Target distance and adaptation in distance perception in the constancy of visual direction*

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Hay and Sawyer recently demonstrated that the constancy of visual direction (CVD) also operates for near targets. A luminous spot in the dark, 40 cm from the eyes, was perceived as stationary when S nodded his head. This implies that CVD takes target distance, as well as head rotation, into account as a stationary environment is perceived during head movements. Distance is a variable in CVD because, during a turning or nodding of the head, the eyes become displaced relative to the main target direction, the line between the target and the rotation axis of the head. This displacement of the eyes during head rotation causes an additional change in the target direction, i.e., a total angular change greater than the angle of the head rotation. The extent of this additional angular displacement is greater the nearer the target. We demonstrated that the natural combination of accommodation and convergence can supply the information needed by the nervous system to compensate for this additional target displacement. We also found that wearing glasses that alter the relation between these oculomotor adjustments and target distance produces an adaptation in CVD. An adaptation period of 1.5 h produced a large adaptation effect. This effect was not entirely accounted for by an adaptation in distance perception. Measurements of the alteration between oculomotor cues and registered distance with two kinds of tests for distance perception yielded effects significantly smaller than the effect measured with the CVD test. We concluded that the wearing of the glasses had also produced an adaptation within CVD.

Hay and Sawyer (1969) reported the discovery that the distance of the observed object is a factor in the constancy of visual direction. The latter is the compensating process which causes the apparent immobility of objects during head movements. It compensates for the angular displacement between a target point and the eyes caused by some rotating head movement. Such a displacement has two components: The main displacement is caused by a rotation of the head as a whole in relation to the stationary environment; every target in the environment will change its direction relative to the head by the angle by which the head is being rotated. The secondary displacement is related to the fact that the eyes are located forward of the various rotation axes of the head. This causes the eyes to be displaced relative to a target's main direction, which is the line that connects a target point with the particular axis of the head rotation. This displacement of the eyes has little effect on distant targets, but, for target distances of less than 2 m, the secondary displacement between a

target point and the eyes attains appreciable amounts. Wallach and Kravitz (1965), who were the first to measure the constancy of visual direction (CVD), avoided dealing with the secondary displacements by using large target distances.¹ Hay and Sawyer measured CVD for a target 40 cm distant, using the method introduced by Wallach and Kravitz, and found complete compensation for the additional secondary displacement. They also tried to show that convergence of the eyes was the main cue mediating distance for the constancy of visual direction of near targets, but the results did not confirm this. The purpose of our work was (1) to show that the natural combination of accommodation and convergence employed as the sole distance cues would yield good CVD for near targets (Experiment 1), and (2) to find out whether CVD could be modified by adapting Ss to spectacles that alter these oculomotor adjustments (Experiment 2).

The previous work of the senior author and his co-workers on CVD was concerned with the compensating process that causes the visual field and individual distant targets to appear stationary during a head rotation. If, for example, the head is turned clockwise through an angle, α , a distant target becomes displaced in relation to the head in a

counterclockwise direction by the same angle. This main displacement of the target normally leads to the perception of a stationary target, while a displacement relative to the head that is not produced by an objectively stationary target, i.e., a relative displacement whose angle does not match the rotation angle of the head but is larger or smaller by a few percent, leads to the perception of a target that is seen to move during the head movement.² When the target is near and the displacement of the eyes in relation to the target's main direction matters, a clockwise rotation of the head through an angle, α , causes a change in the target direction from the vantage point of the eyes amounting to $\alpha + \beta$, where β is the additional target displacement caused by the displacement of the eyes relative to the target's main direction. The relation of β to α depends on the target distance (see Fig. 1). The smaller this distance, the larger β will be for a given head rotation α . Such displacement ratios can be calculated from the following equation:

$$\beta/\alpha = d_E/(d_T - d_E) \quad (1)$$

where α is, as stated, the angle of the head rotation, β is the angle of the secondary target displacement (and hence β/α the ratio of the secondary target displacement), d_T the distance of the target from the rotation axis of the head, and d_E the distance of the eyes from the rotation axis.³ Because of this dependence of the secondary target displacement on target distance—with this displacement ratio inversely proportional to the distance of the target from the eyes ($d_T - d_E$)—a process that compensates also for the secondary target displacement must take this distance into account, and thus depends on cues for the target distance. Such a process would be rather complex: as in CVD of distant targets, it takes into account information about the angle of the head rotation, and, in addition, it takes into account information about target distance.

