Is Adaptation to Perceived Interocular Differences in Height Explained by Vertical Fusional Eye Movements?

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PURPOSE. To find out whether adaptation to a vertical prism involves more than fusional vertical eye movements.

METHODS. Adaptation to a vertical base-up 3 prism diopter prism was measured in a custom-programmed Maddox test in nine visually normal emmetropic subjects (mean age 27.0 ± 2.8 years). Vertical eye movements were binocularly measured in six of the subjects with a custom-programmed binocular video eye tracker.

RESULTS. In the Maddox test, some subjects adjusted the perceived height as expected from the power of the prism while others appeared to ignore the prism. After 15 minutes of adaptation, the interocular difference in perceived height was reduced by on average 51% (from 0.86° ± 0.44°). The larger the initially perceived difference in height in a subject, the larger the amplitude of adaptation was. Eye tracking showed that the prism generated divergent vertical eye movements of 1.2° on average, which was less than expected from its power. Differences in eye elevation were maintained as long as the prism was in place. Small angles of lateral head tilt generated large interocular differences in eye elevation, much larger than the effects introduced by the prism.

CONCLUSIONS. Vertical differences in retinal image height were compensated by vertical fusional eye movements but some subjects responded poorly to a vertical prism in both experiments; fusional eye movements were generally too small to realign both foveae with the fixation target; and the prism adaptation in the Maddox test was fully explained by the changes in vertical eye position, suggesting that no further adaptational mechanism may be involved.

Keywords: vertical prism, adaptation, eye movements

Ophthalmic lenses, used to correct refractive errors, induce prismatic effects when the subject looks through the peripheral part of the lens. Prismatic deviations are also induced when the lens is decentered with respect to the eye in straight position,1,2 emphasizing the importance of careful centration of spectacle lenses. If spectacles are tilted with respect to the sagittal plane, the retinal images shift in the opposite vertical directions in both eyes, which can cause diplopia if they are no longer fused. Long ago, it was found that subjects could adapt to differences in vertical image height, although with different degrees of success. Ogle and Prangen5 found that diplopia, induced by vertical prisms in front of the eyes, typically disappears within 15 to 20 seconds. This was in line with later findings by others.3,5 It was also found, without training, the limit of prism adaptation was in the range of 3 prism diopters (PD).3,4,6 Adaptation was the less successful, the higher the prism power.8 The major part (75%) of adaptation to vertical disparities occurred in the first minutes of exposure6,7 and full compensation was typically achieved in 10 minutes. Adaptation worked equally for prisms base-up or base-down.4

A theory on prism adaptation was proposed by Hoffmann and Bielchowsky in 1900.5,7 According to this theory, adaptation occurs in two steps.9 The “fast fusional system” realigns eye positions in less than 1 second.10 It induces adaptation in the secondary “slow fusional system.” However, it remains unclear whether the “fast fusional system” reflects vertical fusional eye movements while the “slow fusional system” may reflect a cortical adaptation process, for instance through a shift in the positions of the cortical retinotopic maps with respect to each other. Therefore, the goal of the current study was to find out whether vertical fusional eye movements could fully explain the adaptation to differences in image height between both eyes and whether a cortical component must be postulated.

MATERIALS AND METHODS

Subjects

Subjects were recruited from the Ophthalmic Research Institute. They were naive to the experimental procedures but were informed about the goal of the study. For the psychophysical experiment, their average age was 27.0 ± 2.8 years with a range of 24 to 31 years (n = 9). Limited by availability, vertical vergence eye movements could only be measured in six of those subjects, using a binocular eye tracker. They had an average age of 26.0 ± 2.0 years with a range of 24 to 29 years. Only emmetropic subjects with refractive errors within ± 0.5 diopters (D); astigmatism of less than 0.5 D, anisometropia of less than 0.5 D; normal visual acuity (1.0 or
better on a Snellen reading chart); and no known deficits in stereoscopic vision, as tested with Julesz random dot stereograms, were included. None of the subject showed any significant interocular differences in eye elevation, neither when measured with the Maddox test nor when measured with the eye tracker. The study was approved by the Ethics Commission of the University of Tübingen (2012, reference number 127/2012B02) and complied with the declaration of Helsinki. The subjects read and signed a letter of consent as requested by the Ethics Commission.

Measurement Procedures

Two different procedures were applied to measure adaptation to a vertical, base-up 3 PD prism, one psychophysical (the Maddox test) and one with a binocular eye tracker. Both were written using a commercial integrated development environment (Visual C++; Microsoft Corp., Redmond, WA).

