Oculomotor adaptation to induced heterophoria and anisometropia

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In the first part of the paper we demonstrate that the oculomotor system adapts to prism-induced heterophoria over limited motor fields. In the second part we demonstrate that it can also adapt to an induced anisometropia. When normal subjects are made 3 diopters anisometropic, they initially exhibit a phoria whose magnitude is dependent on eye position. After 2½ hr of binocular visual experience, this incomitant phoria has largely disappeared. (Invest Ophthalmol Vis Sci 22:234-240, 1982.)

Key words: heterophoria, anisometropia, oculomotor adaptation

An aspect of the oculomotor system that has received relatively little attention is its ability to keep the two eyes pointing in the same direction when one eye is occluded. In our own laboratory we have found the fidelity of this system to be remarkable. Using a phoria measuring technique, we have calculated that relative eye position is maintained, in the vertical meridian, with a standard deviation of 3 min arc over a period of 3 minutes. Despite the fact that during the occlusion time, the eyes have made a considerable number of binocular excursions, they have remained precisely aligned even though the stimulus to align them, i.e., a fusible target, is absent.

It has been shown by several researchers that the phoria or fixation disparity that occurs after a prism has been placed before one eye gradually disappears as the subject is allowed to view binocularly through the prism. The data of Henson and North show that on average the phoria generated by 2 prism diopters base-up before the right eye is reduced by 1.5 prism diopters with just over 3 minutes of binocular visual experience. They interpreted this finding as indicating that the oculomotor system is capable of adapting the output of the center that normally maintains relative eye position. Schor has presented a model to explain this adaptation, hypothesizing that the output of the fusion mechanism is responsible for adaptation.

Henson and North further hypothesized that a process of adaptation similar to that described by them was essential to the visual system to enable it to compensate for the normal changes in orbital mechanics that occur with age. The gradual enophthalmus that results from a loss of orbital fat and the changes in muscle structure are just two of the normally occurring eye changes that would require major alterations in the patterns of innervation to the extraocular muscles.

The alterations in orbital mechanics that would result from these age changes would not be expected to produce overall shifts in visual direction such as that produced by an ophthalmic prism. It would seem likely that...
their effects would at least be partly dependent on eye position; for example, if the elasticity of a muscle were to change, then the effects as measured by the phoria would be different for each position of gaze. To compensate for these types of changes, the adaptive mechanism must be capable of operating over limited motor fields.

In the first part of this paper we are going to demonstrate this by adapting the eye to a prism while keeping eye position stable and then measuring the degree of adaptation that has occurred at different eye positions.

In the second part of this paper we are going to demonstrate how the oculomotor system deals with a prismatic change whose magnitude is made to vary across the motor field.

**Experiment 1**

**Methods.** Relative eye position (heterophoria) was measured with the eye in different positions within the orbit by getting the subjects to rotate their heads about a vertical axis while maintaining fixation at a fixed point on a screen.

At the beginning of an experiment, each subject's phoria was measured with the head rotated to a series of different positions about this vertical axis, e.g., 20° right, 10° right, straight ahead, 10° left, 20° left. Once these baseline measurements had been taken, subjects were given 3% minutes (15 periods of 15 sec) of binocular visual experience through a 2 prism diopter base-up prism before the right eye. At the end of this period each subject's phoria was again measured at the different head positions.

During the period of binocular vision subjects were instructed to maintain accurate fixation at the center of an internally illuminated test chart that subtended 13° at the eye. The chart was composed of a large number of high-contrast symbols whose angle of subtence ranged from 5 mins arc to 5°. The symbols were arranged so as to make fusion of any two regions of the chart difficult. There were both large and small symbols in the center and the periphery of the chart.

The total range of possible head rotation for each subject rarely exceeded 40°, due to limitations in neck musculature. To investigate beyond 20° left to 20° right of the primary position, the experiments were repeated: (1) with the 3% minutes of binocular vision through the base-up prism given to the subjects with their heads rotated approximately 20° to the right of the primary position and (2) with their heads rotated approximately 20° to the left of the primary position.

The heterophoria was measured subjectively with a red Maddox rod and tangent scale. Prior to a phoria measurement the subject's right eye was occluded with a photographic shutter for a period of 15 sec. During this time the Maddox rod was placed in front of the right eye. At the end of the 15 sec period the shutter, which was set to give an 0.25 sec exposure, was triggered by the subject. The shutter was electronically connected to the test chart and Maddox rod light source in such a way that the chart illumination was turned off only during the period that the shutter was open and the Maddox rod light source turned on only for the same period.

