Eye Movements, Strabismus, Amblyopia and Neuro-Ophthalmology

Vergence Adaptation to Short-Duration Stimuli in Early Childhood

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Purpose. To investigate whether nonstrabismic typically developing young children are capable of exhibiting vergence adaptation.

Methods. Fifteen adults (19.5–35.8 years) and 34 children (2.5–7.3 years) provided usable data. None wore habitual refractive correction. Eye position and accommodation were recorded using Purkinje image eye tracking and eccentric photorefraction (MCS PowerRefractor). Vergence was measured in three conditions while the participant viewed naturalistic targets at 33 cm. Viewing was monocular for at least 60 seconds and then binocular for either 5 seconds (5-second condition), 60 seconds (60-second), or 60 seconds through a 10-pd base-out prism (prism 60-second). The right eye was then occluded again for 60 seconds and an exponential function was fit to these data to assess the impact of adaptation on alignment.

Results. The 63% time constant was significantly longer for the prism 60-second condition (mean = 11.5 seconds) compared to both the 5-second (5.3 seconds; $P = 0.015$) and the 60-second conditions (7.1 seconds; $P = 0.035$), with no significant difference between children and adults ($P > 0.4$). Correlations between the 63% time constant (prism 60-second condition) and age, refractive error, interpupillary distance (IPD), or baseline heterophoria were not significant ($P > 0.4$). The final stable monocular alignment, measured after binocular viewing, was similar to the baseline initial alignment across all conditions and ages.

Conclusions. For a limited-duration near task, 2- to 7-year-old children showed comparable levels of vergence adaptation to adults. In a typically developing visual system, where IPD and refractive error are maturing, this adaptation could help maintain eye alignment.

Keywords: vergence, adaptation, young children, accommodation

When changing fixation to an object at a different viewing distance, the eyes must converge or diverge to realign the images onto each fovea. A change in fixation distance can be simulated by inserting prism in front of the eyes to generate retinal disparity and drive vergence eye movements. These responses to the presence of prism appear to be present soon after birth.[1,2]

Interestingly, the amount of convergence or divergence necessary to align at a new distance changes with age in early development. This is because the distance between the eyes increases over the first years after birth while the head grows, and therefore the eyes must rotate by increasing angles to reach alignment at the same viewing distance. The interpupillary distance (IPD) reaches the adult value at approximately 15 to 16 years of age.[3,4]

Studies of adults have demonstrated that vergence responses consist of a number of components in addition to the fusional response to retinal disparity.[5,6] Maddox[5] defined these as a baseline tonic component, a response to the proximity or sense of nearness of the object (see also Refs. 7, 8), and a coupled response driven by the accommodation system (see also Ref. 9). Clinically, the alignment of the eyes in the absence of the retinal disparity cue (when viewing with one eye, for example) is termed the heterophoria position, representing the combined responses of these other principal components.

Numerous studies have now demonstrated that the heterophoria position in adults shifts or adapts to reflect recent experience. For example, an extended-duration response to an increased convergence demand results in a convergent shift in the heterophoria position (less exophoria or more esophoria).[10–19] This is thought to permit flexibility during times of physiological and/or ocular change.[20,21] Given that the vergence demand for the developing visual system is changing as the distance between the eyes increases over time, do young children also exhibit this adaptation? Might it help them maintain binocular function during growth, while also allowing them to compensate for changes in accommodative vergence resulting from changes in their accommodative demand with maturation of their refractive error?[22–24] Recently, we have shown that the group mean heterophoria position for a target at 33 cm stays relatively constant during early childhood.[25] Could this be achieved through adaptation of the vergence motor system? Might abnormalities in this adaptation be involved in the development of clinical disorders such as refractive strabismus?

This study examined vergence adaptation in children 2 to 7 years of age in comparison with an adult control group. Vergence adaptation has been measured previously in older school-aged children by two groups, but there have been no studies of preschool children when both refractive error and IPD are immature and children are at risk for refractive strabismus. Wong et al.[26] tested vergence adaptation in 18

