Adaptation to optically produced curvature of frontal planes

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A new kind of adaptation was discovered, namely, to glasses that cause frontal planes to appear concave. The effect of this adaptation can be observed without the glasses as an apparent convexity of a frontal plane. We measured this effect by bending a frontal plane into a concave surface that compensated for this convexity. To obtain rapid adaptation, the subject must nod his head during the exposure period so that the concavity is seen to shift through a frontal pattern. Causing the same shift by moving the pattern up and down instead of the subject's moving his head does not produce such an adaptation. Head movements are, however, not necessary for the adaptation effect to become manifest.

When wedge prisms are worn that displace the line of sight laterally in opposite directions, a stereoscopic effect is produced that can be seen as a deformation of frontal planes. This stereoscopic effect is due to a shape distortion caused by wedge prisms, which makes straight lines that are parallel to the prism base reach the eyes with a slight curvature. When the bases of the prisms are vertical and on opposite sides, e.g., both toward the temples, retinal disparities are produced that are best described by their effect on a vertical line. With the prism base temporal, the line seen by the left eye is slightly curved with the concave side to the right and by the right eye with opposite curvature. This disparity causes the line to appear curved in depth, with the hollow side toward the subject. Similarly, a pattern in a frontal plane will appear curved in depth, like a piece of a large cylindrical surface with horizontal axis seen from the inside. Our experiments are concerned with this effect and related effects of the glasses.

As stated, such a pair of prisms changes the lines of sight of the two eyes in opposite directions. They thereby alter the convergence with which objects are viewed. We used a 10-diopter prism in front of each eye. With their bases in temporal position, they forced the eyes to increase convergence by an amount equivalent to an increase in accommodation of 3 lens diopters. To bring accommodation and convergence into agreement, we caused an increase in accommodation by adding a concave lens of -3 diopters to each prism.¹ These combination lenses had a diameter of 4.9 cm and were fitted into the

frames of ordinary welder's goggles.

When one wears these glasses for $\frac{1}{2}$ h and, after they are removed, looks at a patterned frontal plane, the plane appears to be convex. This convexity results from an adaptation to the glasses, amounting to a partial compensation for the stereoscopic effects that the glasses produce. As mentioned, one of the results of the stereoscopic effect of the glasses is the hollowing of a plane frontal surface. Complete compensation for the stereoscopic effect of these glasses would cause a plane frontal surface seen through the glasses to appear flat again. In the case of partial adaptation, the apparent concavity of a plane frontal surface should be diminished. In both cases, a plane frontal surface should appear to be convex when the glasses are taken off. We investigated the compensation for the effect of the glasses as it manifested itself in the perceived shape of a plane frontal surface seen without the glasses. To measure this compensation, we determined the objective hollow curvature of a frontal surface that, with the compensation operating, appears to be plané.² For this purpose, we used a flexible sheet with a dot pattern which was so mounted that its curvature could be adjusted by the subject.

Wedge prisms cause a further shape distortion: With the prisms placed with base temporal, distances between evenly spaced horizontally aligned points appear smaller seen through the base part of the prism and larger where the line of sight passes near the apex. The disparities produced by this shape distortion cause a concave curvature with a vertical axis. However, this effect does not occur as readily as the first one. We eliminated it from our experiment by covering each temporal third of our glasses with a

This work was supported by Grant 25,000X from the National Science Foundation to Swarthmore College, Hans Wallach, principal investigator.

vertical strip, so that only the central third of the field in front was seen binocularly.

