Adaptation of horizontal eye alignment in the presence of prism in young children

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Young children experience decreased convergence and increased accommodation demands relative to adults, as a result of their small interpupillary distance and hyperopic refraction. Those with typical amounts of hyperopic refractive error must accommodate more than an emmetrope to achieve focused retinal images, which may also drive additional convergence through the neural coupling. Adults and older children have demonstrated vergence adaptation to a variety of visual stimuli. Can vergence adaptation help younger children achieve alignment in the presence of these potentially conflicting demands? Purkinje image eye tracking and eccentric photorefraction were used to record simultaneous vergence and accommodation responses in adults and young children (3–6 years). To assess vergence adaptation, heterophoria was monitored before, during, and after adaptation induced by both base-in and base-out prisms. Adaptation was observed in both adults and young children with no significant effect of age, $F(1, 34) = 0.014$, $p = 0.907$. Changes in accommodation between before, during, and after adaptation were less than 0.5 D in binocular viewing. Typically developing children appear capable of vergence adaptation, which might play an important role in the maintenance of eye alignment under their changing visual demands.

Introduction

The accommodation and vergence motor systems work together to maintain focused and aligned retinal images, which in turn enable normal visual development. Maddox (1893) proposed four classical compo- nents of the vergence response as tonic, proximal, accommodative, and fusional vergence, with accurate binocular alignment requiring an appropriately weighted combination of the four. Tonic vergence is defined as the physiological resting position of the eyes in the absence of a detailed visual stimulus (e.g., when using a dim target, dark room, or difference of Gaussian filter), and this position is maintained by the baseline neural innervation to the extraocular muscles (Maddox, 1893; see also Rosenfield, 1997). Proximal vergence is guided by the sense of nearness, which is driven by cues including motion parallax, looming, relative size, occlusion, and shading (Regan & Beverley, 1979; Rogers & Graham, 1979; Schor, Alexander, Cormack, & Stevenson, 1992). It plays a key role in initiating large vergence changes rapidly (Schor et al., 1992), for example, quickly switching fixation from a distant target to a handheld device. Accommodative vergence is driven by accommodation through the neural coupling (Fincham & Walton, 1957; Judge & Cumming, 1986). Neither tonic, proximal, nor accom- modative vergence receives feedback regarding their accuracy and therefore are considered to function in an open loop format. The final component, fusional vergence, driven by retinal disparity, corrects any combined error from the other components and therefore permits vergence responses to function as a closed loop system (Semmlow & Wetzel, 1979; West- heimer & Mitchell, 1956).

Clinicians assess the amount of fusional vergence required to correct the error remaining from the other components by covering one eye to remove the retinal disparity cue. In a nonstrabismic individual, the

covered eye will drift under these dissociated conditions and the magnitude of this drift is called the heterophoria (phoria). Under typical visual conditions the fast-acting disparity-driven fusional vergence system can only compensate for this heterophoria over a limited working range to achieve fusion (e.g., around 20 pd convergence and 12 pd divergence for a target at 80 cm, see Sreenivasan, Babinsky, Wu, & Candy, 2016); however, there is evidence that a slower acting adaptive vergence component may help compensate for larger demands in adults (Schor, 1979). Vergence adaptation was first observed among patients who returned to their original phoria magnitude after starting to wear a prism correction (Carter, 1965), and thus it is also called prism adaptation. The term vergence adaptation refers to a change in the dissociated alignment of the eyes as a result of a sustained fixation effort (Hung, 1992; Maddox, 1893; Rosenfield, 1997; Schor, 1979; Sethi, 1986), and it has been estimated in adults using two approaches: either by directly measuring the change in dissociated eye alignment during a sustained vergence effort (Henson & North, 1980; Sreenivasan, Irving, & Bobier, 2012) or by measuring the time-course of decay of adaptation after the sustained effort (Babinsky, Sreenivasan, & Candy, 2016; Schor, 1979; Wong, Rosenfield, & Wong, 2001). More specifically, the change in dissociated alignment during a sustained vergence effort can be estimated by comparing the phoria position before a prism is inserted with the position at regular intervals while the prism is in place. Complete adaptation is indicated if the measured phoria position before the prism is inserted equals that at the end of the prism adaptation interval. In comparison, the decay of adaptation approach measures the change in phoria after the prism adaptation interval to estimate the time taken to relax to the original phoria position, with a longer decay time indicating stronger adaptation (Schor, 1979). To date there is no clear indication that one method is superior to the other in describing adaptation.

The potential for this vergence adaptation in early childhood is of interest in understanding both typical and atypical visual development. Young children experience decreased convergence demands relative to an adult, resulting from their reduced interpupillary distance (IPD; MacLachlan & Howland, 2002; Pryor, 1969), while at the same time, they typically have an uncorrected hyperopic refractive error causing increased accommodative demands relative to an adult (Mayer, Hansen, Moore, Kim, & Fulton, 2001; Mutti et al., 2005). How do typically developing children maintain their eye alignment without generating excessive accommodative convergence under this apparent conflict in demands? Children with excessive accommodative convergence are believed to be at greater risk for strabismus (Parks, 1958; Raab, 1982),

but only approximately 20% of moderate to high hyperopes develop strabismus in the first years after birth (Anker, Atkinson, Braddick, Nardini, & Ehrlich, 2004; Atkinson et al., 1996; Babinsky & Candy, 2013; Ingram, Lambert, & Gill, 2009). Studies have indicated that the average phoria of typically developing infants and children is small and consistent with age (Babinsky, Sreenivasan, & Candy, 2015; Chen, O'Leary, & Howell, 2000; Lam, LaRoche, De Becker, & Macpherson, 1996; Sreenivasan et al., 2016; Walline, Mutti, Zadnik, & Jones, 1998). Does active vergence adaptation help maintain this phoria in typical development?

