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Nonveridical Visual Direction Produced by Monocular Viewing

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We examined the nonveridicality of visual direction produced by monocular viewing. In Experiment 1, 19 subjects pointed to a small light and moved a small light to their subjective median plane. The extent of constant error under monocular and binocular viewing conditions differed in both tasks ($p < .001$). The monocular-binocular difference was larger when the viewing distance was 25 cm than when it was 50 cm ($p < .01$). Also, correlations between phoria and monocular-binocular differences ranged from .58 to .77, depending on viewing distances and tasks. The effects of phoria within the context of Hering's principle of visual direction can account for these results. In Experiment 2, the same subjects adapted to phoria-induced error by placing a finger over a monocularly viewed target. The difference in their pointing responses before and after the task were reliable ($p < .005$), and the correlations between phoria and the pre- to posttest differences were .45 or .77, depending on the number of adaptation trials. We argue that all monocular experiments dealing with visual direction should control for these effects.

Hering's principles of visual direction (Hering, 1879/1942) predict that the visual direction of objects will be nonveridical during monocular viewing if there is deviation of the occluded eye (phoria). Furthermore, the extent of nonveridicality will be a function of the extent of phoria (Ono, 1979). These predictions are based on the proposition that an object stimulating the fovea is seen on a line passing through the cyclopean eye and the intersection of the two visual axes. If the right eye is occluded, and if this eye deviates temporally (exophoria), the stimulus should be apparently displaced to the right (Figure 1, a), and if it deviates nasally (esophoria), the stimulus should be apparently displaced to the left (Figure 1, b). For the left eye, apparent displacements should be in the opposite directions. The predicted angular extent of the apparent displacement is half of the angular deviation of the occluded eye (see Appendix A for a derivation).

The predicted association between phoria and nonveridicality was indirectly confirmed in two different experimental settings: one in which accommodative vergence changed (Ono, Wilkinson, Muter, & Mitson, 1972) and another in which the monocularly viewing eye alternated (Ono & Gonda, 1978). These studies showed high correlations between an individual's measures of phoria and the extent of apparent movement. There is, however, no direct confirmation of the simpler and more fundamental prediction that displacement of head-centric visual direction will be produced by phoria (Howard, in

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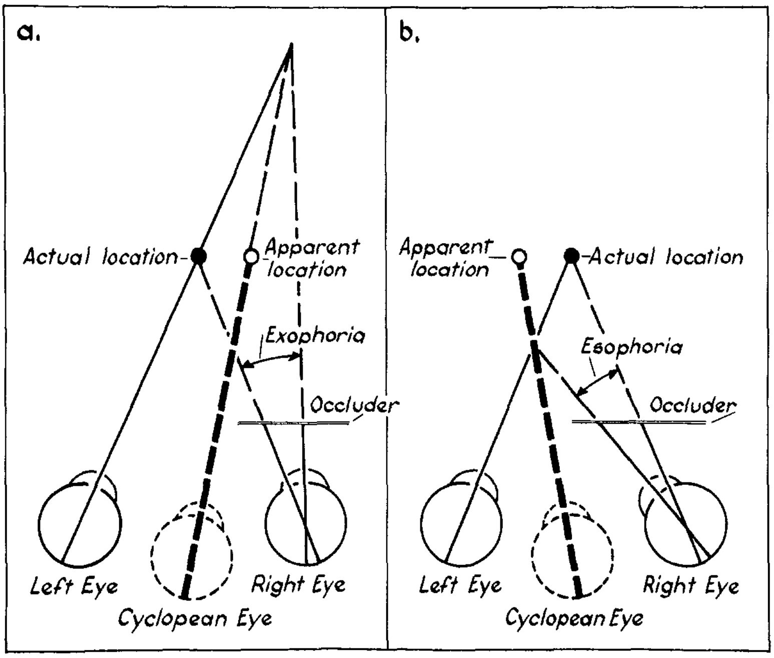

Figure 1. Apparent location of a stimulus as a result of phoria of the occluded right eye. (In Panel a exophoria produces displacement to the right, and in Panel b esophoria produces displacement to the left. The figure is drawn with the assumption that the visual axis of the viewing eye is centered on the stimulus and that the distance of the stimulus is correctly perceived.)

press). This prediction has a direct bearing on the reported shift of subjective straight-ahead (i.e., what subjects perceive as straight in front of their noses) during monocular viewing and, in fact, on the results of all monocular studies on egocentric visual direction. We, therefore, examined the effect of monocular viewing on visual direction.