EXPERIMENT 1 MEASURING THE CONSTANCY OF VISUAL DIRECTION FOR NEAR TARGETS

Our first experiment resembled that of Hay and Sawyer in many ways. These authors measured CVD for three target distances, two of which were simulated by using artificial conditions that caused the eye to converge for the simulated distances. The values of CVD measured under these artificial conditions could then be compared with the measurement of CVD for the true target distance (which was

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Fig. 1. A is the rotation axis of the head and T is a target. AT is, therefore, the main target direction. Initially, the head position is such that AT is straight ahead. Hence, the eyes (E_1) fall on AT; the main target direction and the true direction of the target, its direction from the vantage point of the eyes, coincide. After the head has been rotated clockwise through an angle, α , AC is the new direction straight ahead, and AT, the main target direction, will have been displaced relative to the head by α . E_2 is the position of the eyes after the head rotation, and E_2T is the new true target direction, which now differs by the angle β from the main target direction, which is represented by E_2T_∞ (E_2T_∞ is parallel to AT.) The angle CE_2T is the total displacement of the true target direction relative to the head caused by the head rotation. It consists of α , representing the main target displacement caused by the head rotation, and of β , the secondary target displacement brought about by the displacement of the eyes relative to the main target direction. AT equals d_T and AE equals d_E .

40 cm), and the effects of the alterations of convergence on CVD could thereby be assessed. Though statistically very significant, these effects were small—18% and 16% of the effects predicted for the simulated distances. In our experiment, the true target distance was also 40 cm, measured from the eyes, and the simulated distances were produced by having S see the same target through spectacles that caused him to view objects with accommodation increased by 1.5 lens diopters and convergence increased by 5 prism diopters for each eye (near glasses) or through spectacles having the opposite effect (far glasses).⁴ The near glasses caused the target at the 40-cm distance to be seen with an accommodation and convergence for a distance of 25 cm, and the simulated distance in the case of the far glasses was 100 cm.

As did Hay and Sawyer, we had our S use a nodding motion, a head rotation about a horizontal axis, and had his head connected to a potentiometer whose output controlled the vertical position of the spot on the screen of a cathode ray oscilloscope. Our setup differed in that S saw the oscilloscope screen directly and in that we varied the extent and direction of the motion of the spot in relation to the head movement by means of a variable transmission. Instead of the biteboard arrangement used by Hay and Sawyer to transmit the head movement to the potentiometer, we had S wear a headgear that could be attached to the variable transmission. But these technical differences probably cannot

account for the better results we obtained.

What are the results to be expected under the assumption that CVD completely compensates for the secondary displacement? When the spot is seen without glasses, it would be perceived as stationary when it actually was stationary. For a stationary target spot 40 cm from the eyes, the secondary displacement amounts to 25% of the head displacement, in the direction against the head movement, and at the distances of 25 and 100 cm from the eyes, the distances simulated by the near and the far glasses, the angles of the secondary displacement of a stationary target are 40% and 10%, respectively, of the angle of the head rotation. These displacement ratios were calculated from Eq. 1 by selecting for the distance between the eyes and the rotation axis the value of 10 cm, which is approximately correct for most adult Ss. All our calculations will be based on this value.

If the nervous system did not compensate for the secondary target displacement β/α at all, but still compensated for the displacement of the main target direction *relative to the head*, S would perceive a stationary near target as moving in the direction *against* the head rotation. In order that he see such a target as stationary, it would be necessary to give the target an objective displacement in the direction *with* the head rotation in the amount of β/α . Such an objective displacement would cause the near target to stay in the main target direction, i.e., it would

simulate a target at infinite distance, for which the displacement of the eyes relative to the main target direction does not matter. If the nervous system were partially compensating for the secondary target displacement, a stationary near target would, during a head rotation, still appear to move *against* the head, but less so, and a smaller objective target displacement *with* the head would suffice to make the target appear stationary. This objective target displacement would therefore measure the degree to which the nervous system fails to compensate for the secondary target displacement, i.e., it would measure the lag in compensation for the secondary target displacement. If, for example, a target 40 cm from the eyes, for which the secondary target displacement amounts to 25% of the angle of the head rotation, were to require a displacement in the direction *with* the head amounting to 10% of the head rotation angle ($\beta/\alpha = .1$) in order to appear stationary, we could say that a compensation occurs for 15% of the 25% of secondary target displacement. Such a lag, or an opposite error in CVD, can have two reasons: (1) S does not compensate well for secondary target displacement. (2) The cues giving information about the distance of the target are inadequate.

Measurements of this sort, while S wears one or the other of the mentioned spectacles, permit an assessment of the roles of accommodation and convergence in our experimental conditions. To the degree to which our measurements taken with glasses in place confirm the theoretical predictions given below, accommodation and convergence alone were responsible for the difference in the results obtained under our three experimental conditions.