A convexity that is perceived on a plane surface following exposure to the glasses could also be the result of a figural aftereffect. Köhler and Emery (1947) demonstrated a figural aftereffect in the depth dimension that caused a pattern of straight vertical lines to appear to bulge after a point on a hollow surface showing a similar pattern had been fixated for some minutes. Our first experiment had, therefore, a twofold purpose, to measure the compensation for the glasses and, if possible, to isolate the contribution that figural aftereffects make here. We therefore employed two adaptation conditions, one that was likely to yield a measurement of compensation free of a figural aftereffect and another in which a figural aftereffect might develop also. The latter required that the subject face a plane patterned surface that, seen through the glasses, would look concave, and such an arrangement seemed to be suitable also for the other condition. Because the kind of stereoscopic effect caused by our glasses most reliably develops in a dot pattern, we placed the subject, during the adaptation period, in front of a light wall covered with an irregular pattern of black dots of 1.75 cm diam and spaced at an average distance of 10 cm. The two adaptation conditions differed only in one respect. In one, the subject nodded his head up and down. This made the deformation caused by the glasses move up and down also, so that the concavity shifted through the dot pattern in conjunction with the head movement. We expected that any effect measured after exposure to this condition would be free of figural aftereffects. In the other condition, the subject's head was fitted into a headrest and was stationary throughout the adaptation period. Here the dot pattern on the wall appeared to the subject to have a rigid hollow shape. This stationary condition, we thought, might produce both a figural aftereffect and a compensation effect.

TEST APPARATUS AND VIEWING CONDITIONS

The test surface used throughout consisted of a flexible metal sheet, 91 cm high and 50 cm wide. Near its upper and lower edges, it was solidly attached to horizontal bars which were, in turn, mounted on short levers. When the levers were both in horizontal position, the sheet was stretched and plane, but when they were inclined toward each other, the sheet became curved to assume a concave shape. An inclination of the levers tipped the ends of the sheet in opposite directions, imposing a curvature on it, and at the same time shortened the distance between the ends as required by the curvature. To achieve this concerted action, the effective length of the lever was 5 cm. On the other side of the fulcrum, at distances of 7.5 cm, a nut on a pivot was mounted in a hole in each lever. Screws with opposite threads mounted on the ends of a long shaft were inserted in these nuts, moving them closer together or farther apart as a shaft was turned on in one or the other direction. This action thus changed the positions of the levers and thereby the degree of curvature of the sheet. Two handles connected to the shaft

enabled the subject or the experimenter to turn it and thereby adjust the curvature of the sheet. This curvature was measured as the distance h of the locations of the midpoint of the curved sheet from its location when the shape of the sheet was plane. In other words, if the curve of the sheet is considered an arc of a circle, h is the distance between the center of that arc and its chord. A ruler that slid horizontally in a mount that was attached to a post behind the sheet opposite its midpoint was used to measure its location. h was measured in centimeters and increased as the concave curvature became stronger.³

The sheet was painted white and covered with an irregular pattern of black dots, whose size and average distance from each other were so chosen that the image size of the pattern corresponded to that of the pattern viewed in the adaptation period. The objective viewing distances of the test pattern and of the adaptation pattern were different. In all of our experiments, the distance from the subject's eyes to the dot pattern on the wall was 64 cm. Looking through the glasses, the subject viewed the dot pattern with eyes converged and accommodated for a distance of 22 cm. Since the test sheet was observed without the glasses, the subject viewed it from a distance of 22 cm.

EXPERIMENT I

Subjects

Two groups of 12 subjects were employed. Group M moved their heads up and down during the exposure periods, and Group St looked at the adaptation pattern with stationary head. All subjects were first screened for good depth perception on a mirror stereoscope. Only subjects who reported the correct depth for two pairs of stereoscopic charts were used in this or subsequent experiments.

Procedure

First, each subject made two settings of the test sheet. In this and all subsequent tests, the subject was initially presented with the sheet in a strongly concave setting ($h > 8$ cm) and was asked to turn the handle until the surface of the sheet appeared perfectly flat.⁴ The average h value of these two settings constituted the subject's preexposure test score. In all tests, the subject wore empty goggle frames, with the temporal third of each opening covered with a vertical strip to conform to the openings of the glasses to which the subject adapted. The subject was permitted to nod his head during the test whenever he wanted to see the top or the bottom of the dot pattern. After the preexposure test was completed, the subject was placed in front of the wall pattern, where he put on the prismatic glasses. Subjects of Group St placed their heads onto a headrest. Subjects of Group M were told to nod their heads up and down at a comfortable rate, which amounted to a nod every 3 or 4 sec; they were allowed to take a short rest from nodding at will. To prevent potential boredom, all subjects were listening to a radio program of their choice. After a first exposure period of 10 min, the subject was asked to close his eyes, was led to the test apparatus, and the glasses were exchanged for the goggle frames. Again, he twice set the sheet to appear flat, exactly as in the preexposure test. The average of the h values of the settings was the score for Test 1.