The specific aims of this study were (a) to determine the extent to which phoria makes pointing nonveridical, (b) to examine the effect of this nonveridicality on the setting of a stimulus to the subjective straight-ahead, and (c) to show that subjects can adapt to this nonveridicality in the same way that they adapt to the displacement produced by a wedge prism. Experiment 1 dealt with (a) and (b), and Experiment 2 with (c).

Experiment 1

The apparent displacement associated with phoria should manifest itself in (a) an open-loop pointing task in which arm and hand cannot be seen and (b) a task that requires placing a stimulus in the subjective median plane. In Experiment 1, subjects were asked to point to an illuminated stimulus in an otherwise dark room (pointing task) and to place a visual stimulus straight ahead of their nose (straight-ahead task). These tasks were performed at two distances, because phoria is known to vary with distance (e.g., Ono & Gonda, 1978), and under three viewing conditions: (a) monocular left where the right eye was occluded (ML), (b) binocular (B), and (c) monocular right where the left eye was occluded (MR).

Method

Apparatus. A single light-emitting diode (LED) mounted on a motorized drive unit served as the stimulus for the task of setting a stimulus to the straight-ahead. Subjects controlled a three-way switch that moved the LED to the right or left in a plane parallel to their own frontal plane at a speed of .5 cm/sec. Another switch enabled the experimenter to reset the stimulus to a starting position. The position of the LED along the track was indicated by a scale hidden to the subject.

For the pointing task, the mobile LED was set to the median plane position, and two additional LEDs were attached to it, 4.5 cm on either side for the near viewing distance (25 cm) and 9 cm on either side for the far viewing distance (50 cm). The visual angle (10.2°) between two adjacent stimuli thus remained constant for the two viewing distances. A vertical pointing board was located in the stimulus plane, 2 cm below the row of LEDs. A screen between the stimuli and the pointing board extended toward the subject and prevented visual feedback on the pointing task. Subjects wore a thimble on the index finger of their pointing hand. The thimble had an electrical contact attached to its tip which was connected to a 10-V supply. The point of contact between the thimble and an array of in-series resistors along the pointing board gave a reading on a digital voltmeter and allowed the experimenter to record the position of the subject's finger with a resolution of 3 mm.

Throughout both tasks the subject's head was kept fixed by a biteboard. An occluder was mounted 4 cm in front of the subject's corneal plane. A variable prism and Maddox rod were used to measure phoria. (The Maddox rod in front of one eye optically modifies the monocular view of a stimulus to that eye so that the two monocular images are so dissimilar that they produce no fusional reflex. The power of prism required to superimpose phenomenally the two images from the two eyes indicates the extent of phoria.)

Experimental design and conditions. A similar experimental design was used for measuring the errors of pointing and the errors in setting the LED straight ahead. Half of the subjects performed the pointing task before the straight-ahead task. The order was reversed for the other half. For both tasks there were three viewing conditions—binocular, monocular right, and monocular left, which were repeated for two viewing distances—near (25 cm) and far (50 cm). The order of viewing distances (near-far vs. far-near) was equally divided among subjects. Subjects performed both tasks for one viewing distance and repeated them for the other viewing distance.

For the straight-ahead task, six measurements were taken under each viewing condition. The stimulus had six different starting positions (3 cm, 6 cm, and 9 cm to the right or to the left of the objective median plane). For each condition, the order of starting positions was randomized with one measurement taken for each starting position. The viewing condition was changed after each set of two measurements, following a randomized block design.

For the pointing task, two sets of 12 measurements were taken for each viewing condition. More trials were used for the pointing task than for the straight-ahead task, because the variable error in pointing to a stimulus is greater than that associated with setting a stimulus to a reference point (Barbeito & Ono, 1979). The order of viewing conditions was randomized for each subject. The sequence in which the three LEDs were presented within each viewing condition was randomized with the restriction that each appeared equally often.

Procedure. For each subject, the height of the chair and biteboard was adjusted to place the stimulus display at eye level. For the straight-ahead task subjects were instructed to close their eyes while the stimulus was set to its starting position. They were then asked to move the LED until it appeared to be directly in front of their nose. After two practice trials, six trials were run for each viewing condition, according to the sequence described above.

For the pointing task, two additional LEDs were added to the stimulus display. Subjects were instructed to point with the index finger of their preferred hand to the position on the pointing board directly beneath the stimulus. Three practice trials were given, one for each of the three LED positions, followed by six sets of 12 trials, according to the sequence described above. This procedure was repeated for the two viewing distances. Before and after the pointing task, two measurements of phoria were taken for each eye and for each of the three stimuli.