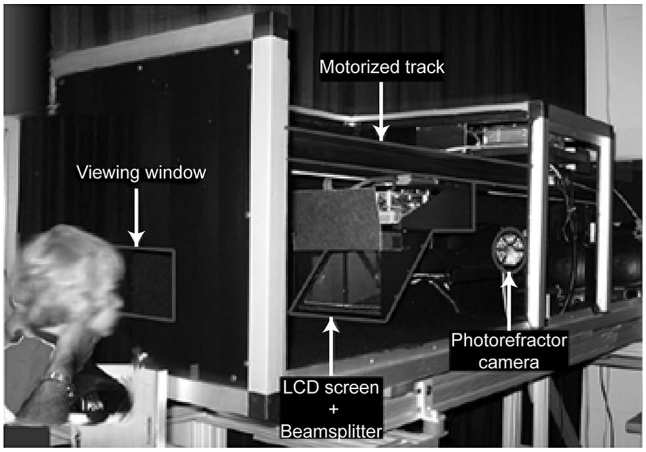

FIGURE 1. Experimental equipment with the side cover removed. Subjects viewed a cartoon movie displayed on a horizontally mounted LCD screen via a beam splitter, while the PowerRefractor camera (at a 1-m viewing distance) measured eye alignment and refraction.

children aged 5.5 to 11.7 years by having them read single letters in binocular viewing at 15 cm for 5 minutes. Adaptation was measured with a synoptophore by comparing pre- and posttask vergence in open-loop vergence and accommodation conditions (the right eye viewed a sentry box and the left eye viewed a soldier, through 0.5-mm pinholes). The magnitude of the vergence shift, measured a few seconds after the adaptation period, was 0.45 MA (SEM ± 0.08) or approximately 2.2 pd in the children (assuming 4.9-cm IPD) and 0.11 MA (SEM ± 0.05) or approximately 0.7 pd in adults (assuming 6.1-cm IPD), a significant difference that may reflect a more adaptive system in these older children. Sreenivasan et al.[27] measured vergence adaptation in 53 emmetropic or myopic children between the ages of 7 and 15 years. Children viewed an animated cartoon movie at 33 cm for 20 minutes while vergence adaptation was quantified by estimating changes in phoria during and after the task using a modified Thorington technique. The direction and magnitude of vergence adaptation (defined as the difference between phoria before and after 20 minutes of near activity) were influenced by the type of phoria, such that exophores displayed convergent shifts while esophores showed divergent shifts in phoria. These studies both suggest that adaptation was making the vergence position more accurate for the task undertaken during the adaptation period.

The goals of this study were to determine whether younger, nonstrabismic children are capable of vergence adaptation during the age range when refractive and accommodative forms of esotropia typically develop. Future studies would then ask whether ability to adapt might be related to clinical outcome in individuals.

METHODS

Subjects

A total of 15 adults (age range, 19.5–35.8 years, mean 25.1 years) and 34 typically developing children (age range, 2.5–7.3 years, mean 4.9 years) completed the study (an additional 5 adults and 16 children were recruited but later excluded due to criteria listed below). The children were recruited from the local community while adults were recruited from the academic department. Only two of the 15 adults had any experience with vergence experiments or specialist knowledge of oculomotor function. All of the children received an eye examination that revealed no evidence of abnormality beyond refractive error. The examination included an age-appropriate assessment of visual acuity, ocular alignment at distance and near, cycloplegic refractive error, and ocular health. Adult participants were functionally emmetropic and had no strabismus or asthenopia. They were prepresbyopic and wore no refractive correction. The children typically had a low hyperopic refractive error (mean cycloplegic spherical equivalent [SE] averaged across the two eyes: + 0.93 diopters [D], SD ± 0.7 D, min = –1.25 D, max = +2.25 D), low astigmatism (averaged across the two eyes: 0.41 D, SD ± 0.19, min = 0.25 D, max = 1.0 D), and low anisometropia (all ≤ 1 D). None were prescribed optical correction by their clinician at the examination. Written informed consent was obtained from adult participants and from the parents of the children tested. Children over the age of 7 also signed an assent form. The study was approved by the local Indiana University Institutional Review Board and adhered to the tenets of the Declaration of Helsinki.

Equipment

The data were gathered at 25 Hz with simultaneous Purkinje image tracking[28] and photorefraction technology,[29,30] using the video-based PowerRefractor (PR) (Multi Channel Systems, Reutlingen, Baden-Württemberg, Germany). The PR uses group-average adult defocus[30,31] and eye alignment[31,32] calibrations. In this study, individual defocus and eye position calibrations were performed on all participants to adjust the data for individual differences. A relative calibration was performed by occluding vision in one eye with a near-infrared filter (Wratten filter no. 87; Kodak, Rochester, NY, USA) while data were collected from both eyes, and placing lenses and prisms of different powers over the filter.[25]

Participants watched a high-contrast cartoon movie with naturalistic spatial amplitude spectra, displayed on a 6.8- × 6.8-cm liquid-crystal display (LCD) screen (Fig. 1). The image from the LCD screen was reflected from a beam splitter to the subject while the apparatus was on a motorized track (see Fig. 1). Participants were carefully aligned so that the visual target and the PR camera were centered on the midline between their eyes. Interpupillary distance was recorded from the photorefractor image with the stimulus screen at 90 cm, and then the distance of the screen was moved to 33 cm for the vergence adaptation assessment.