With eyes closed, the subject was led back to the position in front of the wall. The empty goggles were replaced with the glasses, and a second exposure period began, lasting 20 min. This was followed by Test 2, which was identical to Test 1. Following Test 2, the subject sat blindfolded for 5 min. During this time, the adaptation effect measured with Test 2 had a chance to dissipate. A last test, Test 3, measured the effect of this 5-min interval.

Results

Table 1 presents the mean h scores for the various tests as well as the mean adaptation scores for the two exposure conditions, that is, for Group M and Group St. An adaptation score was computed by

Table 1
Mean Effects of Two Exposure Conditions on Adaptation to Curvature of Frontal Planes

	A Preexposure Test	B Test 1	Adaptation Effect 1 B - A	C Test 2	Adaptation Effect 2 C - A	D Test 3	Dissipation Effect D - C
Group M	1.41	3.09	1.68	3.76	2.35	2.66	-1.10
Group St	1.62	1.53	-.09	1.79	.17	1.54	-.25
t Between Groups	.22		4.00*		3.98*		

* $p < .01$

taking the difference between a test score and the corresponding preexposure test score. The mean adaptation scores based on Tests 1 and 2 are given in the third and fifth column of the table. The exposure condition where the subject did not move his head had no effect at all (Group St). The mean scores measured in Tests 1 and 2 were essentially the same as the mean scores obtained in the preexposure test. This stationary condition thus yielded neither an adaptation effect nor a figural aftereffect. For Group M, the mean curvature of the sheet that was perceived as straight was greater after the first exposure period (Test 1) than in the preexposure test, and was still greater in Test 2 after the second exposure period; the difference between the mean scores of Tests 1 and 2 was significant at the .05 level. The mean adaptation scores were very significantly different from zero. They were also significantly different from the mean adaptation scores for Group St, as the t values in the last row of the table show.

The rest period of 5 min that separated Test 2 and Test 3 also had a significant effect. The decrease by 1.10 cm in the mean curvature that appeared flat to the subjects of Group M was significant at better than the .01 level. The adaptation effect achieved by Group M dissipated measurably in 5 min. The residual mean adaptation effect measured by Test 3 of 1.25 cm was, however, still highly significant. A comparison with the corresponding result for Group St of -.08 cm showed a mean difference of 1.33 cm that was significant at the .01 level.

The two mean preadaptation scores of 1.41 and 1.62 showed that our test sheet had to be given a slightly concave curvature in order to be judged flat. This unexplained effect was highly significant.

EXPERIMENT II

In the tests of Experiment I, the subject was free to move his head up and down or to keep it still, and subjects used both manners of observation. Since only those subjects who moved their heads up and down during the exposure period developed an adaptation, the question arose whether adaptation was tied to such head movements and would manifest itself only in the presence of head nodding. We, therefore, did an experiment in which the procedure for Group M of

Experiment I was followed in all respects except for the test conditions. All 24 subjects nodded their heads in the exposure period. Twelve subjects were always first tested with their heads stationary in a headrest (t_s test) and immediately following with head nodding (t_m test). In both kinds of tests, a fixation mark in the center of the sheet was provided and the subjects were asked to keep their eyes on that mark throughout the testing. In the t_s test, the subject's eyes were therefore stationary also, while in the t_m test, they were moving to compensate for the subject's head movements. These 12 subjects formed Group M_A. The other 12 subjects, designated Group M_B, were treated exactly in the same fashion except that the t_m test always preceded the t_s test.