There are currently only three studies of vergence adaptation in children. Wong et al. (2001) found that older children (mean age = 9.8 years) showed greater adaptation than adults after viewing a target binocularly at 15 cm for 5 min (mean 0.45 vs. 0.11 meter angles). This difference could not be explained by differences in IPD, as the mean IPD measurements were similar for the older children and adults, and therefore their angular rotation demand in degrees would be similar. Sreenivasan et al. (2012) measured the phoria of 7- to 15-year-olds before and after 20 min of viewing at 33 cm. They also found that the phoria adapted to the stimulus. Do children of younger ages show similar or even stronger vergence adaptation during the age range when uncorrected moderate hyperopes often remain aligned or develop strabismus? Babinsky et al. (2016) measured the decay of the adapted dissociated alignment in 2- to 7-year-old children and adults after they viewed a target binocularly at 33 cm for 60 s through a base-out prism. This study found no difference in the 63% time constant between 2- and 7-year-old children and adults indicating comparable levels of recovery from the short duration adaptation.

The current study built upon Babinsky et al.'s (2016) first examination of young children by using the methods of Henson and North (1980) who measured heterophoria both during and after a sustained vergence effort in adults. The current study assessed adaptation in young children between 3 and 6 years of age by measuring the change in phoria position during a longer period of prism adaptation (2.5 min), in both convergent (base-out) and divergent (base-in) directions. Base-out prism introduced extra convergence demand, mimicking the additional convergence needed during the developmental increase in IPD although clearly shorter in duration, while base-in prism introduced extra divergence demand, mimicking the situation when a hyperope would need to compensate for excessive accommodative convergence. Furthermore, this study measured the recovery from adaptation using a method incorporating typical binocular visual experience rather than in dissociated monocular conditions (Babinsky et al., 2016).

Methods

Subjects

Twenty-four typically developing children (age range: 3.1 to 5.9 years; mean: 4.3 years) and 11 prepresbyopic adults (age range: 20.0 to 44.5 years; mean 25.5 years) participated in the study (The one subject who could be considered presbyopic had 3D of accommodation and could focus well for the target. Her data were also no different from the rest of the adult group). Children were recruited from the local community and adults were recruited from the academic department. All but two adult subjects were naïve to the purpose of the study. None of the participants had developmental delays or medical conditions known to affect the visual system. All of the children received a routine eye examination in the pediatric clinic to rule out any ocular abnormalities including strabismus. Refractive error was determined using cycloplegic retinoscopy, using one drop of 1% cyclopentolate in each eye. The children had typical mildly hyperopic spherical equivalent refractive errors (more hyperopic eye mean +1.14 D, SD ± 0.67 D; less hyperopic eye mean +0.98 D, SD ± 0.59 D), with low amounts of astigmatism and spherical anisometropia (both no more than 0.5 D in all subjects). None of the children were judged to need optical correction by their clinician. All of the adults were functionally emmetropic and did not wear optical correction. Informed consent was provided by all of the adult subjects and by the parents of the children. The study was approved by the Indiana University Institutional Review Board and adhered to the tenets of the Declaration of Helsinki.

Equipment

Eye alignment and accommodation were measured simultaneously using video collected at 25 Hz. The images were analyzed using Purkinje image tracking and eccentric photorefraction approaches (PowerRefractor [PR], MultiChannel Systems, Reutlingen, Germany; Choi et al., 2000; Roorda, Campbell, & Bobier, 1997; Schaeffel, Wilhelm, & Zrenner, 1993). The angular vergence alignment in prism diopters generated by the PR was derived from the difference in horizontal gaze positions between the eyes by applying an adult Hirschberg ratio (Riddell, Hainline, & Abramov, 1994). An estimate of each eye's refractive state, for monitoring accommodation, was derived from the slope of the luminance intensity profile across the pupil. The conversion from slope to an estimate of the eye's defocus in the vertical meridian was initially achieved
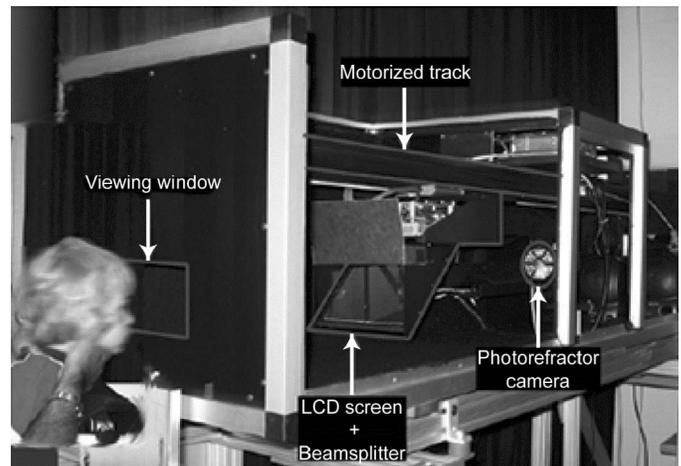

Figure 1. Experimental equipment with the side cover removed. Subjects viewed a cartoon movie displayed on a horizontally mounted LCD screen via a beamsplitter, while the Power-Refractor camera (at 1 meter) recorded eye alignment and refractive state. The LCD screen and the beamsplitter were mounted on a motorized track and placed at a fixed viewing distance of 95 cm (reprinted from Babinsky, E., Sreenivasan, V., & Candy, T. R. [2016]. Vergence adaptation to short-duration stimuli in early childhoodvergence adaptation in early childhood. *Investigative Ophthalmology & Visual Science, 57*(3), 920–927).

using the instrument's adult calibration (Choi et al., 2000; Schaeffel et al., 1993).

