Visual and proprioceptive adaptation to altered oculomotor adjustments*

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Adaptation to spectacles that alter in equivalent amounts the accommodation and the convergence with which objects are viewed was produced under two conditions. In one, S alternately pushed away or pulled toward him a screen that exhibited only a single vertical contour while wearing glasses that caused decreases in accommodation and convergence equivalent to 1.5 lens diopters. Here kinesthesia for these arm movements provided the only veridical distance cues. A small, but highly significant, adaptation effect was obtained with a test in which S, before and after the adaptation period, pointed to the location of a test line in the distance dimension. Corresponding tests consisting in size and in depth estimates did not show an adaptation effect. In the other condition of adaptation, S moved objects by hand toward and away from himself while wearing spectacles that increased accommodation and convergence by the equivalent of 1.5 lens diopters. In addition to the altered oculomotor cues, some veridical visual cues for distance such as are caused by perspective were present. This condition yielded changes in size and depth estimates indicative of an adaptation in visual distance perception and a larger effect of adaptation measured by the pointing test. We concluded that the excess of the adaptation effect measured by pointing over that measured by size estimation represents an adaptation in proprioception, as did the pointing effect produced by our first adaptation condition.

Adaptation in distance perception based on oculomotor cues was first reported by Wallach and Frey (1972a) and has been investigated by Wallach, Frey, and Bode (1972). It is obtained when S wears glasses that alter the accommodation and convergence with which objects are viewed. It consists in an alteration in the relation between these oculomotor adjustments and the distances of objects as represented in perception. This alteration was shown to manifest itself in changes in size and in stereoscopic depth perception, as well as in a motor response to apparent distance, a pointing from the side to a thin vertical wire visible against a narrow luminous area in a dark field. In the previous work, the result of this pointing test was in agreement with that of the size test; the results of both tests implied changes in distance perception of the same magnitude. This was expected because the conditions of the adaptation period were deliberately chosen so that S did not observe his arms through the glasses to which he adapted: S walked with his hands clasped behind his back or sat motionless in the dark. No alteration in the motor processes underlying the pointing response could have resulted from these conditions. In both experiments now to be reported, proprioceptive cues to distance could

have played a role. In fact, in Experiment 1, they furnished the only veridical distance cues necessary for adaptation. In Experiment 2, S manipulated objects and, throughout the adaptation period, saw his hands while doing it, but veridical visual cues for distance were also present.

When a motor response is used as a test of adaptation to a device that alters visual stimulation and when the adaptation conditions involve S's visual observation of his own motor behavior, the test may measure adaptation in visual perception or in proprioception, or in some combination of the two. But only a further test involving solely visual perception will remove this ambiguity of the motor response test. If the amount of adaptation measured by the visual test matches the amount of adaptation measured by the motor response test, as was the case in the experiments of Wallach, Frey, and Bode, the motor response test reflects only adaptation in visual perception. But when the amount of adaptation indicated by the visual test is smaller than that measured by the motor response test, the conclusion is that the motor response measures, in part, proprioceptive adaptation. The adaptation effect measured by the motor response test may thus be regarded as the sum of the visual and the proprioceptive adaptation.

EXPERIMENT 1 Procedure

The issue in this experiment was

whether adaptation to glasses that changed the oculomotor adjustment to the given object distance could be produced with the help of veridical cues for distance that were not visual. Instead, S's alternately pulling a target toward himself and pushing it away from himself provided changing proprioceptive cues for its distance while he observed it through the glasses. Because we know that the changing image size of an approaching object can produce adaptation in distance perception based on oculomotor adjustments (Wallach & Frey, 1972b), our target consisted of the vertical borderline between the black and white halves of a large panel, 100 cm wide and 90 cm high. This panel was mounted on a four-wheel carriage that could be moved on a wide track. The latter was fixed to a 70-cm-high table in front of S's chair in S's sagittal direction. A handle was mounted at the lower edge of the panel, 85 cm above the floor. S wore a black cape-like drape with a hole for his head over his shoulders, the long front end of which was attached to the lower edge of the panel just above the handle. This arrangement hid the handle and his arm from S's view. Black curtains hung on either side of the table, extending from beyond the far end of the tracks to the side of S's chair. The cape and these side curtains thus limited S's visual space to the panel. The glasses consisted of +1.5 diopter lenses and 5 diopter prisms with base temporal. They thus diminished the accommodation and convergence with which objects were viewed in corresponding amounts and caused objects to be given with oculomotor cues for increased distances; hence we call them far glasses.¹ Because they impose a limitation in the objective distances that can be presented—behind these glasses the oculomotor adjustments for a point 66.7 cm from the eyes is for infinity—stops on the track limited the motion of the panel to distances from the eyes that ranged from 25 to 66 cm. S was instructed to look at the border between the black and white areas as he pushed the panel back and forth, with his right hand on the handle. Because the frames of the glasses limited his visual field and because the greatest distance of the panel was short, he could not see the outer edges of the panel. Illumination was by a 300-W light fixture hanging behind S from the ceiling.