Psychophysical Test (Maddox Test). After the room was dimmed, the trial frame was adjusted for the psychophysical measurements and the subject received brief instructions about the task. Using a chin rest that limited head movements in depth and tilt, a red (RGB 50, 0, 0) and green (RGB 0, 70, 0) cross, each subtending a visual angle of 5.1°, with a lateral distance of 4.8°, were presented on a black background and had to be aligned in height 25 times by the arrow keys of the keyboard, each with a different random starting point. One pixel was equivalent to 0.02° visual angle. Viewing distance was 73 cm. Subjects wore conventional red-green-spectrum filters that permitted the right eye to only see the red cross and the left eye only the green. Adjusted height differences (in pixels) were displayed on the screen but remained invisible to the subjects to avoid feedback.

The procedure was done without the prism, then after a 15-minute period, with the prism in place and repeated after another 15 minutes without the prism. To exclude learning effects, the initial height of the green cross was randomly varied from 45 to 55% of the screen height, while the red cross appeared always at 50%.

A test was performed in a single subject (subject 1, see below) to verify that both measurement procedures, the psychophysical test and the eye tracking (described below), could resolve angular changes of less than 1°. Vertical prisms, all base-up, with known power were placed in front of one eye. Their power was 1, 2, 3, 4, 6, 8, and 10 PD, equivalent to 0.57, 1.15, 1.72, 2.29, 2.86, 3.43, 4.57, 5.71° of angular deviation. Subject 1 was chosen because he demonstrated a full response to the power of the prism in the Maddox test. During this test, he was instructed to keep the eyes closed when not engaged in adjusting the height of the two crosses. Measurement time was kept as short as possible to exclude adaptation. A regression analysis of the adjusted deviations versus the known prism powers revealed close correlations both for the psychophysical data and the eye tracker data (Fig. 1), indicating that both measurement procedures could resolve 1° of vertical prism power, or better.

Eye Tracking. Eye tracking was performed in a dimmed room to ensure large pupil sizes (illuminance approximately 10 lux). The computer screen and the green fixation LED, 0.57° above the center of the camera aperture, were the only light sources. Since the subjects were young, they all had large pupil sizes (right and left eyes—subject 1: 6.84 ± 0.36 and 6.75 ± 0.40 mm; subject 2: 6.08 ± 0.37 and 5.92 ± 0.46 mm; subject 3: 5.90 ± 0.50 and 5.65 ± 0.65 mm; subject 4: 7.60 ± 0.90 and 7.32 ± 0.32 mm; subject 5: 7.41 ± 0.17 and 7.35 ± 0.27 mm; subject 6: 6.43 ± 0.47 and 5.71 ± 0.75 mm). Their pupil sizes represented an optimal condition for eye tracking and photofraction (Fig. 2).

Subjects were instructed to keep their head stationary in the chin rest during the whole period. Since head tilts to the side had severe effects on the elevation of both eyes, the head was carefully aligned vertically. The gaze tracker software emitted a beep as soon as the head was tilted by more than half a degree, determined from relative pupil height when no prism was worn. Measurement distance was long (3.54 m) to provide a stationary angular position of the infrared photoretinoscope, attached to the camera, which generated the first corneal Purkinje image necessary for eye tracking. To achieve sufficient image magnification, a long focal length lens (Canon FD 200 mm, f/4; Canon U.S.A., Inc., Melville, NY) was attached to the analogue infrared sensitive video camera (DMK 3002BR/C; The Imaging Source, Bremen, Germany). Otherwise, the algorithms were adopted from the original PowerRefractor. The angular resolution of the eye tracker was verified by viewing distance was 73 cm. Subjects wore conventional red-green-spectrum filters that permitted the right eye to only see the red cross and the left eye only the green.

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They were instructed to fixate a green LED above the camera lens with their open eye. Except for the data between 0.5 and 1.5\degree, the measured differences in eye elevation matched the power of the prisms. Possible reasons may be minor vertical tilts of the spectacles with the IR filter and the prism that may have affected the eye tracker data mainly at the low prism powers.

Binocular eye positions were averaged from 50 measurements, and were acquired by the eye tracker in 2 seconds. The initial measurement, without prism, served as reference in each subject. Subjects were instructed to close their eyes while the 3-PD prism was introduced, base-up, in front of the left eye. Subsequently, they were asked to open their eyes again, and the positions of both eyes were recorded, the left eye through the prism. Measurements were repeated every 2 minutes over a period of 8 minutes. Thereafter, the prism was removed and eye positions were recorded again every 2 minutes, for an additional 6 minutes.