The subjects viewed a high-contrast cartoon movie with naturalistic spatial amplitude spectra (Field, 1987). The movie was displayed on a 6.8 cm × 6.8 cm LCD screen located 95 cm from their eyes. The image of the LCD screen was reflected from a beam splitter to allow the stimulus and photorefractor to be aligned on the same optical axis (Figure 1).

Procedure

The subjects' activities before entering the lab were not known. However, they spent approximately 10 min playing with toys or undergoing the consent process before taking part in the study. They, therefore, fixated at approximately 50 to 100 cm for this time period in an attempt to establish a consistent state of adaptation across participants. Before the PR measurements were gathered, a typical clinical cover test was performed to confirm that no subject had a heterophoria greater than 4 pd at the 95 cm viewing distance. This criterion was used to ensure that no subjects had a phoria larger than the prism used for adaptation and that they would have a clinically insignificant amount of phoria (Tait, 1951). The Hirschberg ratio and the photorefraction calibration factor vary across individuals and therefore
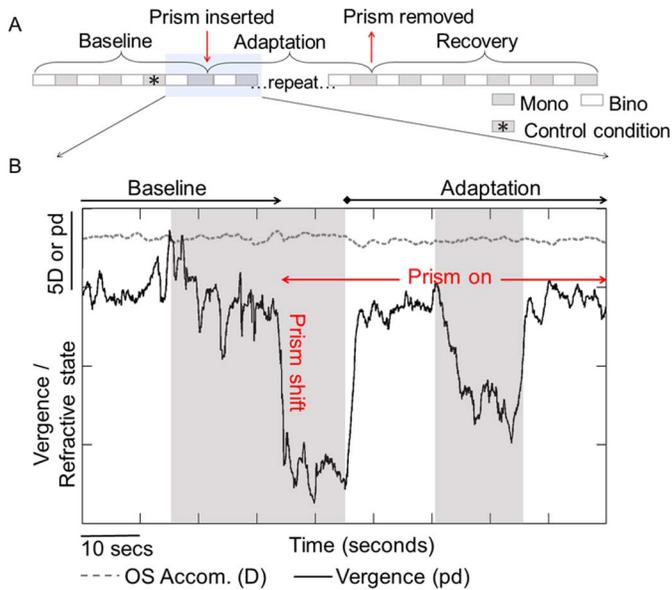
Figure 2. Panel A, a schematic drawing of the full experimental protocol with baseline, adaptation, and recovery intervals. The procedure was the same for base-in and base-out conditions, with the red arrows indicating the positioning of the prism. Note that in the occlusion duration control condition (marked with *), the monocular period for the third baseline heterophoria measurement was modified to 60 s instead of 15 s. Panel B, a section of data showing vergence and accommodation responses during binocular and monocular viewing (the motor responses were separated vertically for clarity). The horizontal red arrow marks the period when a 10 pd BO prism was held in front of the adult's eye, with the "Prism shift" demonstrating the optical shift in monocular viewing induced by the prism. These data were smoothed for presentation purposes only.

relative calibrations were performed for each subject and applied in the data analysis (Bharadwaj et al., 2013; Blade & Candy, 2006; Riddell et al., 1994).

There were two main testing conditions, base-out (BO) and base-in (BI) prism, that were identical in every way except for the prism direction. Each condition was divided into baseline, adaptation, and recovery periods for easy description. Figure 2 Panel A presents a schematic of the approach. Four phoria estimates were collected during the 2-min baseline interval and then a prism was introduced at the end of the fourth monocular viewing period to begin the adaptation interval. Heterophoria was measured using the PR with a technique based on a clinical unilateral cover test. More specifically, after the subject watched the movie binocularly for 15 s, an infrared (IR) filter was placed in front of the right eye for 15 s to remove the disparity cue and create monocular viewing (Henson & North, 1980). The heterophoria estimate was derived from the difference between the binocular and monocular vergence alignments, which represents the fusional vergence effort required to align the eyes in binocular conditions. The average of these four phoria measurements will be referred to as the "baseline phoria" in later analyses. During the adaptation interval a 10 pd prism was used for adults and a 6 pd prism for the young children. These are almost equivalent vergence demands in terms of viewing distance for adults and the young children when their IPD is considered (MacLachlan & Howland, 2002; Pryor, 1969). Both base-in and base-out prism conditions were tested, with the order pseudorandomized across participants. After the optical effect of the prism was measured using the PR, the IR filter was removed and the subjects viewed through the prism for an extended period of time. During this adaptation period the subject viewed the movie in alternating 15-s periods of binocular and then monocular viewing (see Figure 2). This lasted for 5 min for children (due to their limited attention span) and 7 min for the adults. The total duration of binocular viewing during the adaptation interval was 2.5 min for children and 3.5 min for the adults. The recovery period began after removal of the prism at the end of this period. Five additional phoria measurements were taken to study the recovery of phoria towards its baseline. Each test condition took approximately 11.5 min for an adult and 9.5 min for a child, with the subjects viewing the target monocularly for half of that time period. A 10-min resting period was provided between the two prism directions.