This arrangement created a large discrepancy between the pushing and pulling arm movements and the effect they had on the visual distance of the target. Since visual distance was given by oculomotor cues alone, it was entirely subject to the effect of the

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Table 1
Mean Effects of Adaptation to Far Glasses Due to Moving a Single Contour in Depth

	All Sizes and Distances in cm				Pointing Distance
	Size Estimates		Depth Estimates		
Test Distances	33.3	66.7	33.3	66.7	33.3
Object Size and Depth	5.5	11.0	2.5	10.0	
Preadaptation Estimates and Pointing Distances	5.87	10.40	4.71	11.11	35.60
Postadaptation Estimates and Pointing Distances	5.95	10.16	4.75	9.95	33.52
Preadaptation Minus Postadaptation	-.08 ± .73	.24*	-.04 ± .72	1.16**	2.08†

* $p > .8$

** $p > .05$

† $p < .001$

glasses. Hence, moving the panel to and fro by about 40 cm caused a much larger visual distance change, which ranged from a near point of about 40 cm² to whatever distance an oculomotor adjustment to almost infinity denotes.³

Two groups of 16 Ss each, paid undergraduates, were employed. Both were exposed for 20 min to the adaptation conditions just described. One group was given, before and after adaptation, the pointing test described above, and the other gave size and depth estimates for two wire pyramids, one set of estimates before the adaptation period and the other afterwards. Shapes and sizes of the pyramids, the manner of their presentations, and the estimation procedure were the same as described by Wallach, Frey, and Bode. The dimensions to be estimated are given in Table 1 also. The smaller pyramid was 33.3 cm from the eyes, and the distance of the larger one was 66.7 cm. Half of our Ss were first tested with the nearer pyramid, giving first the size and then the depth estimate, and then with the pyramid at 66.7 cm; the other half first gave their estimates for the farther and then for the nearer pyramid. For each S, the test order was the same before and after adaptation. Ss were selected on the basis of the preadaptation test. The size estimate S gave for the more distant pyramid had to be at least 1.4 times larger than that for the nearer pyramid, and the corresponding ratios of depth estimates had to be at least 1.7.

The equipment and procedure in the pointing test was also described by Wallach, Frey, and Bode. Because in the present experiment adaptation was to the far glasses and an adaptation effect on postadaptation pointing was expected to be for a shorter pointing distance, the glasses were *not* worn for the tests. The distance of the test wire from the eyes was 33.3 cm. S made three pointings before and three after adaptation. The mean of such a set of three pointing distances became S's pointing score. The Ss who were given

the pointing test were selected on the basis of two preadaptation tests. After giving the three pointing responses without glasses, they repeated this test looking through glasses that caused an increase in oculomotor adjustments equivalent to 1.5 lens diopters and were therefore called near glasses. If his mean pointing distance obtained in the latter test was less than 3 cm shorter than the pointing score obtained in the first test, S was eliminated.

Results

The results for both groups of Ss are given in Table 1. As shown in the last row, a small but highly significant adaptation effect was measured with the pointing test. The mean size and depth estimates taken before and after adaptation did not differ from zero in the case of the nearer pyramid, which was at the same distance from the eyes as the target wire in the pointing test. In the case of the far pyramid, there was also no adaptation effect where size was concerned, whereas a small effect was obtained for depth which was, however, not quite significant. Thus, very little if any visual adaptation was produced in our adaptation period. At any rate, the result of the pointing test was significantly different ($p < .01$) from that of the size estimation test for the nearer pyramid, whose distance was the same as that of the pointing target. We conclude that the effect measured with the pointing test was largely proprioceptive. It may well be that when the conditions of adaptation consist in a discrepancy between a set of oculomotor cues on the one hand and proprioceptive cues on the other, only proprioception becomes modified.