Subjects. All 19 subjects were members of the York University community and were paid for their participation. The 10 female and 9 male subjects reported normal visual acuity. Four subjects wore contact lenses and two wore glasses. Sixteen were right-handed; the remaining three were left-handed.

Results and Discussion

Each pointing response was scored as a signed deviation from the actual stimulus position, and each setting from the straight-ahead task was scored as a signed deviation from the objective straight-ahead. A deviation to the right was designated positive and a deviation to the left was negative. From these data, constant and variable errors for the two tasks were computed in angular extent with the midpoint between the two eyes on the corneal plane as the origin. For each subject and each subcondition, computation of the constant and variable error is based on 24 responses for the pointing task (8 responses to each of 3 stimuli) and on 6 responses for the straight-ahead task. Mean constant errors across subjects and standard deviations for each viewing condition are presented in Table 1. Mean variable errors and their standard deviations are presented in Table B1 in Appendix B.

The constant errors shown in Table 1 are in opposite directions for the two tasks. This is because a rightward displacement of the stimulus, for instance, would make a subject point to the right of the stimulus but would produce a constant error in the opposite direction for the straight-ahead task. That is, if there is a rightward apparent displacement, for a stimulus to appear straight ahead, it must be placed on the left side of the setting of straight-ahead obtained when there is no apparent displacement.

Table 1 shows that the means of the pointing responses were biased toward the right (all means are positive); and the mean settings of straight-ahead were toward the left (most of the means are negative). The bias

Table 1
Mean Constant Error and Standard Deviations in Degrees for Different Viewing Conditions and From Two Different Tasks in Experiment 1

	Viewing condition					
	ML		B		MR	
Task	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pointing						
Near	2.95	4.02	1.28	3.14	.21	3.23
Far	1.23	2.79	.69	2.65	.30	2.90
Straight ahead						
Near	−3.34	2.45	−.69	2.11	.85	3.07
Far	−2.20	2.60	−1.73	1.75	−.58	1.99

Note. ML = monocular left; B = binocular; and MR = monocular right.

to point toward the right is consistent with the bias reported by Werner, Wapner, and Bruell (1953). In their study, subjects pointed to the subjective straight-ahead while fixating a stimulus objectively straight ahead. The pointing bias to the right may be related to the fact that all subjects in Werner et al.'s study and most of the subjects in this study used their right hand for pointing. However, the bias toward the left in setting the single LED straight ahead is opposite to the bias reported by Akishige (Note 1) and Bruell and Albee (1955) in a similar task. The reason for this difference is not clear, but what is important for the hypothesis is the difference in the constant error among conditions.

Two-way analyses of variance (3 viewing conditions × 2 distances) were performed on the data from the pointing task and the straight-ahead task. The main effect of viewing condition was statistically significant: $F(2, 36) = 8.85, p < .001$; $F(2, 36) = 10.48$, $p < .001$, respectively. The interaction of Viewing Condition × Distance was also significant: $F(2, 36) = 5.43, p < .01$; $F(2, 36) = 25.00$, $p < .001$, respectively. The effect of distance was not statistically significant, which is reasonable because at both distances the effects of the MR and the ML condition should cancel. The Geisser-Greenhouse conservative F test was applied to all the significant differences; they were still significant at $p < .05$.

To elucidate the statistically significant differences, the mean magnitudes of predicted differences between the two monocular conditions and the binocular condition were computed. They are shown in Table 2 along with the observed differences. The predictions are based on the principles of visual direction and signed phoria. By assigning a positive value to exophoria and a negative value to esophoria, the mean phoria across subjects was found to be 8.42Δ ($SD = 6.50$) for the near condition and 3.22Δ ($SD = 3.47$) for the far viewing condition. The predictions of monocular-binocular differences were obtained by transforming the values of phoria in diopters to values in degree of arc and dividing the angle by two. (See Appendix A for details.) (The predicted *SD*s shown in Table 2 were computed from the predicted magnitude of apparent displacement for each subject. The magnitudes of the predicted or the observed values of the *SD*s are not directly relevant to the hypothesis, but they are presented here because they are relevant to the discussion of Experiment 2.)