Vergence Adaptation Protocol

Upon arrival in the lab, participants did not engage in any near work that would elicit adaptation prior to testing. The period prior to testing (approximately 10 minutes) consisted of adult participants listening while the experimenter described the experiment and the consent form, and child participants playing with toys or sitting with a parent during the explanation of the experiment.

Adaptation was measured in three conditions, using a target at 33 cm. Each condition began with a monocular viewing period lasting at least 60 seconds. Participants were rendered monocular using the IR filter, which was placed directly over the right eye. This monocular interval removed disparity information and allowed the eyes to return to their resting heterophoria position while data were collected from both eyes. Following the monocular interval, binocular vision was restored for either 5 seconds (5-second condition) or 60 seconds (60-second and prism 60-second conditions). The short, 5-second interval should not permit significant adaptation to build up,[33,34] and the 60-second interval provided a balance between the limited cooperation of young children and intervals used in adult studies (predominantly between 60 seconds and 5 minutes).[17,26,35,36] In the prism 60-second condition, participants also wore a 10-pd base-out prism during the binocular interval (equivalent to a 5.7° stimulus) to increase their convergent demand and loosely mimic growth of the head and increasing IPD. This demand also tested their adaptation to overcoming exophoria, the typical phoria found at near. Of note, while 10 pd will stimulate the same angular rotation of the eyes in all subjects, the equivalent change in fixation distance, in meter angles, will depend on the participant's IPD. Following the binocular adaptation interval, the right eye was occluded again for 60 seconds to provide another extended monocular recording. Previous studies of adults have found that adaptation is sustained for several seconds to minutes depending on the length of the adaptation interval.[11,17,35,37,38] The three conditions were tested in a specific order, with the 5-second condition occurring first, followed by the 60-second, and then the prism 60-second condition. Two to three minutes passed between each of these conditions, with a calibration performed between the 5- and 60-second conditions.

Adaptation Analyses

While 50 children and 20 adults were recruited for this project, only 34 children and 15 adults provided usable data in at least two conditions. Conditions were excluded if a child did not cooperate or if the data did not meet the inclusion criteria described below. All of the usable datasets included the 5-second condition, and 17 children and 10 adults provided usable data for all three conditions.

Data analyses were performed using MacSHAPA (University of Illinois, Urbana-Champaign, IL, USA), MATLAB (Mathworks, Natick, MA, USA), Excel (Microsoft, Redmond, WA, USA), SPSS (IBM, Armonk, NY, USA), and GraphPad Prism (GraphPad Software, Inc., La Jolla, CA, USA) software. Video of each experimental session was recorded and analyzed offline using MacSHAPA to determine the times when a lens (in the case of a calibration), prism, or IR filter was introduced and removed. Raw accommodation and vergence data from the PR were multiplied by the calibration factors for the individual subject, and then outliers and nonphysiological data samples were excluded before further analysis. Individual points were excluded using the following five criteria: (1) Accommodation fell outside the linear range of the instrument (+4 to –6 D); (2) pupil size was <3 or >8 mm; (3) eye position was greater than 15° eccentricity (the first Purkinje image was more than 15° from the image of the pupil center); (4) accommodation velocity was greater than 12.5 D/s (given a typical range of approximately 1–12.5 D/s for amplitudes of 1–2 D)[39]; or (5) vergence velocity was greater than 175 pd/s (given a typical peak velocity of less than 100°/s (175 pd/s) for a 10° stimulus).[40]

For each condition, 3.5 seconds of stable data from both the first monocular interval and the binocular section was identified for further analysis. In particular, these sections were used to calculate the heterophoria in the 5-second condition, to measure the repeatability of alignment across conditions, and to provide a baseline monocular comparison for the decay response in the second monocular interval. In each case, the 3.5-second monocular interval was identified at the end of the first monocular period.[25] In the 5- and 60-second conditions, the 3.5-second binocular interval was identified 1.5 seconds after the start of the binocular period. In the prism 60-second condition, the 3.5-second binocular interval began approximately 20 seconds into the viewing period to allow time for a fusion response to the prism. The monocular and binocular intervals were considered stable if the accommodation change between the intervals was ≤ 2 D (permitting some vergence accommodation driven in the prism 60-second condition) and the 95% confidence interval (CI) of the mean vergence response, for each interval, was less than or equal to ± 1 pd.[25] If the 3.5-second interval did not meet the criteria for stability, an approximately 1-second step was made either earlier (in the case of monocular data) or later (in the case of binocular data) to identify a new 3.5-second interval. If there was no stable interval, that condition was excluded.