Results

The results for Experiment II are to be found in Table 2, which brings together the mean adaptation scores for all of our experiments. The eight mean adaptation effects measured in Experiment II are listed in Lines 3 to 6 of the table. Six of them, those with asterisks, were significantly different from zero as well as from the corresponding mean scores obtained from Group St (Line 2), and one of them, the one marked with +, was only significantly different from zero. The subjects in Group M_B were different from those of Groups M and M_A in that they yielded altogether lower adaptation values and showed somewhat higher variability. But where the

Table 2
Mean Adaptation Effects After 10- and 20-Min Exposure

	Group	Test	After 10 Min	After 20 Min
1 Experiment I	M		1.68** ^a	2.35** ^b
2 Experiment I	St		-.09	.17
3 Experiment II	M _A	t_s	1.60** ^a	1.99** ^b
4 Experiment II	M _A	t_m	.94** ^a	1.10** ^b
5 Experiment II	M _B	t_m	.98** ^a	.86+
6 Experiment II	M _B	t_s	.57	.98** ^b
7 Experiment III	St _{PM}	t_M		.19** ^c
8 Experiment III	St _{PM}	t_s		.58** ^d

* $p < .05$

** $p < .01$

^aTested against effect of 10-min adaptation for Group St.

^bTested against effect of 20-min adaptation for Group St.

^cTested against effect of 20-min adaptation for Group M.

^dTested against effect of 20-min adaptation for Group M_A (t_s test).

mean adaptation effects obtained from Group MB were lower than those obtained from the other groups, the difference was not significant. The results obtained with Group MA showed that the adaptation could be readily measured with a test in which the subject's head and eyes were kept stationary. That test yielded mean adaptation effects (presented in Line 3) as high as had been measured for Group M (Line 1), and as significant. In the tests in which the subjects nodded their heads (Line 4), the mean adaptation effects were lower but not significantly so, probably because the test was given second for this group of subjects.

EXPERIMENT III

It had been shown in Experiment I that adaptation was obtained only when the subject nodded his head while wearing the prismatic glasses. Merely observing the dot pattern with stationary head did not produce an effect. In Experiment III, we asked what specific feature of the head-movement condition caused the adaptation to develop. When the subject, wearing the glasses and looking at the dot pattern, moved his head up and down, the concavity caused by the glasses moved up and down in relation to the stationary dot pattern; in other words, a deformation shifted up and down in the pattern. We expected that this shifting deformation of an otherwise rigid pattern was responsible for developing the compensation effect we had measured, and we assumed that the head movements that caused this shifting were necessary only for doing just that, but were not essential for bringing about the adaptation. We tested this view by using an exposure condition in which the hollow shifted through a dot pattern while the subject kept his head stationary. This was achieved by moving the dot pattern down and up instead of having the subject nod his head up and down.

Method

An arrangement was built in which a board, 122 cm high and 61 cm wide, moved up and down for a distance of 45 cm in either direction. The board was covered with the same random-dot pattern that in Experiments I and II had covered a wall. The motion rate of the board approximated the rate of head nodding in the previous experiments: a cycle lasted approximately 4 sec. The subject's head was fixed by a molded bite-board. The observation distance was again 64 cm.

As in Experiment II, two kinds of tests were used and given to every subject. One test condition (t_M) was identical to that used in Experiment I. In the other kind of test (t_S), the subject's head was stationary and the test was, therefore, comparable to the t_S test of Experiment II. The subject's head was in a headrest, and the subject was instructed to keep it still. But no fixation mark was provided, and the subjects were permitted to move their eyes freely. This was done to have the test resemble the exposure conditions, where the moving pattern caused pursuit eye movements. Of the 16 subjects who participated in this experiment, half were always given the t_M test first and the t_S test in the second place, while for the other half the order was reversed. Only one exposure period of 20 min duration was employed. Because the subjects' heads were

stationary and the dot pattern was moving during the exposure period, we called the subjects of this experiment Group StPM.

Results

The mean adaptation scores obtained with the two tests are listed in Lines 7 and 8 in Table 2. The t_M test, which was identical with the test given to Group M of Experiment I, yielded no adaptation effect. Its mean adaptation score was also significantly different from the corresponding mean score of 2.35 cm obtained with Group M. It is important to realize that, in the combination with this test, the treatment of Group StPM differed from that of Group M only in regard to the presence or absence of head movements during the exposure period. Only when subjects nodded their heads while wearing the glasses and thereby causing the deformation to shift through the dot pattern was an adaptation obtained; when that shifting occurred because the pattern moved, there was no adaptation.