The statistical significance of the main effect of viewing conditions and the rank orders of the numerical values of the constant errors shown in Table 1 are consistent with our hypothesis. Because the mean phoria is positive (exophoria) for both distances, the mean constant error should be toward the occluded eye in the pointing task (see Figure 1) but toward the viewing eye in the straight-ahead task. Thus, the numerical values of the mean constant errors for the pointing task should decrease in order from ML to B to MR, whereas they should increase in the same order for the straight-ahead task. These directional predictions were confirmed (see Table 1). Table 2 indicates, however, that the magnitudes of the observed differences in constant errors among the viewing conditions were smaller than predicted. Perhaps the reason for this is that each subject served in all conditions. The visual direction of the stimuli seen in the binocular condition may have somehow become incorporated in the responses in the monocular condition, thus making the constant errors smaller than predicted. If this post hoc interpretation is correct, it would also explain the even greater discrepancy between the observed and predicted values for the pointing task, since there were considerably more binocular condition trials for the pointing task than for the straight-ahead task (24 vs. 6). The statistically significant interaction between viewing conditions and distance is also consistent with the hypothesis. Since the mean phoria for the far condition is smaller than for the near condition, the differences in constant errors between monocular and binocular conditions should be smaller for the far condition.

All the preceding analyses were concerned with group means. Further analyses were performed to compare the predicted and observed values for individual subjects. The degree of agreement between these two values was determined by using the Pearson r and the 95% confidence interval. For the straight-ahead task, r was .77 ($.49 < \rho < .91$) for the near condition and .74 ($.43 < \rho < .90$) for the far condition. For the pointing task, r was .58 ($.17 < \rho < .82$) for the near condition and .66 ($.30 < \rho < .86$) for the far condition.

To recapitulate, the constant error covaried with viewing conditions, distances, and also with subjects; phoria is responsible for these covariations. When the biases were removed from the results, the direction of the constant errors agreed with the prediction that exophoria would shift the apparent direction of a stimulus toward the occluded eye and that the setting of a stimulus to straight-ahead would shift toward the viewing eye. One way to visualize the results is shown in Figure 2. The observed value of the difference between the monocular conditions and the binocular condition for the straight-ahead task can be seen as a function of the predicted value. The two sets of dotted lines that intersect at 90° show the relation between the predicted and observed group means, for the near and the far condition separately. The scatter around the regression lines indicates the degree of association between the predicted and observed individual scores. Notice that the group mean phoria is successful in predicting the group mean responses at two distances, and that the individual phoria predicts individual scores.

Table 2
Predicted and Observed Mean Differences and Standard Deviations in Degrees Between Monocular and Binocular Conditions in Experiment 1

	Distance			
	Near		Far	
Condition	*M*	*SD*	*M*	*SD*
Predicted	2.41	1.86	.92	.99
Observed				
Pointing	1.35	2.31	.44	.64
Straight ahead	2.11	2.04	.81	1.67

Our findings confirmed the results of Fischer (reported in Tschermak-Seysenegg, 1952, p. 213) in that monocular viewing shifts the subjective straight-ahead. However, whether the direction of constant error is consistent with that obtained by Fischer is difficult to say, given the way Fischer's results are reported. Howard and Templeton (1966, p. 281) stated, "Fischer found that the apparent straight ahead with monocular viewing shifts toward the eye which is used," an interpretation consistent with our results. But the opposite interpretation (i.e., a shift toward the occluded eye) is possible. This apparent contradiction is not important, however, because our findings imply that a

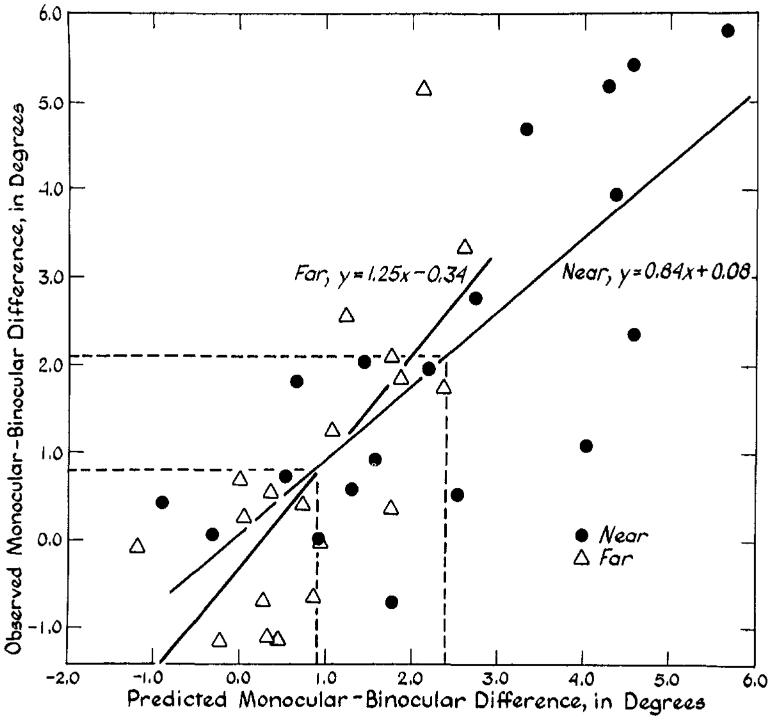

Figure 2. Relation between predicted and observed deviation of apparent direction in the monocular conditions from the binocular condition for the straight-ahead task.