In the first analysis, the monocular and binocular intervals were compared across adaptation conditions to assess the repeatability of those alignments. A condition was excluded if there was a >5-pd difference in either baseline monocular alignment or binocular alignment between conditions. A value of 5 pd (approximately 1 MA depending on IPD) was determined using the 95% limits of agreement for monocular alignment differences across all subjects. This criterion ensures that a stable alignment was achieved across conditions and that there were no significant adaptation effects lingering from one condition to the next. Consistency in binocular alignment across conditions also provides evidence that binocular fusion was achieved, particularly when viewing through the prism. Four children and four adults were determined to have not fused the prism, and they were excluded from all analyses of adaptation.

Vergence alignment in the second monocular phase (following binocular stimulation) starts close to the binocular position and decays toward the stable resting position (Fig. 2). In the second analysis, this decay was quantified using a least-squares fit of Equation 1. Five parameters were estimated: (1) the vergence position (y_0 at the start of the monocular decay interval, initially equivalent to the mean vergence response from the preceding binocular interval); (2) the change in vergence position (a) (negative for an esophore and positive for an exophore); (3) the time at which vergence started to decay toward the stable position (t_b); (4) the time at which vergence reaches the stable position (t_e); and (5) the rate of decay (D).

Decay vector:

$$y(t) = \begin{cases} y_0 & \text{, when } t < t_b \\ y_0 + a\left(e^{\left(-\frac{(t-t_b)}{D}\right)} - 1\right) & \text{, when } t_b < t < t_e \\ y_0 + a\left(e^{\left(-\frac{(t_e-t_b)}{D}\right)} - 1\right) & \text{, when } t > t_e \end{cases} \qquad (1)$$

The fitted parameters were then used to calculate the 63% time constant of the decay[41] and the final stable vergence/heterophoria position.

RESULTS

Repeatability of Baseline Monocular and Binocular Alignment

Baseline monocular vergence alignment was compared across conditions to ensure that baseline behavior was not affected by adaptation. Children ($n = 34$) and adults ($n = 15$) with two or more usable conditions were included in this analysis. Mean baseline monocular alignment was determined by averaging the stable 3.5-second period from the first monocular interval. Participants for whom the difference between conditions was larger than 5 pd were excluded (one adult and one child). For the conditions included in the analyses, a two-way ANOVA revealed no significant difference in baseline monocular alignment between conditions ($F[2,123] = 0.1$, $P = 0.94$, $\eta_p^2 < 0.01$), nor between children and adults ($F[1,123] = 0.1$, $P = 0.72$, $\eta_p^2 < 0.01$) (Fig. 3a). There was also no interaction ($F[2,123] = 0.1$, $P = 0.90$, $\eta_p^2 < 0.01$). An intraclass correlation