The theoretical predictions for the measurements with glasses are derived in the following manner. When the near glasses are worn, and the oscilloscope screen is 40 cm from S's eyes, the oculomotor adjustment of the eyes is for a distance of 25 cm.⁵ This is the target's equivalent distance.⁶ But the secondary displacement of the target is still 25% in the direction *against* the head movement, because the actual distance of the spot on the screen remains 40 cm and its secondary displacement depends on the actual distance. Since, theoretically, a target at an actual distance of 25 cm has to undergo a secondary displacement of 40% of the head rotation in order to appear stationary, the spot at 40 cm distance must be made to displace during every head movement in the direction *against* it at the rate of 15% in order to

appear stationary, because this brings its displacement ratio up to 40%. Since the far glasses produce an equivalent distance of 100 cm, and since the secondary displacement ratio at that distance is 10% in the direction against the head movement, the spot on the screen must be given a displacement ratio of 15% in the direction *with* the head to diminish its 25% displacement ratio normal for its objective distance of 40 cm to one of 10%.

Equipment

The S wore a welder's headgear with a mounting extending on the right side down to the level of his upper neck. There, an aluminum rod was attached in a position perpendicular to the median plane of S's head. The mounting had to be adjusted for each S in such a way that the rod formed the extension of the rotation axis of the nodding movement S had to perform.⁷ The rod could be attached to the input shaft of a variable transmission, which was mounted on a heavy stand on the right of S's seat. With this arrangement, S's head was rigidly coupled to the transmission so that his nodding movements turned the input shaft. This attachment served also to position S's head so that his eyes were at the level of the oscilloscope screen and 40 cm from it. The height of S's seat was adjusted to bring his head to the proper level. The transmission was of the ball and disk type. By means of a large knob mounted in front and to the right of S at the level of his lower chest and of an arrangement of shafts, gears, and angle gears, S could turn the control shaft of the transmission and change its ratio and the direction of rotation of the output shaft in relation to that of the input shaft. A Veeder counter also attached to the control shaft permitted E to read the transmission setting. The output shaft of the transmission was connected with the shaft of a potentiometer used as a voltage divider of a 25-V dc source. A pointer fixed to the potentiometer shaft permitted E to read the potentiometer setting whenever necessary. The output of the potentiometer controlled the vertical position of the spot on the oscilloscope screen. Initially, E also could position the spot by using the controls on the oscilloscope. A special tube with minimal afterglow was used. To eliminate the faint glow of the face of the tube when it was in operation, the intensity of the target spot was made low. Also, the tube was covered with black cardboard, except for a vertical gap through which the path of the target spot was visible, and testing was done in total darkness. Work with CVD requires absence of lines or

boundaries which could serve as a visual framework for the target displacements to be presented.

When his head was attached, S could, by nodding it up and down, cause the spot to shift up and down, or down and up, depending on the transmission setting which he controlled. From a center position at which the rate of transmission was zero and the spot remained at rest, S could gradually increase the ratio of the motion of the spot in relation to his head movement, and, depending on the direction in which he turned the knob from this center position, the spot would move *with* or *against* the direction in which the head movement displaced the eyes. The resulting ratio of the angular displacement of the spot γ (measured from a point behind the eyes in the vertical plane of the input shaft) and of the angle of the rotation of the input shaft (representing the angle of rotation of the head α) was the γ/α -displacement ratio, the unit of measurement that our equipment yielded. Once the gain control on the oscilloscope was adjusted, these displacement ratios were in a fixed relation to the readings on the Veeder counter, and that relation was empirically determined.

The displacement ratio that is measured by our device is not the same as the displacement ratio β/α discussed earlier. The latter measures the secondary target displacement, the displacement of the direction between a stationary target and the eyes caused by a head rotation; this change in the target direction is due to the fact that the head rotation displaces the eyes relative to the main target direction. The displacement ratio γ/α measured by our device is concerned with the objective target displacement produced by that device, and is geometrically different from the β/α ratio. The angular displacement γ of the target spot is measured from the rotation axis of the head and is, thus, geometrically the same as the angle of the head rotation α , whereas the apex of the angle β is at S's eyes. Whereas our equipment measures the objective target displacement needed to compensate for the stationary target's apparent displacement in γ/α ratios, the theoretical predictions for the effects of the glasses on CVD were made in terms of β/α ratios. The following equation can be used to transform a γ/α ratio into a β/α ratio:

$$\beta/\alpha = \gamma/\alpha \cdot d_T/(d_T - d_E)$$

where, as before, d_T is the distance from the rotation axis to the target and d_E the distance from the rotation axis to the eyes, i.e., 10 cm. Our results will be transformed in this

fashion and presented as β/α ratios. To correspond to the units of measurement used in earlier papers on CVD, these ratios will be multiplied by 100 and given as percent β -displacement ratios, abbreviated % β -DR.