EXPERIMENT 2

In our other experiment, the cue discrepancy that produced adaptation was not as simple: there were visual as well as kinesthetic cues that represented the veridical distances. S faced a table top with objects or drawn patterns that presented him

with fair perspective cues,⁴ and he moved objects toward and away from himself. He thereby produced changing image sizes that also furnished veridical information about distance change in conflict with the oculomotor cues produced by the glasses (Wallach & Frey, 1972b). But he also observed his right hand moving these objects about and thus obtained proprioceptive cues for the various locations of his hand, which were in conflict with the deceptive visual cues for distance provided by the oculomotor adjustments forced by the glasses. Seeing his hand in the context of the arrangement on the table top also furnished veridical visual cues for his hand's location. Similar adaptation conditions had previously been used by Wallach and Frey (1972a) and had produced strong effects as measured with size estimation tests. There was one difference: Wallach and Frey permitted Ss to move their heads (as much as was compatible with being seated) in order to make parallax cues for distance available, whereas our Ss sat still.

Procedure

Near glasses were used because, for Wallach and Frey (1972a), they had produced the stronger effects under the present adaptation conditions. They consisted of -1.5 diopter lenses and 5 diopter prisms with base nasal. During the adaptation period that lasted 15 min, S sat on a 51-cm-high stool at the edge of a table on which lay a white cardboard sheet, 79 x 57 cm. On it were drawn the outlines of the bases of 10 differently shaped wooden blocks ranging in size from 7 to 13 cm. Beyond, another white sheet was fixed to the table. On it lay the 10 blocks which were painted black. S's task was to take each block, find the outline of its base, and fit the block into it. When this was achieved, S had to move all blocks back toward the rear. E replaced the loose cardboard sheet with another with a different arrangement of the outlines, and S again fitted the blocks into them. Six such sheets were available to keep S busy for 15 min.

The test conditions were the same as those in Experiment 1, except that S wore the near glasses for the pointing test, as had been done in Experiment 3 of Wallach, Frey, and Bode, where adaptation also was to the near glasses. The glasses caused the pointing target to be seen with an oculomotor adjustment for a distance of 22.2 cm. Also, in the present experiment, the same group of Ss was used for both tests. The Ss were selected in the same manner as in Experiment 1, with both the pointing and the estimation criteria applied to

each S. Twenty-eight Ss were tested to yield 16 experimental Ss.

First, S gave the preadaptation size and depth estimates. Then he put on the glasses and took the pointing test. This was followed by the adaptation period and the postadaptation pointing test. Only then were the glasses removed, and S then gave the postadaptation estimates. This procedure was followed because it permitted S's wearing the glasses continuously. It was permissible because in the original work of Wallach and Frey (1972a), there was no decline in the adaptation effect measured by size estimation during the time needed for four individual size estimates. There would be no decline in the effect measured by the size estimation tests due to the small lapse of time caused by the intervening pointing test.⁵

Results

Substantial and highly significant adaptation effects were obtained, as the mean differences between the pre- and postadaptation scores and their *t* values given in Row 3 of Table 2 show. In the pointing test, all individual pointing distances were larger after adaptation than before. In Row 4, the mean changes due to adaptation are given as proportional increases. The last rows list corresponding proportional scores from experiments by Wallach, Frey, and Bode. Row 5 shows the results of their most effective adaptation condition, walking for 20 min with the near glasses in place (Experiments 1 and 3), and Row 6 shows the effect of viewing for 20 min a scene similar to the arrangement on the table top seen in the adaptation period by our Ss but with objects stationary and without motor activity (Experiment 4). It is obvious that our estimation results resemble more those presented in Row 6 that were produced by adaptation conditions where only perspective cues mediated the objective distances. Row 4 shows that in our experiment, nearly identical proportional size increases were measured at the two test distances. A comparison of the proportional size and depth increases shows the latter to have been larger. This difference was significant here only for the 33.3-cm test distance ($p < .025$). Corresponding differences were consistently obtained by Wallach, Frey, and Bode, who discussed their implications.