**Effects of Lateral Head Tilt on Eye Elevation.** It was found that even small angles of lateral head tilt caused severe asymmetries in vertical eye elevation in one subject. To achieve a better control over head alignment, the nose bridge and the chin were aligned to a thin wooden rotatable bar and alignment was checked in the video frame. Furthermore, the elevation of the two pupil centers in the video frame was determined and the angle of the connecting line was evaluated—although it is clear that this mode of head position control is valid only when no asymmetrical vertical eye movements occurred.

The effect of lateral head tilt on the direction of the fixation axes in both eyes of one subject is shown in Figure 3. There was a linear relationship between both variables. Strikingly, in subject 1 (below) the differences in eye elevation induced by lateral head tilt were much larger than one would expect to keep the fixation target in the foveae of both eyes. Since the light source generating the first corneal Purkinje image was so far away, any changes in the distances between the pupil center and the first Purkinje image were due to changes in the fixation axes of the eyes. It can be excluded that they originated from measurement artefacts resulting from changes in eye position relative to the light source. In general, head movements introduced noise to our data and probably increased the standard deviations but did not render our conclusions invalid since they were based on statistical analyses.

**Data Analysis and Statistics**

Prism adaptation was defined as the difference between the perceived angular elevations in both eyes immediately after the prism was imposed to what was perceived at the end of the prism wearing period (i.e., between the “no adaptation”...
and the “prism adapted” phases shown in Figs. 4A (individual data) and 4B (average data). The same definition applied to the angular difference in eye elevation as measured with the binocular eye tracker. Psychophysical data on perceived height were simply copied from the screen and entered into spreadsheet software (Microsoft Corp.) or imported into a numerical computing environment (MathWorks). Data from the eye tracker were automatically stored by the software into an ASCII file and imported into a numerical computing environment. Data collected during blink artifacts, evident as short, large amplitude and rapid binocular changes in apparent eye position, were discarded. Eye position data gathered at different time points after the prism was introduced were normalized to the individuals’ baseline eye positions. This procedure corrected for all different vertical kappa angles in the different individuals that generate variable offsets of the eye tracker.

Data over time were analyzed by ANOVA with subsequent LSD–post hoc tests against baseline values.

RESULTS

Psychophysical Experiment

Without the prism in front of one eye, the red and green crosses on the computer screen were adjusted to the same height by the nine subjects. Accordingly, the angular difference between both eyes was approximately zero (Fig. 4A, “baseline”). Right after the prism was introduced, the subjects’ estimation of relative height of the two crosses became asymmetrical. Differences matched the power of the prism (1.72°) in some subjects but not in others, who appeared to largely ignore the prism (Fig. 4A, labeled as “no adaptation”). After the prism was worn for 15 minutes, the perceived difference in height was reduced by adaptation in most of the subjects, except for those who had ignored the prism before. Even though not all subjects showed adaptation effects, the averages of the adaptation amplitudes measured in all nine subjects were also significant (Figure 4B, mean value 0.003°) before adaptation, labeled as “no prism, baseline”; and 0.44°, labeled as “prism, adapted [15 min]”; difference significant at $P < 0.05$, ANOVA–post hoc LSD). Adaptation was incomplete on average since the perceived height difference between both crosses remained large even after the adaptation phase (mean value 0.86°, labeled as “no adaptation”; and 0.44°, labeled as “prism, adapted [15 min]; difference significant at $P < 0.05$). After removal of the prism and another 15 minutes of recovery,
the subject adjusted the two crosses again to the same height (Fig. 4B, labeled as ‘no prism, recovered’).

There was a strikingly large inter-individual variability as to how the subjects perceived the height differences and how they adapted to it. Amplitudes of adaptation were clearly determined by the initially perceived strength of the prism (Fig. 5). To find out whether the large intersubject variability could be explained by intersubject variability in vertical fusional eye movements, six of the subjects were measured with the binocular eye tracker.