Control experiments

Two control experiments were also performed on a subset of participants to determine: (a) the effect of occlusion duration on the phoria, and (b) phoria stability in the absence of the prism.

Occlusion duration

The occlusion duration of 15 s in the testing protocol was chosen based on the assumption that alignment would reach a stable phoria position in that time (Babinsky et al., 2015; Henson & North, 1980; Ludvigh, McKinnon, & Zaitzeff, 1964). To test this assumption, two prolonged occlusion periods of 60 s were used for five adults and eight children (with three adults and five children being tested in both BI and BO directions). The 60 s occlusion sections replaced the 15 s occlusion section for the third heterophoria measurement during the baseline interval (Figure 2, Panel A). In all other respects, the control condition matched the experimental condition. The phorias derived from the 60 s occlusion periods were compared to those derived from 15 s of occlusion.

Stability of the phoria without prism

Three adults completed this condition on another day. The protocol was performed as described for the main study, but without the prism during the adaptation period. The aim was to determine whether the phoria remained stable during the 7-min "adaptation" period of recording with no prism stimulus to overcome. Any systematic changes in these phoria estimates would indicate the influence of factors other than the prism, perhaps, for example, the accumulated effect of multiple monocular and/or binocular intervals across the adaptation interval.

Data analysis

The data were analyzed using MacSHAPA (University of Illinois, Urbana-Champaign, IL), MATLAB (Mathworks, Natick, MA), Excel (Microsoft, Redmond, WA), and GraphPad Prism (GraphPad Software, Inc., La Jolla, CA). Time stamps indicating the placement and removal of the filter or prism were synchronized to the PR measurements of accommodation and vergence. Five filtering criteria were then applied to the raw vergence and accommodation responses, and then the calibrations were applied. Data were excluded if: (a) Measurements of refractive state (accommodation) were outside the linear measurement range of the instrument (−6 D to +4 D; Choi et al., 2000), (b) Pupil size was outside the manufacturer's recommended range of 3 mm to 8 mm (Choi et al., 2000; Schaeffel et al., 1993), (c) The eye position was greater than 15° eccentricity in any direction, which could introduce errors in refractive state estimates due to peripheral refraction (Navarro, Artal, & Williams, 1993), (d) Apparent vergence velocity was greater than 175 pd/s (Collewijn, Erkelens, & Steinman, 1995) or (e) Apparent accommodation velocity was greater than 10 D/s (Anderson, Glasser, Manny, & Stuebing, 2010). These last two criteria were used to exclude data that change faster than the known physiological limits of the visual system.

Phoria estimation

Eye alignment estimates were made using the median of 3.5 s of data (88 data points) collected at the end of each 15 s section of binocular or monocular viewing. Two criteria were applied in identifying the 3.5 s window: a minimum of 20 usable data points were required and the standard error of the mean (SEM) had to be < ± 0.51 pd. If these criteria were not met, the algorithm slid the window earlier by a step of 1 frame (40 ms). Each heterophoria value was estimated as the
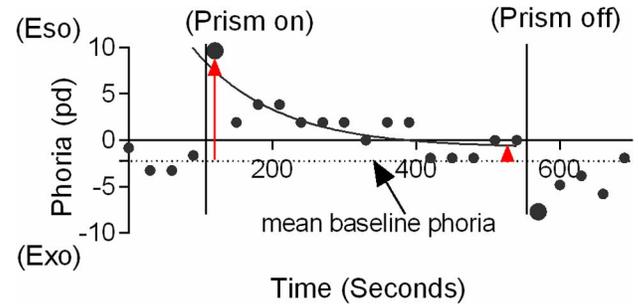

Figure 3. Phoria measurements before, during, and after viewing through BI prism, from an adult. The two vertical black lines mark the insertion and removal of the prism. The two large dots are the two optical shifts resulting from the insertion and removal of the prism. The two red arrows mark the optical shift when prism is introduced and then the phoria shift from baseline at the end of adaptation. The difference between them indicates the adaptation to the prism. The dotted horizontal line indicates the subject's averaged baseline phoria position and the exponential function indicates the adaptation trend.

difference between a binocular alignment and the monocular alignment immediately following it.

Percentage adaptation

The optical effect of adding the prism during the monocular interval (Figure 2, Panel B) was determined by subtracting the alignment after the prism was inserted from the alignment immediately before the prism was introduced. One advantage of continuous measurement was the ability to observe a realignment response to the baseline binocular alignment during binocular viewing with the prism. This provided confirmation that the subject was fusing through the prism in binocular conditions (Figure 2, Panel B). If fusion was not achieved, the apparent binocular vergence position would be different in the baseline and adaptation intervals.

The change in phoria induced by the prism insertion was quantified as the difference between the baseline phoria and the first phoria measurement immediately following prism insertion (Figure 3, see left red arrow). The final adapted phoria measurements were derived from the end of the adaptation interval, with the prism still on (Figure 3 see right red arrow). The percentage of vergence adaptation was then quantified using the following metric:

$$\left(1 - \frac{\text{phoria shift from baseline at end of adaptation}}{\text{optical shift when prism is introduced}}\right) \times 100\%$$

Complete adaptation during prism viewing would be indicated by a return to the original baseline phoria position at the end of adaptation. If the subject showed no adaptation to the prism, the phoria would remain

constant at the prism shift value throughout the presence of the prism.