Our main concern is, however, with a comparison between the effects measured with the pointing test and with size estimation. To this end, we computed the proportions of complete adaptation that the measured increase

Table 2
Mean Effects of Adaptation to Near Glasses Due to Manipulating Blocks

Test Distances Object Size and Depth	All Sizes and Distances in cm				Pointing Distance
	Size Estimates	Depth Estimates	Size Estimates	Depth Estimates	
	33.3	66.7	33.3	66.7	22.2
	5.5	11.0	2.5	10.0	
1 Preadaptation Estimates and Pointing Distances	5.71	9.62	5.16	10.74	29.5
2 Postadaptation Estimates and Pointing Distances	7.00	11.86	6.98	13.84	37.3
3 Postadaptation Minus Preadaptation	1.29 $t = 5.06$	2.24 $t = 4.20$	1.83 $t = 4.32$	3.09 $t = 4.15$	7.8
<i>Proportional Increases (Percent)</i>					
4 This Experiment	22.3	25.8	37.4	31.7	27.4
5 W, F, and B Experiment 1 + 3	53.4	68.6	102.9	100.8	40.9
6 W, F, and B Experiment 4	17.5	14.8	32.2	31.2	

in pointing distance and the increase in estimated size represented. In the case of size, the effect of full adaptation on the pyramid at 33.3 cm distance is given by the preadaptation size estimate for the pyramid at the distance of 66.7 cm. This follows from the following considerations: Complete adaptation to the near glasses means that a given oculomotor adjustment causes a registered distance larger than normal by the equivalent of -1.5 diopters. The distance of 66.7 cm stands in that relation to the test distance of 33.3 cm. Because the objective sizes of the two pyramid bases were so chosen that they produced identical images, the perceived sizes of the bases should be proportional to their registered distances. Therefore, when after adaptation the base at 33.3 cm distance is perceived with a registered distance of 66.7 cm, its apparent size should be the same as the apparent size of the base at 66.7 cm prior to adaptation. The proportion of complete adaptation (effect ratio) that the postadaptation size estimate for the 33.3-cm-distant pyramid represents can thus be computed as the ratio of the postadaptation size estimate at 33.3 cm minus the preadaptation size estimate at 33.3 cm over the preadaptation size estimate at 66.7 cm minus the preadaptation size estimate at 33.3 cm. This effect ratio amounted to .337. The effect ratio for the result of the depth estimation test for the pyramid at 33.3 cm distance can be computed in a corresponding manner, because the shape of the pyramid at 66.7 cm distance was so chosen that, at its distance, it produced the same retinal disparities as the pyramid at 33.3 cm. This effect ratio amounted to .332. It is in good agreement with the effect ratio for size.

To compute the effect ratio for the

result of the pointing test, we transformed the pre- and postadaptation pointing distances into their diopter equivalents and computed the ratio of the difference between these diopter equivalents over 1.5 diopters, the latter the value for complete adaptation. The resulting effect ratio was .490. To subject the mean difference of .154 between the effect ratios for pointing and for size to a *t* test, effect ratios were computed for individual Ss. The difference was significant at the .025 level.

The pair of mean effect ratios obtained in this experiment may be compared with those obtained in two other experiments where the pointing and size estimation tests were used in a manner similar to our experiment, but where the conditions of adaptation precluded the development of kinesthetic adaptation. One pair is from the work by Wallach, Frey and Bode, where the effect of 20 min of walking while wearing the near glasses was measured with size estimation in Experiment 1 and with a pointing test in Experiment 3. The effect ratio for the size estimation test here was $.80 \pm .15$; for the pointing test it was $.70 \pm .11$. In the experiments by Wallach and Frey (1972b), adaptation was to conditions that simulated the effect of near glasses equivalent to one lens diopter and where S neither moved nor saw his arm. The effect ratio measured with size estimation of the pyramid at 33.3 cm distance amounted to $.19 \pm .09$, and the one obtained with a pointing test with the target at the same distance was $.19 \pm .06$. Either pair of effect ratios shows good agreement between the results of the size estimation and the pointing test, when there was no opportunity for the development of proprioceptive adaptation. That, on the other hand, in our experiment the adaptation effect measured with the

pointing test was larger than the one measured with the size estimation test, we attribute to partial adaptation in proprioception, which increased the effect ratio measured with the pointing response.