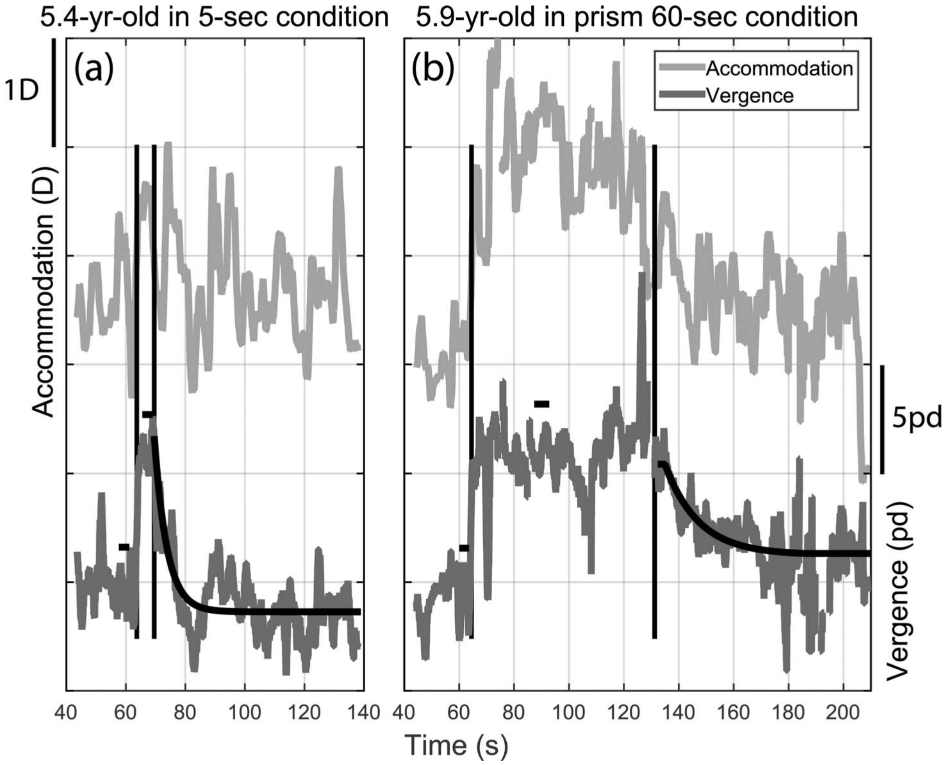

Figure 2. Representative vergence and accommodation responses during (**a**) the 5-second condition and (**b**) a prism 60-second condition (accommodation shifted vertically for clarity). The *first (leftmost) vertical black bar* marks the end of the first approximately 60-second occlusion period while the *second vertical black bar* marks the end of the binocular interval. The *horizontal black bars* represent the intervals used for the measurement of vergence and accommodation. A least-squares fit is represented by the exponential function. Increasing values on the *y*-axes represent relative convergence and increased accommodation. Note that (**b**) shows an example where accommodation increased during binocular viewing.

coefficient (ICC) confirms this agreement when comparing the stable monocular positions across adaptation conditions (children: ICC = 0.988, 95% CI 0.973–0.995; adults: ICC = 0.990, 95% CI 0.970–0.997). These results demonstrate that there was no consistent lingering effect of adaptation from the previous conditions on baseline monocular alignment, in that only two participants were excluded from this analysis.

Binocular vergence alignment was also compared across conditions. Mean binocular response was determined by averaging the stable 3.5-second binocular intervals. Participants for whom the difference between conditions was larger than 5 pd were excluded (four adults and four children). A two-way ANOVA revealed no significant difference between conditions ($F[2,123] = 0.05$, $P = 0.95$, $\eta_p^2 < 0.01$) nor between children and adults ($F[1,123] = 0.4$, $P = 0.55$, $\eta_p^2 < 0.01$) (Fig. 3b). The interaction effect was also not significant ($F[2,123] = 0.3$, $P = 0.76$, $\eta_p^2 < 0.01$). The lack of a significant difference in binocular alignment across conditions demonstrates that these subjects maintained the same binocular alignment across the three adaptation conditions.

An ordinary least-squares linear regression was used to examine the relationship between children's age and their difference in binocular alignment (comparing 5-second and prism 60-second conditions). The regression did not reveal a significant effect of children's age ($R^2 < 0.01$, $F(1,25) = 0.01$, $P = 0.92$), and therefore suggests that even the youngest children were fusing the images in the presence of prism.

Measures of accommodation were also compared across conditions in part because the accommodation and vergence systems are neurally coupled and therefore can influence each other. Mean accommodation was calculated by averaging the responses in the 3.5-second baseline monocular and binocular intervals. A two-way ANOVA revealed no significant difference in accommodation between conditions when measured during the baseline monocular interval ($F[2,123] = 0.2$, $P = 0.85$, $\eta_p^2 < 0.01$) but a small significant difference between children and adults ($F[1,123] = 9.4$, $P = 0.003$, $\eta_p^2 < 0.07$) (Fig. 3d). The interaction effect was not significant ($F[2,123] = 0.1$, $P = 0.91$, $\eta_p^2 < 0.01$). Accommodation in the binocular interval, as assessed using a two-way ANOVA, did not change significantly between conditions ($F[2,123] = 1.3$, $P = 0.27$, $\eta_p^2 = 0.02$) nor between children and adults ($F[1,123] = 0.46$, $P = 0.45$, $\eta_p^2 < 0.01$) (Fig. 3e), and the interaction effect was not significant ($F[2,123] = 0.3$, $P = 0.76$, $\eta_p^2 < 0.01$). Overall, these results indicate that closed-loop accommodation remained stable across conditions during monocular and binocular viewing in both adults and children (Figs. 3d, 3e), and that the neural coupling between accommodation and vergence did not result in a change in the final accommodation response with vergence adaptation differences across conditions.