Results

Thirteen of the 24 children recruited (54%) provided usable data in at least one condition (BI/BO), and eight of them provided data in both conditions. Of the 11 children excluded, nine were excluded from the analysis because they did not provide sufficient data to estimate a phoria, and two were excluded because they did not fuse through either base-in or base-out prism during the adaptation period: in total, four out of five 5-year-olds, two out of nine 4-year-olds and five out of ten 3-year-olds were excluded. Ten of the 11 adults (91%) provided usable data in at least one condition (BI/BO), and seven of them provided data in both conditions. One adult was excluded because he was unable to fuse through both the 10 pd BO and BI prisms.

Four children who completed the adaptation protocol did not provide calibration data, and therefore the population calibration factor was used for their PR data. The other subjects' accommodation and vergence data were individually calibrated. At the 95 cm viewing distance, the mean baseline phoria in the base-out condition was -0.18 pd (range -1.64 to 1.64 pd) in young children and -0.69 pd (range -3.22 to 1.37 pd) in adults (no significant difference, t test, $t(20) = 0.97$, $p = 0.35$). These ranges reflect the requirement that the phoria measured using a clinical cover test was less than 4 pd.

Adaptation

The young children demonstrated vergence adaptation to a 6 pd prism in both base-in and base-out directions (Figure 4, Panel A; blue circles for BO and red triangles for BI). The amount of adaptation was quantified as the percentage achieved. Full adaptation (100%) would be indicated by a return to the original baseline phoria position at the end of the adaptation period. A two-way factorial analysis of variance (ANOVA) of the percent of adaptation found no effect of age, $F(1, 34) = 0.014$, $p = 0.907$, but a significant main effect of base-in/base-out prism direction, $F(1, 34) = 11.26$, $p = 0.002$, with no interaction, $F(1, 34) = 1.203$, $p = 0.28$. At this viewing distance the mean ($\pm$SD) percentages of adaptation were higher in the base-in direction than the base-out for both adults (BI 85 $\pm$ 21% vs. BO 48 $\pm$ 26%) and young children (BI 75 $\pm$ 23% vs. BO 56 $\pm$ 28%).

The prism induced phoria tended to reduce during the adaptation period (Figure 4, Panel A). An exponential function was fit to the mean phoria data in
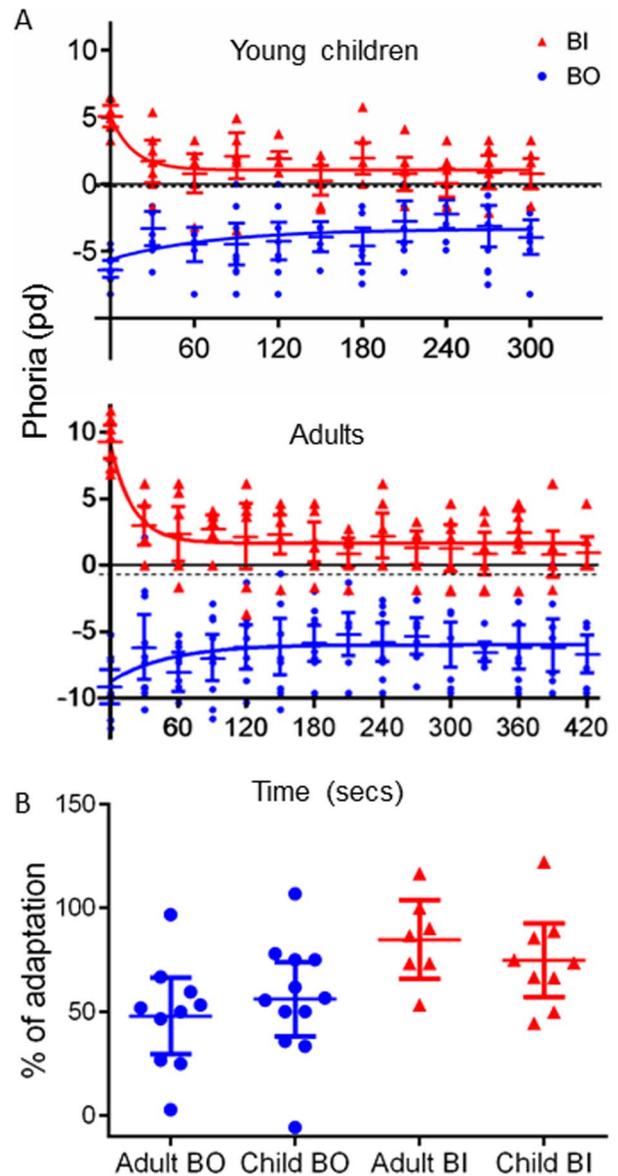

Figure 4. Panel A, adaptation to BO and BI prisms in young children and adults. Each data point (blue circles for BO; red triangles for BI) is the phoria of an individual subject at the corresponding time point. Horizontal bars represent mean values $\pm$95% CI of the mean. The dashed horizontal line represents mean baseline phoria at the 95 cm viewing distance in each group. Panel B, the individual percentage adaptation values for each condition along with the group mean $\pm$95% CI of the mean. Note that in some cases subjects appeared to adapt to a position slightly beyond the original baseline (>100%).

each condition for both adults and young children. The 63% time constants calculated from the exponential fits were all shorter than 32s (young children BI 17.99 s, BO 31.97 s; adults BI 22.80 s, BO 28.09 s) indicating that more than half of the adaptation magnitude was reached before the second phoria measurement. The subjects did not all reach a stable phoria position during this period of adaptation and, if data were

	Children			Adult		
	Mean phoria (pd)	±SD	Range	Mean phoria	±SD	Range
Base out						
Baseline	−0.18	1.10	−1.64 to 1.64	−0.69	1.37	−3.22 to 1.37
Recovery	0.23	1.45	−2.18 to 2.95	−0.02	2.29	−3.89 to 3.96
Base in						
Baseline	−0.74	1.12	−2.46 to 1.09	−0.79	1.09	−2.05 to 0.69
Recovery	−1.67	1.31	−3.27 to 0.29	−3.77	1.32	−5.83 to −1.64

Table 1. Mean of the individual phorias from the baseline and recovery measurements.

collected over a longer interval, further adaptation may have occurred (Brautaset & Jennings, 2005).