Because we had found in Experiment II that the adaptation could be measured with a test in which the subject's head remained stationary, the result obtained from Group StPM with the test in which the subject's head remained stationary (t_S) is also of interest. A mean adaptation score of .58 cm was obtained here, which, though small, was significantly different from zero at the .05 level. This mean was, however, not significantly different from the mean adaptation score obtained with the t_M test. (The results of these two tests came from the same subjects.) Neither was there a significant difference between this mean and the corresponding mean adaptation score obtained from Group St of Experiment I. The critical comparison, however, is with the result of the same kind of test given after an exposure period in which the subjects nodded their heads. The mean adaptation score of 1.99 cm obtained with the t_S test from Group MA was significantly larger than the mean of .58 cm measured for Group StPM. That result demonstrates again that head movements during the exposure period were essential.

The question may be raised whether the groups of subjects that are here compared are similar enough for these results to be accepted. In Table 3, the means of the pre- and postexposure test scores obtained from Group StPM with the t_M and the t_S tests are given together with the corresponding means for Group M and Group MA, with which they were compared. The means of the preexposure scores differed somewhat, and when the differences between the preexposure means of those groups for which adaptation effects were compared were tested, they were found to be significant at the .05 level. However, an inspection of Table 3 shows that the critical differences in the adaptation effects are not likely to be the result of these sampling errors.

Table 3
Mean Pre- and Postexposure Test Scores

	Experiment III (ST _{PM})		Experiment I (M)	Experiment II (M _A)
	t _M	t _S		t _S
Preexposure	2.28	2.57	1.41	3.83
Postexposure	2.47	3.15	3.76	5.82
Adaptation Effect	.19	.58	2.35	1.99

The same conclusion can be reached by considering the slopes of the regression lines of the postexposure scores on the preexposure scores. The slopes of the scores obtained with the t_M test from Group ST_{PM} and Group M were .74 and 1.19, respectively. A test showed that these slopes were not significantly different from each other and that the two regression lines were therefore approximately parallel. This made it permissible to compute the mean of the two preexposure means and to solve the regression equations for the two postexposure means. These corrected postexposure means were 2.16 and 4.26, respectively, and their difference of 2.10 was significant ($p < .01$). This comparison of the corrected postexposure means that result when the corresponding preexposure means are equalized confirmed the result that had been obtained by comparing adaptation effect means.

The slope of the scores obtained with the t_S test from Group ST_{PM} was .50 and the slope for the scores from Group M_A was .39, and this difference was also not significant. The corrected postexposure means here were 3.46 and 5.58, and this difference was significant at the .001 level. Again, the difference between postexposure means based on equalized preexposure means confirms the result obtained with adaptation effect means.⁵

SUMMARY

Partial adaptation to glasses that by means of a stereoscopic effect caused a flat surface on a frontal plane to look concave was produced rapidly by having the subject nod his head while observing a dot pattern. An exposure period in which the subject kept his head stationary produced no perceptual change in the

shape of the test surface, showing that prolonged viewing of a curved dot pattern caused no figural aftereffect. Observing the concavity shift through the dot pattern as a deformation did not suffice to cause adaptation. It was necessary that the shifting deformation be caused by head movements. Head nodding, however, was not necessary for seeing the manifestation of adaptation, a convexity in a plane pattern, when no glasses were worn, nor was it necessary for measuring the adaptation effect by compensation. Nodding movements were a necessary factor only among the conditions that caused adaptation.

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NOTES

1. For a more detailed explanation, see Wallach and Frey (1972). It might be added that we used plano-concave lenses, whereas Wallach and Frey used meniscus lenses, a lense shape that avoids some of the shape distortion we are here making use of.
2. Another way of looking at these measurements is that we objectively compensated for the apparent bulge that the adaptation effect caused on a plane surface.
3. We are grateful to Otto Hebel for constructing this apparatus.
4. This procedure, where both settings were made starting with a concave curvature that was clearly perceived as concave, was used because the test apparatus did not yield convex curvatures. It had the further advantage that it avoided presenting the subject after the exposure period with curvatures that looked convex to him and could have interfered with an adaptation that had developed. The procedure was acceptable because all effects were measured as differences between the post- and preexposure scores.
5. We are indebted to Gudmund R. Iversen of the Department of Mathematics of Swarthmore College for proposing these tests.

(Received for publication October 4, 1974;
 revision received April 11, 1975.)