This arrangement allowed the subject to view the test chart (situated at 4 m) up until the moment that a phoria measurement was taken and hence gave a better control over the accommodative system than is normally available with the Maddox rod test. With this technique subjects were able to report the amplitude of their phorias with an accuracy of better than 0.25 prism diopters.

The timing sequence of the shutter, chart illumination, prism, and Maddox rod is given in Fig. 1. It can be seen from this figure that there was always 15 sec of occlusion prior to a phoria measurement and 15 sec of binocular viewing prior to a period of occlusion.

When measurements of the phorias were taken with the head rotated away from the position where binocular visual experience had been gained, the head rotation was made during the period that the

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**Fig. 1.** Time sequence of chart illumination, shutter, Maddox rod, and prism.
shutter was closed. The head was then turned back before the shutter was again opened to give a further 15 sec of binocular visual experience.

The sequence of measurements taken during a typical experiment are given in Fig. 2. During the measurement period a single measurement of the phoria was taken at a single head position after each occlusion period. At least two measurements of the phoria were taken at each head position during a single experiment. These two measurements were not made one after the other but were separated by a measurement at every other tested head position.

**Results.** All subjects showed, at the position where binocular visual experience was given, between 1 and 1½ prism diopters of adaptation during the 3½ minutes of binocular viewing through the prism. That is to say, their phorias decreased by this value during the adaptation period. The difference between the amount of adaptation with the head in its zero position (where binocular visual experience was given) and with it rotated to the left and right of this position is shown in Fig. 3. It can be seen that the amount of adaptation was maximal at the position where binocular visual experience through the prism was obtained. When the eyes were rotated away from this position, the amount of adaptation was seen to decrease.

At 20° from the position of binocular visual experience, the adaptation was approximately half of that experienced at the zero position, indicating a fairly large amount of spread in the adaptive mechanism from the point where binocular information was obtained. This spread was certainly much greater than would be expected from the small eye movements that occurred during the adaptation period when subjects were asked to maintain fixation at the center of the chart.

No noticeable difference in the spread of adaptation, from the position where binocular visual experience was given, occurred when adaptation was confined to directions other than the primary one (Fig. 3, solid line).

In the first experiment, we have shown how the oculomotor system adapts to a prismatic deviation when all binocular visual experience is confined to a particular oculomotor position and all other oculomotor positions have received no vergence information throughout the test period.

In the second experiment, we are going to demonstrate what happens when the magnitude of the adapting stimulus varies across the motor field and the subjects are allowed free eye movements during the adaptation period.

**Experiment 2**

**Method.** The magnitude of the prism to which the subjects had to adapt was made to vary across the motor field by fitting one eye of each subject with a negatively powered soft contact lens and then correcting the induced refractive error with a positive spectacle lens. Because the contact lens moves with the eye, the subject experiences a
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Fig. 3. Spread of adaptation across the motor field. Zero on the abcissa represents the point at which binocular visual experience was given through a 2 prism diopter ophthalmic prism placed base-up before the right eye. Three sets of data were taken on each subject: (1) with the binocular visual experience given in the primary position (α); (2) with the binocular visual experience given while the eyes were turned approximately 20° to the left (•); and (3) with the binocular visual experience given while the eyes were turned approximately 20° to the right (⊙).

prismatic effect, base toward the center of the lens for the right eye, at all positions of gaze other than that through the optical center of the spectacle lens. The magnitude of this effect is proportional to the distance from the optical center of the spectacle lens to the point where the line of sight passes through the lens.

A haploscopic device was used at the beginning of the experiment to measure the subjects' phorias with their eyes turned 7.6°, 14.9°, and 21.8° up, down, to the left, and to the right from the primary position. Subjects then performed normal office/laboratory type visual functions such as reading and writing while wearing the contact lens/spectacle lens system. They returned to the equipment, at approximately 10-minute intervals in order to have their phorias measured at the different test positions of gaze. All these measurements took place with the head in the primary position. The subjects wore the contact lens and spectacle lens for periods of up to 3 hr. Measurements with −1.50 and −3.00 D contact lenses were made on four subjects and with −4.50 D contact lens on two subjects.

Results. The oculomotor systems of all the subjects were found to adapt to the induced prismatic effects created by the −1.50 and −3.00 D contact lenses at all the positions of gaze tested.

The results of one subject, which were typical of those for all subjects, are given in Fig. 4.