general statement about the shift of the apparent straight-ahead should not be made. The direction of the shift is a function of the direction of phoria, and therefore the shift can be toward either the viewing or the occluded eye (see the data points from esophoric subjects in Figure 2). If the viewing distance were 2 m, for example, where subjects tend to be esophoric, then the mean shift should be toward the viewing eye (see Ono & Gonda, 1978).

Our findings also imply that monocular viewing will affect the results of any experiment dealing with egocentric visual direction. One effect will be demonstrated in Experiment 2.

Experiment 2

The results of Experiment 1 indicated that the extent of the nonveridicality of visual direction varies among subjects. Given a stimulus at 25 cm, the largest individual phoria measured was 20Δ, which was associated with mean constant errors across the two monocular conditions (disregarding the direction) of 9.1° and 5.8° for the pointing task and the straight-ahead task, respectively. This constant error is comparable to that produced by a wedge prism used in an adaptation experiment, and one would expect adaptation to occur if an appropriate sensory-motor task were provided. For subjects with a small phoria, the apparent displacement may be too small to demonstrate any adaptation, but for the group as a whole, one would expect a shift in pointing response after an appropriate sensory-motor task. Furthermore, the adaptation caused by the sensory-motor task should be greater for subjects with a large phoria—there should be a positive correlation between the extent of an individual's adaptation and phoria. Experiment 2 was designed to test these expectations. The usual paradigm involving a pretest, adaptation task, and posttest was used. In both the pretest and the posttest, subjects pointed to a target in a manner similar to the binocular condition in Experiment 1. The sensory-motor task required placing a finger over a small target viewed monocularly.

Method

Apparatus. Three light-emitting diodes (LEDs) in otherwise dark surroundings were the stimuli for the pre- and posttests and the sensory-motor task. The LEDs were arranged in a horizontal line at eye level, parallel to the subject's corneal plane at a distance of 25 cm, with the central LED located in the subject's objective median plane. The other two LEDs were placed 4.5 cm on either side of the central one, a distance that corresponds to 10.2° of visual angle. A cardboard strip placed 3 cm below the stimulus display recorded the subject's marking responses on the pre- and posttests. The marking strip was hidden from view by a screen extending toward the subject. The screen was removed for the sensory-motor task. Biteboard and occluder arrangements were identical to those of Experiment 1.

Experimental design and conditions. The pre- and posttests measured the accuracy with which subjects pointed to the location of a visual stimulus without visual feedback. Viewing for these tasks was binocular. During the sensory-motor task, viewing was monocular. The sensory-motor task was repeated once for the MR viewing condition and once for the ML condition. The order of these two conditions was random for each subject.

Within each condition, the sequence was identical: (a) pretest, (b) sensory-motor task, (c) posttest 1, (d) sensory-motor task, (e) posttest 2. Twelve measurements were taken for each pretest as well as posttest (four for each of the three stimuli). Each sensory-motor task consisted of 30 pointing responses (10 for each of the three stimuli). The three stimuli were presented in random order, with the restriction that each stimulus appeared equally often.

Procedure. The height of the chair and biteboard was adjusted to place the stimulus display at eye level. Each subject received three practice trials for the pre- and posttest task and three for the sensory-motor task. Subjects were instructed to adjust their initial pointing errors during the sensory-motor task until their finger touched and covered the LED. Subjects used their preferred hand for all tests and tasks.

During each pre- and posttest, the experimenter attached a strip of cardboard to the apparatus and provided the subject with a marking pen. Twelve measurements were taken within each test, four for each of the three stimuli. For each sensory-motor task, the experimenter occluded one of the subject's eyes, removed the cardboard strip, and removed the screen that had blocked the subject's view of his or her hand in the previous test. Each task consisted of 30 pointing trials.

Before and after the sequence of tests and tasks for one eye, two measurements of phoria were taken for each eye and for each of the three stimuli. After a short break the sequence was repeated, this time occluding the subject's other eye during the sensory-motor task.

Subjects. The same 19 subjects that had participated in Experiment 1 participated in Experiment 2.