Effects of a Vertical Prism in Front of One Eye on Vertical Eye Positions

There was no significant difference measured in vertical eye position without the prism (Fig. 6). Right after the vertical prism was introduced to the left eye (‘no adap.’), an average difference in elevation of 1.20° was measured between both eyes, a little less than expected from the power of the prism (1.72°). After 2 minutes with the prism, the measured differences in vertical eye positions had disappeared (‘2-min adap.’). Because the eye tracker measured through the prism, this indicates that the eyes had adopted different elevations. There was no further change over the following 6 minutes (‘6-min adap.’). When the prism was removed, the eyes had different elevations in the opposite direction (‘no rec.’). Already after 2 minutes, they had returned to their baseline positions (‘2-min rec.’) and remained there. Error bars are SDs. * P < 0.05, ** P < 0.01 (ANOVA with LSD–post hoc tests).

Are the Individual Differences in Adaptation in the Maddox Test Explained by Individual Differences in Fusional Vertical Eye Movements?

The large variability of the response of the subjects in the Maddox test, linked to large differences in adaptation, raises the question as to what functional differences might exist
among the subjects. Therefore, adaptation amplitudes with the prism were plotted against the differences in vertical eye positions (Fig. 7).

Only because subject 1 showed such large amplitudes of adaptation in the Maddox test, the regression was not significant. However, after subject 1 was excluded, the correlation became significant (slope of regression 0.22, $R^2 = 0.78$, $P < 0.01$), suggesting that the interindividual differences in adaptation to the vertical prism are largely due to differences in the amplitude of vertical fusional eye movements. The average angular adaptation in the Maddox test (0.44 in the amplitude of vertical fusional eye movements) is even less than the average amplitude of fusional eye movements (0.96 in 83%), suggesting that these eye movements represent the primary mechanism by which the visual system compensates for unilateral vertical shifts in retinal image height.

**DISCUSSION**

The question leading to this study was whether adaptation to a vertical prism in front of one eye involves only vertical fusional eye movements or may also trigger further adaptational processes like shift in the retinotopic cortical maps. Certainly, "prism adaptation" could occur both at the sensory and the motor level, but the current study did not attempt to separate these two levels. However, using both a psychophysical test and a binocular eye tracker, it was found that:

1. In the Maddox test, differences in perceived height were induced between both eyes when a vertical prism was introduced on one side, but the perceived height difference declined over a period of 2 minutes.
2. Adaptation was incomplete, leaving significant interocular differences in retinal image height that did not, however, cause diplopia.
3. The initially perceived difference in height determined the amplitude of the subsequent adaptation—those subjects who saw a large height difference with the prism also adapted more.
4. In line with the literature, 3-6,8,14,15 a vertical prism in front of one eye triggered vertical fusional eye movements that reached their maximum in 2 minutes and persisted as long as the prism was in place.
5. The average amplitude of adaptation in the Maddox test was even less than the average amplitude of fusional vertical eye movements, suggesting that eye movements represented the primary adaptational mechanism.
6. Lateral head tilt generated surprisingly large differences in vertical eye alignment in one subject. While the changes in eye elevation were in the right direction to compensate for the vertical displacement of the retinal images, they were much too large (i.e., measured: 4° differences in eye elevation for 30° lateral head tilt, required/calculated: only approximately 0.6°).

The experiments largely answer the question posed in this study, namely whether adaptation to perceived interocular differences in height are fully explained by vertical fusional eye movements. Since the average amplitudes of fusional vertical eye movements were similar to the amplitudes of adaptation in the Maddox test, and because there was a correlation between both variables in the six subjects (Fig. 7), there is no reason to postulate an additional cortical adaptation mechanism, at least not for the short-term experiments done here. Of course, it cannot be excluded that other longlasting adaptation mechanisms may be activated when the vertical prism is worn for hours or days.16 The latter authors found that if subjects wore vertical prisms with stepwise increasing power over a period of 3 days, vertical fusional eye movements occurred with an amplitude of up to 6.3 ± 1.7°, as measured with a search coil technique. After 3 days, the subjects also showed a change in the orientation of Listing’s plane, but it is possible that the oculomotor system operated at the limits of its physiological range. These authors did not conduct a psychophysical test to measure perceived height so that the question about a secondary adaptation mechanism cannot be answered based on their data.

In line with literature, we found fast adaptation to the prism, followed by fast recovery.17,9 Compared with Maxwell and Schor9 we did not see any hints for a two-step adaptation process: Everything seemed to be completed in little more than 2 minutes.