It can be seen from this figure that after the contact lens and spectacle lens had first been placed before the eye, the oculomotor system demonstrated a phoria whose amplitude was dependent on eye position. As the subjects
Fig. 4. Oculomotor adaptation of one subject to the spectacle-corrected anisometropia induced by the wearing of a −3.00 D contact lens. Each line in this figure represents the change in phoria for positions of gaze: 7.6°, 14.9°, and 21.8° up, down, to the right, and to the left. The lines drawn through the data are the best-fitting exponential curves of the following form: $y = P \cdot \exp^{-Bx}$. The value of $B$ is given at the end of each line.

Analysis of the $B$ values for the different positions of gaze showed that the rate of adaptation was invariably faster in downward gaze than in upward gaze. In 24 subjects out of the 30, adaptation was faster in downward gaze. We believe that this difference resulted from the larger amount of time that the subjects spent viewing through the lower part of their corrections during the adaptation period. Although we have no quantitative measure of this, the types of visual task carried out by the subjects, such as reading and writing, would give a larger amount of visual experience through the inferior parts of the correction.

Another finding was that the rate of adaptation showed a slight tendency to be faster in the center of the motor field. Comparing the $B$ values of the 7.6° excititions with the 21.8° excititions shows that in 25 subjects out of 40, adaptation was faster at the more central position. Again, we believe this was due to the larger amount of the time spent looking through the central region of the correction, although it may also have been affected by the magnitude of the prismatic difference be-
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Fig. 5. Rate of adaptation as represented by the value of B from the best fitting curves of the equation \( y = P \cdot \exp(-Bx) \) for different degrees of anisometropia. Each symbol represents the mean value of all subjects for all positions of gaze in either the vertical or horizontal meridian. C.L., Contact lens.

Fig. 6. Adaptation of one subject in the vertical meridian for the different values of anisometropia and fixation positions. For each of the three fixation distances, 7.6°, 14.9°, and 21.8°, the values of the phorias in the up and down positions have been algebraically added. Dashed lines, Data from the −1.50 D contact lens; solid lines, data from −3.00 D contact lens; dashed/dot lines, data from −4.50 D contact lens.

Finally, analysis of the B values showed that the rate of adaptation decreased as the power of the contact lens and correcting spectacle lens increased. With the −4.50 D contact lens, the rate of adaptation declined to practically zero (Fig. 5). This finding is again shown in Fig. 6, where the results for one subject in the vertical meridian are shown for all fixation positions and three different contact lens powers. The rates of...
adaptation for the −1.50 and −3.00 D contact lenses were similar, whereas the rate for the −4.50 D contact lens was considerably slower. It can also be seen from Fig. 6 that the slowing down of adaptation with the higher-powered contact lenses occurred at all three fixation positions. The prismatic effect for the small-fixation position with the −4.50 D contact lens was however initially no greater than that experienced with the large-fixation position and lower-powered contact lenses.

Discussion

The data from the first experiment indicate that there is a spread of adaptation from the position of binocular visual experience. This spread aids the oculomotor system in adapting the whole oculomotor field. Without it, binocular visual experience would be required in every position of gaze for adaptation to be complete. However, while it aids in this manner, it puts a limit on the rate of change of prism per degree of eye movement that the oculomotor system can adapt to. When the rate exceeds a certain value, binocular visual experience in one position of gaze will disadapt neighboring positions and vice versa.

In the second experiment each contact lens/spectacle lens system presented the oculomotor system with a different rate of change of prism per degree of eye movement. From the data taken at time zero, the rates have been calculated to be approximately 0.07, 0.13, and 0.46 prism diopters per degree for the −1.50, −3.00, and −4.50 diopter contact lenses, respectively. The results show that with the −4.50 D contact lens, the adaptation rate declined to a very low value. This decline occurs for all fixation distances and is independent of the amplitude of the prism. The results of this experiment therefore support a hypothesis that the adaptive mechanism is limited more by the rate of change of prism with eye position than the amplitude of the prism.

Further evidence in support of this hypothesis comes from the works of Ogle et al.² and Carter.⁶ Both these researchers have reported that subjects can adapt to prisms whose power does not vary across the motor field, of considerably higher values than those used in this experiment.

Ogle et al.² report on a case of a subject adapting to 28 prism diopters base-out, and Carter⁶ reports on several subjects adapting to their maximum fusible prism in the horizontal meridian. These researchers did however use longer adaptation periods than the present study.

The type of oculomotor adaptation recorded in this experiment is identical to that required of naturally occurring anisometropes when they receive their first spectacle correction. The results of this experiment would indicate that anisometric subjects would, with time, adapt their oculomotor systems in the manner predicted on purely optical grounds, so that their phorias would not vary when they were looking through different parts of their spectacle lenses. The works of Ellerbrock and Fry,⁷ Ellerbrock,⁸ and Allen⁹ have already shown that this is, in fact, the case.

REFERENCES