesthesis but a change in visual distance. The apparent agreement between this change in pointing distance and the distance change implied in the increase in size estimates of an object at a similar test distance would support the view that the change in pointing distance was also a manifestation of registered distance.

B. ADAPTATION IN AN IMMOBILE SUBJECT

EXPERIMENT 4

Experiment 2 was one of a series in which we tried to restrict the variety of cues that represented veridical distance during the adaptation period. In that experiment, all of the cues that may have been responsible for the achieved adaptation were produced by S's locomotion, namely, growth of image size with approach of the object and kinesthetic information about his locomotion. S's visual field was not structured in the depth dimension at all. In Experiment 4, we restricted the conditions of stimulation to the distance and depth cues available to an immobile S. We also excluded from his field familiar objects and those that occurred only in standard sizes. The tests were identical with those used in Experiments 1 and 2.

Procedure

S sat on a high stool at the narrow end of a 5 x 2½ ft table, his head held in position by a chin- and headrest. He looked down on the table top which was covered with an oil cloth. Its checkerboard pattern yielded excellent cues for perspective depth. Scattered over the table surface were 10 black wooden blocks, all representing solids of different geometrical shape. The retinal images of these blocks, by being distributed over the retinal projection of the table top, served as further cues for perspective depth. The scene on the table was well illuminated. The remainder of the room was blocked from S's view by a tall screen of white cloth which surrounded S and the table.

During the adaptation period, which lasted 20 min, E gave S tasks to perform that, in effect, caused him to make a series of eye movements and frequently to refocus his eye for different distances. For instance, S received the instruction: shift your eye from a near to a far object and back; count the number of edges on the tetrahedron; invent a maze, of such and such specifications, among the objects; count the number of squares on the tablecloth between two objects, etc.

Twenty Ss participated, of whom nine had taken part in one or more of our previous experiments. The results of the latter did not differ significantly from those of the new Ss. The selection criteria had been relaxed for the present experiment, stipulating only that the size estimate prior to adaptation for the more distant pyramid had to be at least 1.4 times as large as that for the near pyramid.

Results

As shown in Table 1 under Experiment 4, the mean adaptation effects here obtained were small. They were, however, highly significant. With each of 20 Ss giving four pairs of pre- and postadaptation size or depth estimates, there were only four cases of an individual pair not changing like the mean, three where the postadaptation size estimate was smaller instead of larger than the corresponding preadaptation estimate, and one where a depth estimate changed in the wrong direction. As in our previous experiments, the difference between the mean size increase and the mean depth increase due to adaptation was significant in the case of each pyramid, for the smaller pyramid at the .05 level of confidence and for the larger one at the .005 level.

In spite of the restrictions on depth cues, these are respectable adaptation effects. With the mean size increase for the smaller pyramid near 18% and the mean depth increases amounting to 32%, which means 31% and 30% of complete adaptation, respectively,[11] the effects are as large as any that have been obtained with brief adaptation periods in other kinds of adaptation. As far as we can see, only the perspective deformations in the retinal projection of the table scene and retinal disparities operated here as spatial cues. Whereas perspective distortions in the projection of the scene on the table top can serve as cues to veridical distances (Gibson, 1950, p. 176), we do not believe that retinal disparity alone could. In the first place, retinal disparity gives rise only to perceived depth between objects and is not a cue for distance from S. Neither is it by itself a veridical cue to depth, since the distance from S of the depth interval causing a disparity is needed in its evaluation (Zuckerman's law). With convergence and accommodation altered by the glasses, only perspective cues were thus available to represent these distances veridically.

EXPERIMENT 5

Our last experiment employed the

familiar size of objects that only occur in standard sizes as the veridical distance cue. Such use of familiar size derives from the equivalence between perceived size, on the one hand, and the product of size of the retinal image times registered distance, on the other (Emmert's law). If familiar size, which is a given, is substituted for perceived size, and with image size given also because it is physically dependent on object size and objective distance, registered distance becomes determined and may function like a distance cue. Although the way in which familiar size is ultimately related to distance perception is still under investigation, we were encouraged in using objects of familiar size to represent veridical distance by the success which Wallach and Frey had measuring registered distance with the normal size adjustment test. In this test, the size of images of familiar objects was varied until they appeared normal; in short, with familiar size again a given, retinal image size was here the variable that was dependent on registered distance.