Procedure

Our tests were designed to determine the limits of the range of displacement ratios that did not cause S to report apparent target displacements during his head movements (no-motion range). But we did not employ the procedure developed by Wallach and Kravitz (1965, 1968), because work by Wallach and Frey (1969) and by Wallach and Floor (1970) had demonstrated very rapid adaptation in CVD. To keep to a minimum exposure of S during the test to target displacements that might cause small adaptation effects, we let S change displacement ratios, and determined only one upper and one lower limit of the no-motion range. The average of the two limits was recorded as S's no-motion point. E made a setting of the transmission that produced small apparent target displacements in one of the two vertical directions and told S in which sense to turn the control knob to diminish the target motion caused by his head movements. S was instructed to stop changing the transmission setting as soon as the target no longer seemed to move. If S thought he had overshot the limit, E reset the transmission to cause mild target motion in the former direction and asked him to make his changes more slowly. When S had found one limit, he closed his eyes and E read the transmission setting from the Veeder counter with a small flashlight. E then set the transmission to produce target motion in the opposite direction and asked S to find the other limit. With half the Ss, the limit for apparent target motion in the direction *with* the head rotation was found first, and for the other half, the limit of target displacement *against* the head movement was first determined. For all Ss, the no-motion point was first measured without glasses and then with the near and the far glasses, in that order. No instructions were given to fixate the target spot, because we wanted S to behave as naturally as was compatible with the test conditions. As in our previous publications on CVD, the question of whether target displacements relative to the head are registered by the eyes through image displacement or through taking pursuit movements into account is not raised here. Research designed to answer this question is in preparation.

Thirty-one paid undergraduate Ss

participated. Of these, 20 Ss completed the experiment. Eight Ss were eliminated because their no-motion point for the directly viewed target differed from objective immobility by a displacement larger than 2% of the head rotation in one or the other direction. For three other Ss, the upper limit of the no-motion range taken with the far glasses could not be determined, because these Ss tried to use a displacement ratio that was beyond the range of the transmission.

Results

The mean midpoint of the no-motion range for all 31 Ss amounted to $.67 \pm .89\%$ -DR in the direction *with* the head movement for the directly viewed target spot 40 cm from the eyes. That is, for randomly selected Ss, the target spot had to be given a displacement *with* the head movement of .67% of the head rotation to appear stationary.⁸ This deviation of the mean no-motion point from objective immobility was, of course, smaller for the 20 selected Ss, namely, $.19 \pm .42\%$ -DR. When the near glasses are worn and the head is moved, a stationary target spot will appear to move in the direction *with* the head movement, and an objective target displacement in the direction *against* the head movement is needed to compensate for this apparent target displacement. The mean no-motion point measured with the near glasses amounted to a target displacement of $6.90\% \pm 1.58\%$ of the head rotation in the direction *against* the head movement. As explained above, a target displacement in the direction *against* the head movement of 15% -DR was expected to compensate for the effect of the near glasses on a target objectively 40 cm away. Our result shows that even with selected Ss, compensation for the secondary target displacement is incomplete for a distance as small as 25 cm. This interpretation of the result is justified by the quite different result for the far glasses. To appear stationary, the target at an objective distance of 40 cm had to undergo a mean β displacement of $15.76\% \pm 2.52\%$ in the direction *with* the head movement when the far glasses caused an equivalent distance of 100 cm from the eyes. This result agrees well with the difference between the secondary displacements of targets at objective distances of 40 cm and of 100 cm, which amounts to 15% -DR and shows that accommodation and convergence suffice as distance cues when CVD compensates for secondary target displacements.

Discussion

The experiment just reported shows that, in the case of near targets, the

constancy of visual direction compensates not only for the main target displacement brought about by a head rotation as such but also for the secondary target displacement. CVD is virtually complete in the case of the target distances of 100 cm and 40 cm, whereas compensation for the secondary target displacement was incomplete in the case of the 25-cm distance. There are two possible reasons why, in the case of simulated distances, our results differed so much from those obtained by Hay and Sawyer. These authors manipulated only convergence, whereas our glasses altered convergence and accommodation in corresponding fashion. It seems unlikely, however, that this alone could account for so large a difference. Hay and Sawyer probably failed to keep the surround of the target spot completely dark. Visual landmarks cause an objective target displacement to be noticed that otherwise would not be perceived (Wallach & Kravitz, 1965).