Results and Discussion

The judged locations of the three stimuli as indicated by the marking responses in the pre- and posttests were the basic data for analysis. For each subject and for each viewing condition, the mean difference in indicated location between the pretest and the first posttest was computed (averaged across the three stimulus positions). Similarly the mean difference between the pretest and the second posttest was computed. A change toward the viewing eye was coded positive, and a change toward the occluded eye was negative.

Across all subjects and both viewing conditions, the mean changes were 1.33° (SD = .69°) for the pretest–first posttest difference and 1.47° (SD = .62°) for the pretest–second posttest difference. These values were both significantly different from zero, $t(18) = 8.29$ and $t(18) = 10.18$, respectively, with $p < .005$ for both. The Pearson r (and the 95% confidence interval) between the extent of phoria and the coded pretest to posttest changes was .45 ($.00 < \rho < .75$) for the pretest–posttest 1 difference, and .77 ($.49 < \rho < .91$) for the pretest–posttest 2 difference. (Phoria obtained in Experiment 2 was comparable to that of the near condition in Experiment 1.)

The statistically significant pretest–posttest difference and the degree of correlation confirmed our expectations. The mean pretest–posttest differences are the effects of the adaptation of the group to the apparent displacement produced by phoria, and the correlations measure the expected association between individual magnitude of adaptation and individual magnitude of phoria. Thus, the results indicate that phoria-induced error can be reduced in the same way as prism-induced error.

The fact that phoria produces apparent visual displacement and the fact that a subject can adapt to this displacement have methodological implications for any studies dealing with egocentric visual direction, particularly those prism adaptation studies in which viewing is monocular. We examined a sample of 60 published studies on prism adaptation and found that 25% of these used monocular viewing. None of these considered phoria as an additional source of apparent displacement. The implications of our findings concern the intersubject variability and between-conditions variability as they will be discussed below.

The factors that explain our results predict that individual differences in the extent of adaptation will be larger for monocular studies than for binocular studies. Yet this increase in individual difference is not discussed or implied in the current relevant literature (e.g., Epstein, 1967; Rock, 1966; Welsh, 1978). The literature implies simply that subjects should experience an apparent angular displacement of .57 × prism diopter value. However, the results of Experiments 1 and 2 show that we cannot specify the extent of apparent displacement produced by a prism in front of one eye unless we know the position of the occluded eye as well, since visual direction depends on the position of both eyes. For example, consider placing a 20Δ prism in front of one eye and occluding the other eye. The apparent displacement should be 11.4° if the visual axis of the occluded eye as well as that of the eye with the prism deviates 11.4° from the actual position of a given stimulus. But it should be 5.7° if the visual axis of the occluded eye is pointed toward the target while the eye with the prism foveates the stimulus. And there should be no apparent displacement when the visual axis of the occluded eye deviates 11.4° in the direction opposite to that of the eye with the prism. It is even possible to have "negative" adaptation (or displacement), if the occluded eye deviates more than 11.4°.

Thus, in monocular experiments of prism adaptation one can expect a wide range in the extent of apparent displacement and adaptation. To check this expectation, we reanalyzed the data from Wilkinson's (1971) adaptation study, in which the stimulus was located 45 cm from a subject who was wearing a 12° displacement prism spectacle on one eye with the base toward the temporal side. The range of the pretest–posttest difference was 1.65° to 13.68° ($SD = 3.04$, $n = 20$). It is likely that part of this variability is due to the individual differences in the extent of phoria. Our estimates of this variability for viewing distances of 25 cm and 50 cm are presented in Table 2 of Experiment 1.

The explanation of our results also predicts an asymmetry of the extent of displacement and adaptation when the base of a prism is to the right versus when it is to the left. (For data consistent with this prediction, see Bailey, 1957. There are many studies that use both the base-right and the base-left conditions, but they only report the average of the two conditions.) The effects of phoria observed in Experiment 1 add to or subtract from the displacement intended by the experimenter in prism experiments, and the kind of adaptation to displacement observed in Experiment 2 adds to or subtracts from the expected extent of adaptation. Consider placing a prism in front of the right eye of an exophoric subject. If the base of the prism is to the right, the apparent displacement toward the left will be enhanced. If the base is to the left, the apparent displacement toward the right will be reduced. This example should hold for most adaptation studies because most subjects are exophoric for a stimulus at reaching distance. Thus, we would expect a greater extent of adaptation in the base-right condition.