Previous work on adaptation to our glasses had left open the question whether an adaptation produced with one range of oculomotor adjustments would transfer fully to another range. We therefore saw to it that as much as possible the oculomotor adjustments caused by looking at the two test pyramids would also occur during the adaptation period, and this involved taking into account the effect of the glasses on accommodation and convergence. We therefore presented during the adaptation period familiar objects that occur in only one standard size at three properly chosen distances. In a completely dark room, they were put under illumination in alternation, in order to eliminate retinal disparities to which simultaneous presentation would have given rise. Whereas in Experiments 1-4 adaptation was only to the near glasses, in the present experiment two groups of Ss were used, one adapting to the near glasses and the other to the far glasses. The latter, by causing accommodation and convergence to diminish, produce larger equivalent distances. By compensating for this, adaptation would cause a change in the relation between oculomotor adjustments and the distances they represent in the nervous system such that smaller than normal registered distances now correspond to accommodation and convergence of particular amounts. This, in turn, should cause smaller perceived size and depth.

Procedure

The following objects were used during adaptation: a black card on which a 1 cent and a 5 cent stamp and a gum wrapper were mounted, a dollar bill, and a telephone receiver painted white. Three small spotlights, each consisting of a 5-W bulb mounted on the end of a 63-cm-long cylindrical tube, 8.5 cm in diam, were used to illuminate these objects obliquely from the right front. Each was aimed at one object, with the excess light hitting a black cloth curtain on the wall to the left. A screen in frontal position to the left of the displays hid what little light was reflected by the black curtain from S's view. The supports for the three objects were concealed so that they appeared to float in space when illuminated. A switch under E's control operated the three spotlights, one at a time. During the adaptation period, which again lasted 20 min, E illuminated an object for a minute or two and then switched to another one in random order. S's head was held in fixed position by a chin- and headrest. S was asked to look at each object as soon as it appeared, but he was not instructed to fixate it. Inasmuch as the illuminated object was the only thing visible, we counted on S's gaze being on it most of the time. When adaptation was to the near glasses, the card with the stamps, etc., was at a distance of 33.3 cm from S, the dollar bill at 66.7 cm, and the receiver at 133.3 cm. With the changes in accommodation and convergence caused by the near glasses, the equivalent distances, that is, the distances for which the eyes behind the glasses were adjusted, were 22.2, 33.3, and 44.4 cm, respectively. In the case of the far glasses, the distances to which the eyes behind the spectacles were adjusted were larger than the actual object distances. We therefore placed the familiar objects nearer to S than they were during adaptation to the near glasses. They were now 25, 33.3, and 50 cm distant. This made the equivalent distances 40, 66.7, and 200 cm. The tests for adaptation were the same as in Experiments 1, 2, and 4, and the criterion for the selection of Ss was the one used in Experiment 4. Twenty Ss participated in the adaptation to the near glasses and 16 Ss to the far glasses.

Results

The mean adaptation effects, presented in Table 2, show the same pattern as the results of Experiments 1, 2, and 4. Although the effects were smaller than those for our first two experiments, they were still highly significant. In the case of the near glasses there was among 80 individual pairs of pre- and postadaptation estimates only one where any estimate was not larger after the adaptation period, and for the far glasses there was also one individual case that failed to show the expected effect of adaptation, namely, a smaller estimate after the adaptation period than before. In the case of both glasses and for both test distances, the mean adaptation effects on depth were proportionately larger than that on size and all four differences were significant, as the values for p listed on Line 7 of Table 2 show.[12]

The results of this experiment are valuable in several respects:

(1) Consistent adaptation effects were obtained with Ss inactive, thereby confirming the results of Experiment 4.

(2) As in Experiment 2, changes in

Table 2
Experiment 5: Mean Size and Depth Estimates (20 Min Adaptation)

			Near Glasses (N = 20)		Far Glasses (N = 16)	
1	Test distance		33.3 cm	66.7 cm	33.3 cm	66.7 cm
2	Objective size and depth of pyramids (in cm)	S	5.5	11.0	5.5	11.0
		D	2.5	10.0	2.5	10.0
3	Preadaptation size and depth estimates (in cm)	S	6.01	9.73	6.66	10.85
		D	5.21	10.96	6.07	12.54
4	Postadaptation size and depth estimates (in cm)	S	6.91	11.72	5.87	9.41
		D	6.55	14.10	4.91	9.74
5	Difference between pre- and postadaptation estimates (in cm)	S	0.90	1.99	−0.79	−1.44
		D	1.34	3.14	−1.16	−2.80
6	Adaptation effect as change in size and depth	S	16.24%	20.75%	14.52%	16.31%
		D	26.87%	28.94%	24.51%	28.18%
7	Significance of difference between effects on size and depth		$p < .005$	$p < .01$	$p < .01$	$p < .005$

stereoscopic depth estimates were produced without any practice of depth perception during the adaptation period. With any depth lacking in two of the visible objects and with the third, the receiver, being a round object free of edges and lines at different depth, no retinal disparities occurred while the glasses were worn. Again, the adaptation in depth perception could only have been the result of changes in distance perception, that is, a recalibration in the relation between oculomotor adjustment and registered distance.