Since the amount of secondary target displacement becomes larger as target distance decreases, compensating for it means taking target distance into account. The measurements of CVD with the far glasses show that accommodation and convergence, in combination, can here serve as potent distance cues. We therefore adapted Ss to our near glasses and tested for changes in CVD in the same manner in which we had tested for the effect of wearing the near and the far glasses in Experiment 1. If we succeeded in obtaining a change in CVD on the basis of adaptation to near glasses, we might thereby demonstrate still another manifestation of adaptation in distance perception⁹ and contribute to the investigation of the role that registered distance plays in the operation of CVD.

EXPERIMENT 2

ADAPTATION TO NEAR GLASSES

There are two ways in which such an adaptation might operate. The glasses may alter the relation between these oculomotor adjustments and the distance they denote in perception, i.e., the registered distance, as they were shown to do by Wallach and Frey (1972) and by Wallach, Frey, and Bode (1972). After such an alteration of registered distance, CVD should be altered also. Wallach, Frey, and Bode found that, when such an adaptation had taken effect and was tested under conditions where only oculomotor cues operated, a change in registered distance manifested itself when S represented the perceived distance of a target by pointing to it, as well as by changes in perceived size and

stereoscopic depth. If such a change of registered distance alters CVD also, complete adaptation to near glasses would eliminate the apparent target motion in the direction *with* the head movement observed when these glasses are worn. Inasmuch as adaptation to the near glasses consists in increased registered distance, its effect on CVD when no glasses are worn would be the same as that of wearing our far glasses. Such adaptation would cause a stationary target nearby to be registered as farther than it actually was and make it appear to move in the direction *against* the head movement, because the target's actual secondary displacement is larger than its secondary displacement at the registered distance would be. An objective displacement of the target in the direction *with* the head would be needed to make it appear stationary and would, thus, measure the effect of adaptation on CVD.

Another form that adaptation to our glasses might take is a modification of CVD itself. When the near glasses are worn, objects at all distances are given with oculomotor cues that place them nearer to S than they objectively are. The secondary displacements the objects actually undergo during a head rotation are smaller than would be warranted by the registered distances that these oculomotor cues normally produce. This discrepancy between distance cues and the given object displacements during head movements may cause an adaptation such that apparent target immobility will result from a different combination of secondary displacements and oculomotor adjustments than the normal one. An adaptation produced by this discrepancy may take one of two forms: It may consist in a modification in distance perception such that oculomotor cues will produce registered distances more in agreement with the given object displacements caused by head movements. This would be the same kind of adaptation we discussed above; it would, however, be caused by field displacements during head movements. The adaptation may, however, also consist in a modification within CVD such that the process that compensates for the object displacements relative to the eyes caused by head movements is altered. This is the same kind of modification that results from exposure to objective target displacements or from optical field displacement during head movements, produced, for instance, by wearing magnifying or minifying glasses (Wallach & Kravitz, 1968). Since the near glasses cause registered target distances smaller than the true distances, the secondary displacements

of any target due to head movements would be smaller than that shortened distance would warrant, and apparent target motion in the direction *with* the head movement should result. When the target is a luminous spot in an otherwise dark field, this motion is observed; our first experiment is based on this fact. But when the whole field is visible, it does not appear to move when S nods or turns his head and S experiences no apparent field displacements during the adaptation period.¹⁰ Nevertheless, S is exposed to a discrepancy between the actually given field displacements and distance cues that would warrant larger field displacements *against* the head movement than those actually given. If this were to cause an adaptation within CVD, it would be an adaptation to field displacement in the direction *with* the head movement and would cause an objective target displacement *with* the head movement to appear stationary. In the end, this is, of course, the same overt effect that a modification in distance perception resulting from wearing near glasses would produce in a CVD test; only the underlying processes are different.

How, then, can we distinguish between the two possible forms that adaptation to near glasses may take—an adaptation process within CVD and an adaptation in distance perception? One could prevent modification in CVD by keeping S's head stationary throughout the adaptation period, but this is difficult to do. We made it possible to distinguish between the two forms of adaptation by also testing for adaptation in distance perception in other ways, using two of the tests Wallach, Frey, and Bode had employed. Ss were given a pointing test and size estimation tests in addition to being tested for a modification in CVD. If the amount of adaptation measured by these tests corresponded to the change in registered distance implied in the CVD test results, adaptation would consist only in a modification in distance perception. If the change in CVD were larger than the changes in registered distance implied by the two other tests would warrant, it would seem likely that adaptation within CVD also occurs. Adaptation within CVD would account for that part of CVD adaptation that cannot be ascribed to the change in registered distance as measured by the other tests.