DISCUSSION

In both of our experiments, greater effects of adaptation to glasses that alter oculomotor adjustments were measured with a pointing test than with size estimation. While a change in size estimation is a strictly visual effect, a change in pointing may result either from an increased apparent visual distance of the target or from a change in proprioception that affects the pointing response. In Experiment 1, the far glasses produced a contradiction between visual distance based on oculomotor cues and normal proprioception. Adaptation might have produced a change in visual distance perception or a change in proprioception controlling the arm movement of pointing, or a combination of the two. Our result seemed to indicate that adaptation was only in proprioception. It would appear then that, in the conflict between oculomotor cues for distance and proprioceptive cues, the perceptual process produced by the latter becomes modified. Such ready modification in kinesthesia was observed in our Experiment 2, where not only proprioceptive, but also veridical visual cues were in conflict with the oculomotor cues. Along with visual adaptation that manifested itself in changes of size and depth estimation and in the pointing response, modification in kinesthesia developed also and produced an additional effect on the pointing response. It is possible that such proprioceptive adaptation develops only when the veridical visual cues for distance are somewhat weak or not numerous, which was the case in Experiment 2. No pattern of parallel lines or of repeated identical shapes enhanced the perspective cues

provided by the edges of the table top, and no movements on the part of S produced parallax distance cues.

This is not the first time that a visual pointing test was shown to represent in part an adaptation in proprioception. In their excellent experimental analysis of adaptation to optical displacement of the visual direction, Hay and Pick (1966) showed that the effect of such adaptation on a pointing test has a visual and a proprioceptive component. They measured these components independently of each other, the visual one by having S find the direction of a source of sound on a visual scale and the proprioceptive one by having him mark the apparent location of a sound source. No analogous procedure is possible in the case of our kind of adaptation because audition does not yield the necessary distance perception.

The modification in proprioception obtained in our experiments is an example of counteradaptation. This term was introduced by Wallach and Frey (1972b) for a modification of a process produced by veridical stimulation that occurs during an adaptation period. Like true adaptation, such process modification serves to diminish the results of the cue discrepancy inherent in the adaptation conditions, but it changes the outcome of that process in a direction away from veridicality. In our experiments, the conditions of the adaptation period provided a discrepancy between oculomotor cues and proprioceptive cues for distance. (In Experiment 1, this was the only cue discrepancy; in Experiment 2, there were also discrepancies between oculomotor cues and other visual cues for distance.) The effect of discrepancy between oculomotor cues and proprioceptive cues can be diminished by a modification of either the visual process or the proprioceptive process, or of both. But only a modification of distance perception based on oculomotor cues

will make perception more veridical under the adaptation conditions, i.e., when our glasses are worn; the modification in proprioception means a change away from veridicality, since the proprioceptive cues have not been tampered with.⁶

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NOTES

1. A detailed discussion of the operation of these glasses can be found in Wallach and Frey (1972a).
2. Viewing a target 25 cm distant (4 lens diopters) through the far glasses causes oculomotor adjustments for a distance of 40 cm ($4 - 1.5 = 2.5$ lens diopters).
3. Wallach and Floor (1971) found that oculomotor adjustments can serve as fair cues for a distance of 2 m or less.
4. Experiment 4 in the work of Wallach, Frey, and Bode (1972) demonstrated that perspective cues alone can represent veridical distance in the adaptation to our glasses.
5. The fact that the estimation tests took approximately four times as much time as the pointing test provided another argument against varying the test order.
6. We do not consider the proprioceptive component in the adaptation to displaced visual direction that was demonstrated by Hay and Pick (1966) a case of counteradaptation. Inasmuch as visual directions refer to the body rather than to the head, proprioceptive cues that enable the nervous system to take the head position into account form as much a part of the visual perception of egocentric direction as information about eye position.

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