Recovery of phoria

After removal of the prism, the phoria showed recovery from its adapted position towards the baseline value (Figure 3 after the second vertical line). The mean value of the last three phoria measurements during the recovery period (beginning approximately 60 s after removal of the prism) was compared to the baseline phoria in both BO and BI conditions (Table 1). While both age groups showed significantly more adaptation to BI prism, they also showed less recovery to baseline phoria during the limited recovery time. In the base-out condition the mean percentage recovery was 91% (SD ± 29%) in adults and 94% (SD ± 28%) in young children, and in the base-in condition it was 67% (SD ± 19%) in adults and 81% (SD ± 31%) in young children. A two-way factorial ANOVA found no effect of age, $F(1, 34) = 0.851$, $p = 0.363$; prism direction, $F(1, 34) = 4.059$, $p = 0.052$; or interaction, $F(1, 34) = 0.321$, $p = 0.575$, on the percentage of recovery, although the main effect of prism direction was borderline. The similar level of baseline phoria in the BO and BI conditions suggests that the time interval between the two conditions was sufficient to relax the adaptation effect from the previous trial.
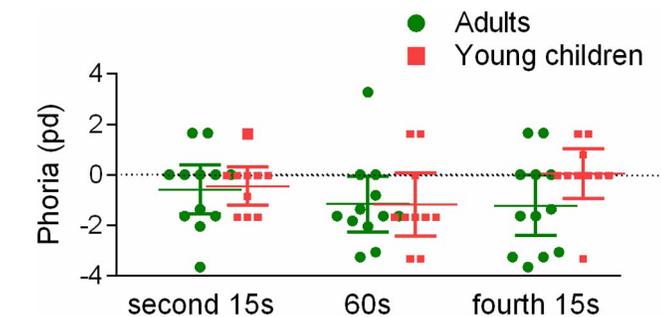

Figure 5. Baseline interval phoria estimates with different durations of occlusion from young children and adults. Horizontal bars represent mean values ±95% CI of the mean.

Therefore the testing order should not have affected the final results.

Control conditions

Occlusion duration

In a subset of participants, the third phoria measurement in the baseline interval was modified to 60 s of occlusion instead of 15 s. Phorias derived from the 60 s of occlusion were compared with the adjacent 15 s periods (the second and the fourth estimates). The mean estimates across these periods varied by on the order of 1–2 pd (Figure 5) and a two-way mixed ANOVA found no significant effect of occlusion duration (within subjects variable), $F(1, 20) = 0.063$, $p = 0.804$, or age (between subjects variable), $F(1, 20) = 0.860$, $p = 0.365$, on the phoria estimates.

Stability of the phoria without prism

Repeated phoria measurements without prism in the adaptation interval were collected from three adults (Figure 6). The fluctuations in phoria during this period were relatively small when compared with the optical effect of the prism and to the trends recorded in the adaptation interval with the prism. The multiple 15 s occlusion intervals did not lead to a systematic shift in phoria of the magnitude seen in the vergence adaptation protocol, and therefore suggest that the shifts noted with the prism were an active adaptation response.