The demonstration that subjects adapt to phoria-induced error also suggests that what Day, Singer, and Keen (1967) have called "behaviour compensation" may be, in fact, another instance of adaptation to phoria-induced error. Their subjects monocularly viewed one hand through an aperture and produced a change in "manual centering responses." Their results were explained by Ono and Angus (1974) as an adaptation to a displacement produced because the two visual axes of the subjects were directed toward the center of the aperture. However, the results of this experiment show that subjects in Day et al.'s experiment could have monocularly accommodated or fixated on their hand through the aperture and that phoria could have produced an apparent displacement to which subjects adapted.

General Discussion

Hering's principles of visual direction (1879/1942) are based on the general idea that the two eyes work together as one (cf. Walls, 1951). Accordingly, the position of the occluded eye together with the position of the viewing eye should calibrate or give value to a local sign (stimulation of a given retinal location) to determine the visual direction. It is not the case that the position of the viewing eye calibrates the local sign from that eye. To state it more precisely, a stimulation at the center of the fovea of either eye will signify a visual direction on a line that passes through the intersection of the two visual axes and the cyclopean eye (see Figure 1). This hypothesis makes the counterintuitive prediction that when the visual axis of the viewing eye is directed toward the stimulus, the extent of nonveridicality of direction of the stimulus or of setting of the straight-ahead is a function of the position of the occluded eye.

The results of Experiment 1 confirmed this prediction. The group data showed that in the near condition, where exophoria was larger, the extent of nonveridicality in angular units was larger than in the far condition, where the phoria was smaller. The individual data showed that for subjects with large phoria, the extent of nonveridicality was larger than for subjects with small phoria. Furthermore, the constant errors for the settings of straight-ahead covaried with the extent of nonveridicality. The relation between the extent of nonveridicality and deviation of the occluded eye is not limited to the normal population. It also holds for esotropes and exotropes who are constant suppressors, but not for those who are alternating suppressors (see Mann, Hein, & Diamond, 1979).

The conclusion that phoria is responsible for the constant errors implies that one should not always expect, as a general rule, that pointing or the setting of a stimulus to straight-ahead should always shift toward the occluded eye or always toward the viewing eye. If viewing distances are greater than the distances used in this study, subjects tend to be esophoric, and the direction of the nonveridicality should be in the direction opposite to what we found in Experiment 1 (see Ono & Gonda, 1978).

The underlying mechanism that produces the nonveridical visual direction associated with phoria is the same one that produces the nonveridical visual direction associated with a wedge prism. Both are outcomes of the joint position of the two eyes calibrating the local sign of a stimulus. Both phoria-induced error and prism-induced error are due to the fact that the joint position of the two eyes with phoria or prism is different from their joint position when there is no phoria or no prism. In this light, the results of Experiment 2 are not surprising. However, the explanation for the results predicts relatively large individual differences in the extent of adaptation in a monocular prism study and asymmetry in the extent of adaptation when the base of a prism is on the right as opposed to when it is on the left. Since the position of the occluded eye can influence the results of experiments dealing with visual egocentric direction as demonstrated in Experiments 1 and 2, it is important to control for phoria in any monocular experiment.

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Appendix A

Our prediction of the extent of nonveridicality of direction produced by a given phoria is based on one of Hering's principles of visual direction summarized by Ono (1979): "An object which stimulates the center of a fovea in either eye or the centers of the fovea in both eyes will be seen on a line passing through the cyclopean eye and the point of intersection of the two lines of sight (visual axes)." This is illustrated in Figure 1. Thus, the predicted extent depends on an assumption about the location of the cyclopean eye. The prediction that the angular extent of displacement of visual direction (α) is one half the angular deviation of the occluded eye (β) is based on the assumption that the cyclopean eye is midway between the two eyes and that it is on the Vieth-Mueller circle that passes through the intersection of the two visual axes. The angle α is exactly equal to $\beta/2$ only when the stimulus is in the objective median plane. For example, if the right eye of an exophoric subject is occluded, α will be smaller than $\beta/2$ for a stimulus on the right of the median plane and larger for a stimulus on the left. However, we used $\beta/2$ as the predicted value of angular displacement in all cases, because the exact values of α are close to $\beta/2$, as will be shown.

The exact value of α can be calculated with the following formula in which it is assumed that the nodal point of each eye is located at its center of rotation.

$$\alpha = \frac{\beta}{2} + \frac{a_2 - a_1}{2} + \tan^{-1} \frac{D_1}{D_2 + \frac{i}{2} \cot \frac{(\beta + a_1 + a_2)}{2}},$$

where a_1 = angle at the nodal point of the left eye subtended by the stimulus and the nodal point of the right eye, a_2 = angle at the nodal point of the right eye subtended by the stimulus and the nodal point of the left eye, D_1 = the perpendicular distance of the stimulus from the median plane, D_2 = the perpendicular distance of the stimulus from the line passing through the two nodal points, and i = interocular distance. The derivation for the above formula is cumbersome, but a proof that $\alpha = \beta/2$ when the stimulus is on the median plane is straightforward. It is shown below and in Figure A1.