Procedure

Because we planned to use a set of five tests, two tests for CVD, a pointing test, and two size estimation tests, we made the adaptation period longer than it had ever been in

adaptation to our near glasses, and in order to gain information about the long-range growth of the adaptation effect, we interrupted the adaptation period for a set of tests. After the preadaptation tests, S wore the near glasses for 1.5 h, was given a set of tests, and immediately resumed wearing the glasses. After this second adaptation period, which lasted 3 h, another set of tests was given. Afterwards, S sat quietly with eyes closed for 15 min and then was given still another pointing test and the two size estimation tests. This retesting was done to learn at what rate the adaptation effects would weaken with mere time lapse between exposure to the adaptation conditions and the tests. This information was needed because the three kinds of test were always given in the same order. The retesting after a time lapse would allow us to estimate the loss in adaptation effect due to the duration of the tests. We always gave the CVD test first, because our primary interest was in the effect of adaptation to our glasses on CVD, and because we believed that the test did not provide conditions tending to reestablish normal distance perception. Then came the pointing test that took very little time; it was taken with S wearing the glasses and therefore could not provide "unlearning" conditions either. Two size estimation tests followed, which had previously been used by Wallach, Frey, and Bode (1972). Wallach and Frey (1972) had found that the effect of adaptation does not decline during a sequence of four size estimation tests.

Because such long adaptation periods had never been used in connection with glasses that alter oculomotor adjustment, we had to envisage the possibility that distance adaptation might be complete. We, therefore, employed only two of the conditions of testing CVD we had previously used, namely, viewing a target 40 cm from the eyes either directly or through the near glasses. We omitted testing with the far glasses, because they cause the target at 40 cm to be seen with an oculomotor adjustment equivalent to 1 lens diopter. Complete adaptation to the near glasses, on the other hand, would mean an increase in registered distance equivalent to 1.5 lens diopters and could not become manifest when the test object was seen with oculomotor adjustments corresponding to 1 diopter of accommodation.

On all three occasions, the CVD test with direct viewing preceded the one with glasses. The test procedure was the same as before, except that each test started with a setting of the transmission that produced clearly

visible target displacement *with* the head rotation. This is the target displacement associated with wearing the near glasses. When such a displacement occurs during the test, it cannot possibly weaken an established adaptation. After, under these favorable conditions, one limit—and thereby the approximate value of the no-motion range—was found, the other limit could be found by presenting S initially with a weak apparent target displacement *against* the head movement, avoiding a larger apparent displacement that might tend to diminish the adaptation.

The procedure for the pointing test and for the size estimation tests was as described by Wallach, Frey and Bode. In the latter tests, half of the Ss were always tested first with the test object at the distance of 33.3 cm and then with the test object at 66.7 cm; for the other half, these tests were given in the reverse order. The object sizes to be estimated were so transposed that they produced identical retinal images. During the two adaptation periods, Ss, paid undergraduates, spent their time as they pleased, accompanied by a guide. They were, however, asked to walk about for the last 20 min before returning for a set of tests. Our 10 Ss were selected on the basis of two CVD tests, one without and the other with the near glasses, given on the previous day. To participate, an S's no-motion point measured without glasses could not deviate from rest by more than .5% β -DR in the direction *with* the head movement. Also, with the near glasses in place, the target displacement *against* the head movement needed to produce apparent rest had to amount to at least 7% β -DR.

Results

The first two columns of Table 1 give mean no-motion points for the CVD tests. The results for the preadaptation tests, which are again given in % β -DR, differ from those reported earlier, because we employed a highly selected group of Ss. Whereas previously the mean no-motion point amounted to 6.9% β -DR *against* the head rotation direction when the near glasses were worn, the present group gave a mean of 10.08% β -DR, which was considerably closer to the value of 15% expected for the near glasses under the assumption that compensation for the secondary displacement of a target 25 cm distant is complete. The mean of .61% β -DR found with direct viewing of the target point was in the direction *against* the head movement and therefore does not represent a lag in compensation; it simply reflects the smallness of our sample, as do the high confidence

Table 1
Mean Effect of Adaptation to Near Glasses

Tested With Test Distance	CVD Test in % β -DR		Pointing Distance in cm	Size Estimation in cm	
	40 cm	40 cm With Near Glasses	33.3 cm With Near Glasses	33.3 cm	66.7 cm
Preadaptation	.61 $\pm$ 1.49 Against	10.08 $\pm$ 3.30 Against	29.7 $\pm$ 3.10	6.36 $\pm$ 0.95	9.44 $\pm$ 1.52
After 1.5 h adaptation	10.44 $\pm$ 6.59 With	2.09 $\pm$ 3.11 Against	36.4 $\pm$ 2.20	7.84 $\pm$ 1.53	12.03 $\pm$ 3.21
Change from preadaptation	11.04	7.99	6.7	1.48	2.59
After 3 h more adaptation	8.65 $\pm$ 3.55 With	1.13 $\pm$ 2.21 Against	36.0 $\pm$ 1.81	7.67 $\pm$ 1.50	11.91 $\pm$ 3.18
Change from preadaptation	9.26	8.95	6.3	1.31	2.47
After 15 min dissipation			37.0 $\pm$ 2.62	7.84 $\pm$ 1.73	12.15 $\pm$ 3.34
Effect ratio for 1.5 h adaptation		.89	.44	.47	

limits of all means in the table.