Accommodative status

The accommodation and vergence motor systems work together to provide focused and aligned retinal images in typical viewing conditions. The neural-coupling between them (Fincham & Walton, 1957; Judge & Cumming, 1986) implies that there may be changes in accommodation with the additional vergence response driven by the prism. Divergence driven by base in prism would be expected to lead to reduced
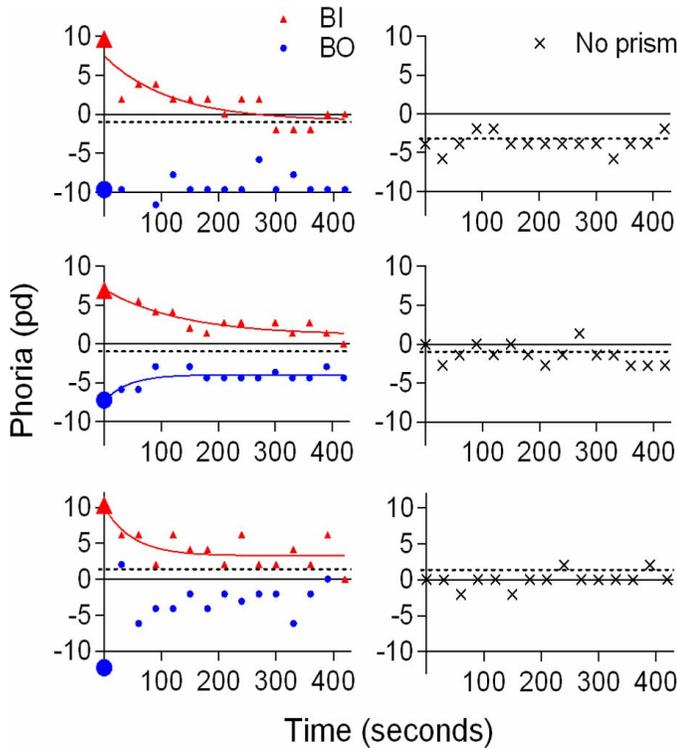
Figure 6. Left column, adaptation condition: adaptation data from three of the adults presented in Figure 4. Right column, control condition: repeated phoria measurements from the same subjects with no prism. Each individual symbol represents one single phoria measurement. Dotted horizontal line represents the baseline phoria. The first and third adults do not have exponential fits for base-in prism because the data did not follow that trend consistently.
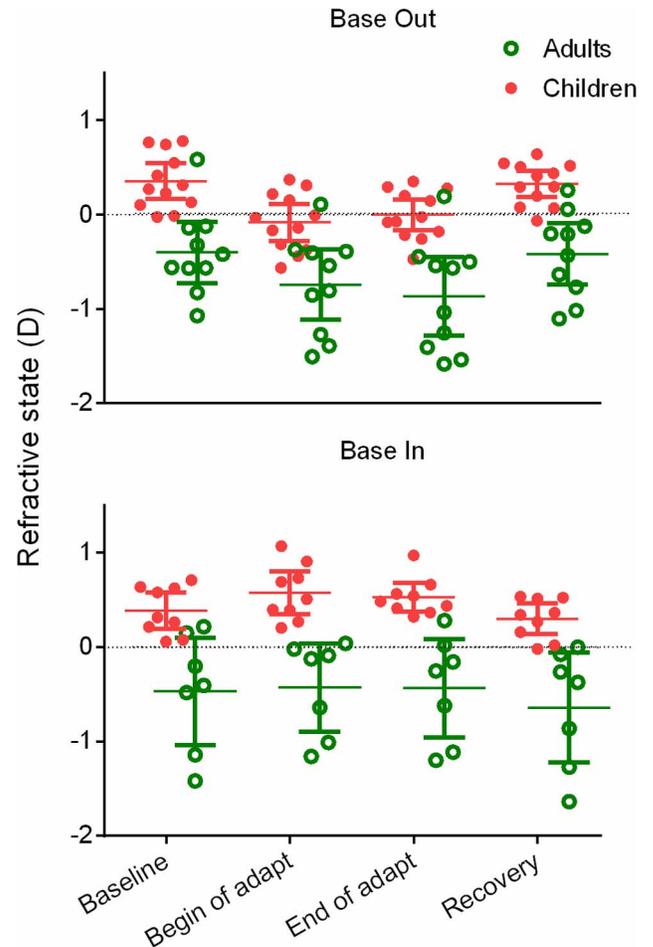

Figure 7. Refractive state in binocular viewing before, during, and after adaptation to base-out and base-in prism, with the means and 95% CI of the mean. Negative values indicate increasing accommodation.

accommodation, although under binocular, full cue viewing conditions the accommodation system has access to feedback through the blur cue to compensate for this change. In the presence of base out prism, accommodation responses would be expected to increase as a result of the coupling. To understand the subjects' accommodative performance during vergence adaptation, four sections of refractive state data collected during the binocular viewing vergence measurements were analyzed: at the end of baseline, the beginning and end of adaptation, and at the end of recovery. The results for each section for each subject are shown in Figure 7. The change in refractive state between the "Baseline" and "Begin of adapt" sections shows the accommodation changes at prism insertion (Adults: Mean $\pm$ SD change -0.34 ± 0.29 D for BO and 0.04 ± 0.45 D for BI, Children: Mean $\pm$ SD change -0.44 ± 0.22 D for BO and 0.19 ± 0.11 D for BI), and the change from "End of adapt" to "Recovery" shows the accommodation change with prism removal (Adults: Mean $\pm$ SD change 0.45 ± 0.30 D for BO and -0.21 ± 0.14 D for BI, Children:

Mean $\pm$ SD change 0.33 ± 0.17 D for BO and -0.23 ± 0.19 D for BI).

The accommodation data tended to follow the expectation based on the coupling: The children's responses followed the coupling expectation in both directions, while the effect in adults for base-in prism was less clear. In the base-out condition, there were significant main effects of time, $F(3, 60) = 40.967$, $p < 0.001$, and age, $F(1, 20) = 23.953$, $p < 0.001$, with no significant interaction, $F(3, 60) = 1.440$, $p = 0.24$. The significant effects of time, $F(3, 42) = 4.862$, $p = 0.005$, and age, $F(1, 14) = 23.583$, $p < 0.001$, were also found in the base-in condition, with no significant interaction, $F(3, 42) = 0.391$, $p = 0.76$. Under these closed-loop conditions with blur feedback, the maximum fluctuations of accommodation in adults and young children were not clinically significant. In the absence of the blur feedback, convergence accommodation would only be expected to be on the order of 0.5 to 1 D for these

vergence stimuli (Bobier, Guinta, Kurtz, & Howland, 2000).

Discussion

Young children aged 3 to 6 years showed vergence adaptation after only a few minutes of exposure to increased convergent and divergent demands, with responses that were comparable to adults. One role of this adaptation may be to help them maintain eye alignment during longer duration developmental changes, such as head growth and emmetropization. In particular, an increase in IPD and decrease in hyperopia during emmetropization may introduce a more convergent fusional vergence demand, while any excessive accommodative convergence (with persistent hyperopia) may introduce a more divergent demand. These developmental demands on adaptation would be above and beyond those experienced by the typical adult.