(3) This is the only experiment where we used both kinds of glasses and therefore obtained adaptation effects in both directions, decrease in size and depth as well as increase. Some alternative interpretations of our results were thereby eliminated, such as satiation or fatigue, which can be considered only when changes take place in only one direction. Since Experiment 5 confirmed the two main results of the present work, namely, proof that our adaptation effects operated via registered distance and that they could be brought about with S inactive, to have obtained here adaptation effects in opposite directions was particularly appropriate.

(4) Because familiar size was the only indicator of veridical distance available in the adaptation period and did produce an adaptation effect, we can assume that it functions as a perceptual cue to distance. This is interesting in view of the work of Gogel (1969) which leads him to conclude that judgments of distance are derived from the image sizes of familiar objects by an inferential process.

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NOTES

1. For a more detailed description of the effects of the two pairs of glasses, see Wallach and Frey (1972).

2. Geometrical proof for these relations may be found in Stevens (1951) p. 888, an explanation in Wallach and Zuckerman (1963).

3. The relation between the perceived depth that results from disparity and the distance of the corresponding depth interval from the eyes was discussed by Foley (1967a), who also referred to previous work concerned with this relation. It seems possible that the differences between Foley's results (see also Foley, 1967b) and those obtained by Wallach and Zuckerman are related to the amount of disparity employed, small disparities by Wallach and Zuckerman and larger ones by Foley.

4. Whereas perceived depth is larger than proportional to registered distance, disparity in such stereoscopic displays is inversely proportional to the first power only of S's distance from the display. Compensation for distance is therefore in excess of disparity loss with distance. Hence perceived depth increases with increased distance from the display, ideally in proportion to distance but actually somewhat less.

5. When a pendulum, moving in a frontal plane of S, is binocularly observed and a filter dark enough to delay neural transmission is placed over one eye, the pendulum bob appears to move on an elliptical path. With other conditions remaining the same, the apparent depth of the path will increase with increased distance of S from the pendulum. The explanation is similar to that for the analogous effect observed with stereoscopic displays (Note 4).

6. For an explanation in terms of the constancy of stereoscopic depth of this effect of binocular optical magnification, see Wallach and Zuckerman (1963).

7. To be exact, the near glasses cause the eyes to view an object at infinity with an oculomotor adjustment corresponding to 1.5 lens diopters and an object 1 m away with one of 2.5 lens diopters.

8. Ss for this experiment were selected on the basis of a normal size adjustment test (see Wallach and Frey, 1972). Ss whose settings were larger than 150% of normal size were eliminated.

9. Normally, the oculomotor adjustments to an object distance of 33.3 cm correspond to 3 lens diopters. With the glasses causing an increase by 1.5 diopters, the eyes behind the glasses are adjusted for a distance of 22.2 cm, corresponding to 4.5 lens diopters.

10. It is interesting that adaptation as such did not result in a larger variability in the individual postadaptation pointing distances. With the mean postadaptation pointing distance larger by 40%, one would, in the normal course, expect a corresponding increase in its standard deviation. That is what we found: it rose from 3.67 for the preadaptation scores to 5.09, an increase of 39%. But adaptation did not cause an independent increase in variability.

11. The mean preadaptation estimates for the pyramid at 66.7 cm distance represent the expected mean postadaptation estimates for the nearer pyramid under the assumption of complete adaptation, because a distance of 66.7 cm is 1.5 lens diopters less than the distance of the nearer pyramid, and the image sizes and disparities produced by the two pyramids are the same. With the mean preadaptation estimates for the nearer pyramid representing zero adaptation and the mean preadaptation estimates for the distant pyramid 100% adaptation, the mean postadaptation estimates for the nearer pyramid represent 31% for size and 30% for depth of complete adaptation.

12. In the case of the far glasses, the proportional adaptation effects were computed as ratios of the preadaptation over the postadaptation estimates.

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