In the case of tests without glasses, the means of 10.44% β -DR and 8.65% β -DR measured after 1.5 and 3 h of adaptation, respectively, amount to changes of the no-motion point of 11.04% β -DR and 9.26% β -DR in the direction *with* the head movement. These changes represent more than half of complete adaptation, since complete adaptation would have meant a change of the no-motion point by 15% β -DR in the *with* direction. The effect of complete adaptation to near glasses is the same as that of wearing the far glasses, since the far glasses diminish accommodation and convergence in the same amount as the near glasses increase it, i.e., by the equivalent of 1.5 lens diopters. We had found in our first experiment that the effect of far glasses on a target 40 cm distant was not different from the theoretical value of 15% β -DR, namely, 15.76% β -DR. To find out whether adaptation to the near glasses was complete, we compared this value with the mean no-motion point of 10.44% β -DR and 8.65% β -DR, measured after the adaptation periods. For the 10.44 value, because of high variance, the difference from the value for full adaptation failed to be significant, but for the mean no-motion point obtained at the end of the period of 3 h, this difference was significant ($p < .01$).

In the case of the test with the near glasses in place, adaptation consisted in a decrease in the target displacement needed prior to adaptation to compensate for the effects of the glasses; as reported, that compensating displacement amounted to 10.08% β -DR in the direction *against* the head movement. After the adaptation periods, the mean no-motion points were different by

7.99% β -DR and 8.95% β -DR, respectively. A comparison of these effects with those obtained when testing was without glasses shows that the effects measured under the two test conditions were approximately the same. Further, a comparison of the adaptation effects measured after the first adaptation period (11.04% β -DR and 7.99% β -DR) with the effects measured after the second period (9.26% β -DR and 8.95% β -DR) gives no evidence of larger effects after the second and longer adaptation period.

Corresponding results were obtained with the two other tests; they are given in the last three columns of Table 1. Here, too, the effects of adaptation measured after the second adaptation period were not larger than after the first. Another striking result is the small adaptation effects measured with the pointing test and the two size estimation tests. They are about half as large as the effect obtained by Wallach, Frey, and Bode, in their Experiments 3 and 1, after 20 min of walking with the near glasses in place. Whether this is due to the fact that we did not select our Ss for good performance on these tests, as the previous authors had done,¹¹ or is the result of the much longer adaptation periods cannot be ascertained. Experiments are being planned to explore the course of adaptation to near glasses over extended periods.

To compare the magnitude of the adaptation effects measured with our three kinds of tests, we determined the degree to which each effect differed from complete adaptation. This was done by computing for each kind of test an effect ratio, the proportion of the adaptation achieved over the change representing complete adaptation. In the case of CVD, complete adaptation to our glasses

means, of course, that S, with glasses in place, accepts the same target displacement as stationary which prior to adaptation appeared to him stationary without the glasses. Thus, for the mean of 10.08% β -DR measured prior to adaptation *with* glasses, the preadaptation mean of .61% β -DR obtained *without* glasses represents complete adaptation, and the difference of 9.47% β -DR between these means is the empirically determined effect of complete adaptation in the case of the test *with* glasses. This value can be compared with the actual adaptation effect measured with the glasses, which amounted to 7.99% β -DR. The effect ratio, therefore, is approximately 7.99/9.47. We computed such effect ratios for individual Ss and used them to compare the result of the CVD test statistically with our other two adaptation measures. The mean effect ratio for 1.5-h CVD adaptation measured with the near glasses in place and computed in this manner was .89.

The effect ratio for the size estimation test was computed in corresponding fashion. This was possible because the distances of the two test objects from S were 33.3 and 66.7 cm, and these distances differed by the equivalent of 1.5 lens diopters. Complete adaptation to the near glasses means that the registered distance that corresponds to a given oculomotor adjustment is greater by the equivalent of 1.5 lens diopters. Thus, in the case of a test object 33.3 cm distant, the registered distance corresponding to complete adaptation is 66.7 cm. Because the sizes of the two test objects were so chosen that they produced identical retinal images, a size estimate of the object at 66.7 cm, given prior to adaptation, represents the postadaptation size estimate of the

object at 33.3 cm under the assumption of complete adaptation. The difference in the size estimates of the two test objects given prior to adaptation therefore represents the effect of complete adaptation measured at the 33.3-cm test distance. This difference, thus, becomes the denominator in the effect ratio, with the difference between the post- and preadaptation size estimates of the object 33.3 cm distant becomes the numerator. The mean of the effect ratios computed for individual Ss amounted to .47.