Let C, R, and L mark the location of the cyclopean, the right and the left eye, respectively. Point I is the intersect of the two visual axes. Point A is the intersect of the Vieth-Mueller circle and

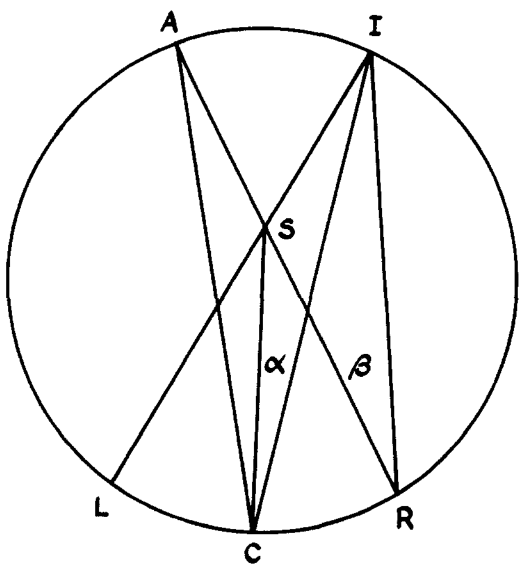

Figure A1. Relation between α and $\beta/2$ when a stimulus is in the objective median plane.

the line that passes through the stimulus (S) and the nodal point of the right eye.

1. ∠ CIL = ∠ RAC (Angles subtended by chords of equal length [LC = CR]).

2. ∠ ISR = ∠ASL (Opposite angles).

3. ∠ RSC = ∠ CSL (CS bisects RSL [the condition that the stimulus is in the median plane]).

4. α = ∠ SCA (CSI and CSA are similar triangles because all angles are equal).

5. $\beta = \alpha +$ ∠ SCA (Angles subtended by the same chord).

6. $\beta = 2\alpha$, thus $\alpha = \beta/2$ (4 and 5).

The value of $\beta/2$ is a good approximation for predicting the value of constant error in the monocular condition (or the binocular-monocular difference) for the two tasks used in Experiment 1. Consider the "average" subject (with i = 6 cm) in the near condition. His exophoria would be 8.42Δ, and $\beta/2$ would be equal to 2.41°. The exact values of α for the three stimuli used in the pointing task are 2.46°, 2.41°, and 2.36° for the left, middle, and right stimuli, respectively. Notice that the prediction for the stimuli on each side of the median plane is close to the value of $\beta/2$ and that the mean of the three predicted values equals that of $\beta/2$. For the far condition, the predictions are even closer to the value of $\beta/2$, because the extent of phoria is smaller. Notice also, that one need not assume that the cyclopean eye is located on the extension of the Vieth-Mueller circle. If, instead, we assume that the cyclopean eye is located on the straight internodal line between the two eyes, the predicted values become 2.35°, 2.42°, and 2.50° for the corresponding near stimuli. Again $\beta/2$ is a good approximation.

Appendix B

We made no prediction about the magnitude of variable error. However, for anyone interested in the precision of the responses in the two tasks, we computed the standard deviation of each subject's responses for each condition. This variability represents variable error. The mean variable errors across subjects for the three different viewing conditions and the two distances are presented in Table B1. We also performed an analysis of variance on the variable errors (exactly the same form as the analysis of the constant errors) with the following results.

The main effect of viewing condition was significant for the pointing task but not for the straight-ahead task: pointing task, $F(2, 36) = 7.46$, $p < .005$; straight-ahead task, $F(2, 36) = .46$, *ns*. The main effect of distance was significant for both tasks: pointing task, $F(1, 18) = 13.58$, $p < .005$; straight-ahead task, $F(1, 18) = 5.35$, $p < .05$. None of the interactions (Viewing Condition × Distance) was significant.

Table B1
Mean Variable Error and Standard Deviations in Degrees for Different Viewing Conditions From Two Different Tasks in Experiment 1

	Viewing condition					
	ML		B		MR	
Task	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pointing						
Near	3.52	2.06	2.36	.99	2.66	1.98
Far	2.26	.79	1.82	.45	2.16	.64
Straight ahead						
Near	2.61	1.21	2.82	1.72	2.73	1.31
Far	2.10	1.16	2.03	.86	2.40	1.24

Note. ML = monocular left, B = binocular, and MR = monocular right.

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