**Potential Limitations in the Experimental Design**

The time points of data collection in both experiments did not exactly match. While the first measurements after application of the prism with the eye tracker were completed in 2 minutes, there was a 15-minute gap in the psychophysical experiments. The reason was the long duration (5 minutes) of the psychophysical measurement procedure. If we had a chance to measure also at 2, 6, and 8 minutes in the psychophysical experiment (Fig. 4) we would have known whether adaptation followed a linear or exponential time course. But the lack of these data did not change our conclusions that there is a high interindividuale variability in adaptation and those subjects who did not adapt in the psychophysical experiment also showed no vertical fusional eye movements. The reason is that those subjects who did not show any adaptation after 15 minutes would also not have shown adaptation earlier at 2 to 8 minutes.

Another potential problem was that different viewing distances were used in the psychophysical experiment and in the eye tracking experiment. Bharadwaj et al.17 have demonstrated that the vertical fusion amplitude (VFA) depends on the viewing distance, which is plausible because vertical disparities increase with proximity. Using Bharadwaj's linear approximation, we have calculated the expected VFA in our psychophysical experiment (VFA = 0.10 × horizontal convergence angle [in PD] + 1.82 + 2.67 PD) and in the eye tracker experiment (VFA = 1.99 PD). Since the power of the prism that was used in the current study was only 1.72 PD, the limits of fusion were not reached in either experiment. Therefore, the different target distances should not have changed our conclusions.

**Incomplete Compensation of the Vertical Prism**

An interesting question is why both the fusional eye movements and the adaptation to the subjective perception of height were generally less than expected from the power of the prism. The average amplitude of vertical fusional eye movements was only 1.2° (approximately 70% of the prism power). Similarly, the average perceived shift in height in the Maddox test was only 0.89°, (approximately 52% of the prism power). Apparently, the subjects could fuse the two retinal images even if they did not match in height because of sufficient fusional reserves. There was a striking variability both in the perceived height with the prism and in the compensatory vertical eye movements among the six subjects. Subject 2 (compare Figs. 4-7), for example, did not respond to the prism in either test but still did not report diplopia. It must be assumed that this subject had particularly large fusional reserves of more than 1.5° vertically (i.e., large Panum’s areas for vertical disparities). Another possible confounding factor could be a manifest vertical heterophoria in the subjects. However, this was not detected in the psychophysical test.
procedure (Fig. 4, all data on eye elevation differences close to zero before the experiment). In the eye tracker experiment (Fig. 6), the initial differences in eye elevation were nonzero in three of the six subjects, but it is assumed that they trace back to residual small lateral head tilt angles. Assuming that head tilt did not change during the experiment, it would generate a baseline shift but should not have affected the measured amplitudes of adaptation. The individual strategies to cope with vertical displacements of the retinal image were also not spontaneous but preserved over time: The experiments with the eye tracker were done weeks after the psychophysical measurements. It would be interesting to know whether the adaptation amplitudes, measured both psychophysically and by eye tracking, could be predictors as to how well subjects tolerate progressive addition lenses. It is well known that the tolerance of subjects to such lenses varies considerably. It could be that those who have large fusional reserves and small fusional eye movements are more tolerant, but it could also be the other way around—an interesting topic to study in the future.

**Height of the Retinal Image Determines Perceived Height in the Maddox Test**

Since the adaptation amplitude in the Maddox test was similar to the amplitude of vertical fusional eye movements, it can be concluded that subjective height differences were estimated based on different vertical positions in the retinal image. As soon as the eyes had moved to compensate for the vertical disparity with the prism, the subjects also saw a reduced height difference. Therefore, there is little evidence for feedback from the oculomotor system, like an efference copy that is forwarded to the presumed cortical “height estimator.” Information from the ocular motor system about vertical eye positions seems to be ignored.

Another striking observation was, while the elevation of both eyes did change in the right direction to compensate for lateral head tilt, in the single-tested subject (1), the changes in eye elevation were more than 8 times larger than necessary to move the fixation target back into the two foveae (calculated 0.58°, measured above 4° [Fig. 4]). The data would have matched if the subject had fixated at a distance of 25.6 cm rather than 3.54 m. A possible explanation would be massive vestibular input when the head was tilted although the advantage of the overcompensation is not obvious. Maxwell and Schor measured only approximately 0.3° differences in vertical eye alignment in four subjects when the head was tilted laterally by 4°.18 The reason for the difference is not clear since subject 1 had no known oculomotor pathologies.

**Conclusions**

Unilateral vertical prisms are partially compensated by vertical fusional eye movements with amplitudes that vary considerably among individuals. Adaptation to interocular differences in perceived height traces back largely to these eye movements. There was no evidence for an additional, potentially cortical adaptation mechanism, at least not in the 15-minute test intervals used in this study.

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