Because it had previously been found that pointing distances are approximately linearly related to object distances, effect ratios could here be computed in a different manner. The pre- and the postadaptation pointing distances of individual Ss were changed into their diopter equivalents, and the ratio of the difference between these diopter equivalents over 1.5, the diopter value of complete adaptation, was computed. The mean effect ratio amounted to .44, and was thus quite similar to that computed for the size estimation test.

Both these mean effect ratios were smaller than the effect ratio for the CVD test. In spite of the small sample, the difference between the effect ratios for the pointing test and the CVD test was significant at better than the .01 level, and for the corresponding difference between the size estimation test and the CVD test, we found $p < .025$. These differences cannot be ascribed to the test order. As the fifth line in Table 1 shows, retesting with pointing and size estimations 15 min after the second postadaptation tests revealed no dissipation of the adaptation effect as a result of the preceding tests and of the time lapse. All means were the same (or insignificantly higher) in this retest as in the two preceding tests.

DISCUSSION

Above, we have stated that an adaptation effect measured with CVD may represent two different adaptation processes, an adaptation within CVD and an adaptation in distance perception, the latter measurable also by other tests for adaptation in distance perception. Our finding that adaptation measured with the CVD test was significantly greater than the effects measured with the pointing test and the size estimation test shows that part of the effect measured with the CVD test resulted from adaptive change within CVD. If

this inference is correct, we have obtained a modification of CVD by means of an adaptation period in which S was not aware of field displacements during head movements. Only the conditions of stimulation necessary to bring about such an adaptive modification were given: Object displacements relative to the head as normally produced by head movements (and normally leading to a stationary experienced field) were paired with oculomotor adjustments that corresponded to object distances normally associated with larger object displacements. When a single target is observed in the dark, displacements are experienced that are warranted by the oculomotor adjustments. But no such object displacements were experienced during our adaptation periods. It seems that conscious experience of object displacements during head movements is not necessary for adaptation and that only the conditions of stimulation—the discrepancy between the given object displacements and the given oculomotor adjustments—matter.

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NOTES

1. Wallach and Kravitz (1965) obtained a small but significant deviation from ideal CVD and ascribed it to this secondary displacement of the eyes, but the senior author did not anticipate Hay and Sawyer's discovery.

2. Excellent compensation for the main target displacement due to head movements was measured by Wallach and Kravitz (1965 and 1968). The article of 1968 contains the more detailed description of CVD and its measurement. Measurements of CVD concerned with nodding of the head were reported by Wallach and Floor (1970). These three articles, as well as those by Wallach and Frey (1969) and Wallach, Frey, and Romney (1969), also report work on adaptation in CVD to conditions of abnormal field displacements during head movements.

3. This equation is an approximation derived from the following relation:

$$\tan \beta = \frac{\sin \alpha}{d_T/d_E - \cos \alpha}$$

The approximation is based on the assumption that head movements will not exceed 10 deg to either side of the target direction. Under this assumption $\tan \beta$ and $\sin \alpha$ may be replaced by the respective angles and $\cos \alpha$ given the value one.

4. For a description of these glasses and the way they operate, see Wallach and Frey (1972).

5. A distance of 40 cm from the eyes is equivalent to 2.5 lens diopters. The glasses cause the eyes to increase accommodation by 1.5 lens diopters (and cause a corresponding change in convergence) to a total of 4 lens diopters, and that value corresponds to a viewing distance of 25 cm.

6. The term "equivalent distance" was introduced by Leibowitz and Moore (1966) for the distance for which the eyes are adjusted behind devices that alter accommodation and convergence in corresponding amounts.

7. A description of the headgear may be found in Wallach and Floor (1970).

8. This result represents a lag in compensation for the secondary displacement of a stationary target. A displacement of the target spot in the direction with the head movement compensates objectively for an apparent target displacement against the head movement, and when an S sees that, his nervous system fails to compensate for the secondary target displacement.

9. Wallach and Frey (1972) and Wallach, Frey, and Bode (1972) measured adaptation in distance perception in three ways: by having S indicate apparent distance by pointing and by the effect that a change in distance perception has on perceived size and on perceived stereoscopic depth. They also demonstrated the existence of an intervening variable, called registered distance, that results from cues for distance, whose relationship to these cues can be altered by adaptation, and which, in turn, manifests itself in size and in depth perception.

10. This is probably due to the fact that vertical distance cues are available when the whole field is given, in addition to the oculomotor cues, which the glasses modify.

11. Our Ss were selected for good performance on the CVD test only.

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