This demonstration of adaptation is consistent with two previous related studies, one of older children (Wong et al., 2001), and another of recovery after binocular prism exposure lasting one minute in young children (Babinsky et al., 2016). While methodological differences between these studies, including the presence or absence of a conflicting demand with the accommodation system, are likely to have led to quantitative differences in the amount of adaptation, they have all simulated aspects of the challenges faced by the developing visual system. The current study used prism to introduce a vergence demand without changing viewing distance and, therefore, created a small relative conflict between accommodation and vergence. Wong et al. (2001) used a target at 15 cm to stimulate vergence adaptation, which made the accommodation and vergence demands consistent with each other.

When thinking about the mechanism responsible for the adaptation, studying the roles of individual vergence components, such as proximal or fusional, requires controlling the activity of the other components, either by fixing their level and creating a cue conflict situation (Ramsdale & Charman, 1988; Smithline, 1974) or by reducing the available information to make a cue uninformative and open loop (Schor, 1979; Wong et al., 2001). In the current study, the approach taken by Henson and North (1980) was adapted for use with children. An objective eye-tracking approach was used here to avoid asking young children for subjective responses, and accommodation responses were measured simultaneously so that the relationship between the motor systems could be assessed. Based on the Maddox classification of

vergence response components, proximal and accommodative vergence cues remained constant at the 95 cm distance throughout the study. Therefore, these components should not have demonstrated adaptation in the presence and absence of the prism. The disparity cue for fusional vergence was also removed during measurement of heterophoria and, therefore qualitatively, the adaptation demonstrated in the current study is consistent with tonic adaptation described in previous studies of adults (Carter, 1965; Maddox, 1893). Previous studies that have measured tonic vergence positions directly in infants show inconsistent findings (Aslin, 1986; Rethy, 1969). When both the accommodation and vergence loops were open during tonic vergence measurements, environmental and voluntary factors could still induce vergence response changes and therefore complicate the study (Rosenfield, 1997). In recent oculomotor models, slow fusional vergence (Schor, 1992) and adaptive time components (Hung, 1992) were proposed to underlie this adaptation in the sense of Maddox's tonic vergence. In one study of adults, vergence positions were found to adapt to an increased IPD generated using an optical device (Fisher & Ciuffreda, 1990), which also simulates increasing head growth experienced during infancy and childhood. Given that infants and young children are typically hyperopic (Ingram, Arnold, Dally, & Lucas, 1990; Mutti et al., 2005) and have a narrower IPD than adults (MacLachlan & Howland, 2002; Pryor, 1969), this form of adaptation would be helpful in relieving stress on fast fusional disparity-driven vergence (Judge, 1996; Mitchell & Ellerbrock, 1955; Ogle & Prangen, 1951; Sreenivasan & Bobier, 2015) at an age when refractive strabismus may develop (Parks, 1958).

In the current study there was a higher percentage of children (3/13) than adults (1/11) who could not fuse through BI prism. This is reasonable in that preschoolers have demonstrated a mean divergence fusional range of close to 6pd at a similar viewing distance of 80 cm (Sreenivasan et al., 2016). For some young children, who didn't fuse initially, ramping from 4 pd to 6 pd did help them maintain fusion. Sethi and North (1987) found that, for vertical prisms, three increasing prism steps were easier to fuse than one large step during the same binocular viewing time (Sethi & North, 1987). These small and gradual changes are presumably more similar to the developmental changes that occur during childhood. At the moderate viewing distance (1 m), percentage of adaptation was higher in base-in than in base-out conditions for both age groups. This adaptation might be helpful in relieving stress on the divergence fusional vergence system, given that the divergence fusional vergence range was significantly smaller than the convergence range at a similar viewing distance (Sreenivasan et al., 2016). The mean percentage of BO adaptation in adults [48% (SD

± 0.26) – Figure 4, Panel B] was consistent with values found in previous studies of adults (Henson & Dharamshi, 1982; McCormack, 1985; North & Henson, 1981, 1982; North, Sethi, & Owen, 1990).

The fact that we are capable of adapting and yet have a phoria during habitual conditions suggests that a typical phoria may be an endpoint of adaptation. There is some debate about whether the purpose of adaptation is to maintain a phoria (McCormack, 1985) or to achieve orthophoria (phoria = 0 pd; Dowley, 1987), although patients adapting back to their original phoria after the prescription of prism suggests that at least some individuals are adapting to retain their phoria (Carter, 1965). One limitation of the current study is the absence of subjects with a phoria greater than 4 pd, which would have given insight into this question.

Besides any role in a three-dimensional environment for typically developing children, vergence adaptation is an interesting topic to consider in children at risk for clinical abnormalities such as refractive strabismus. Excessive accommodative convergence is proposed to underlie refractive esotropia development in young children (Parks, 1958). However, only approximately 20% of the children with hyperopia greater than +3.5 D develop this deviation (Anker et al., 2004; Atkinson et al., 1996; Babinsky & Candy, 2013; Ingram et al., 2009). Could the remaining 80% utilize sufficient vergence adaptation to avoid developing misalignment? To date, there has been no study of vergence adaptation in young hyperopes at risk for esotropia. Other evidence suggests that subjects with non-strabismic binocular vision problems show poor vergence adaptation to prisms and that visual training was helpful in improving adaptation and relieving their symptoms (North & Henson, 1982; Sreenivasan & Bobier, 2015).

Keywords: vergence adaptation, prism adaptation, heterophoria, hyperopia, young children

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