Distributions of Baseline Heterophoria

All of the children and some of the adults tested in this study also participated, that same day, in our study of near heterophoria.[25] In that study, we found a mean near heterophoria (at 33 cm) of −5.0 pd (SD ± 3.7) in young children (2–7 years of age) and −5.6 pd (SD ± 4.7) in adults after approximately 1 minute of dissociation (a nonsignificant difference). Figure 4 displays the distribution of near heterophorias found in the children ($n = 34$) and adults ($n = 15$) in the baseline 5-second condition for the current study. Here the

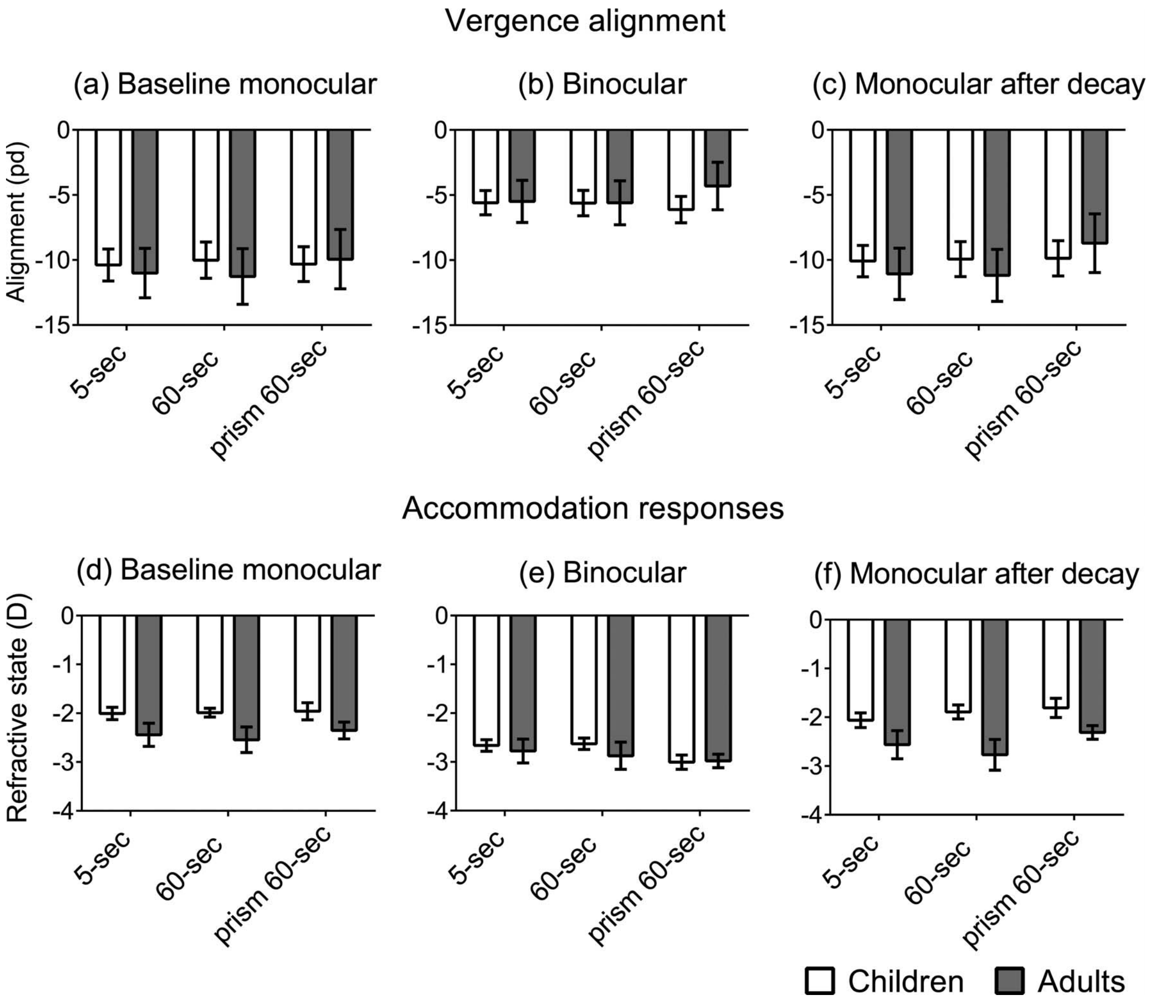

Figure 3. Vergence alignment and accommodation responses compared across conditions and ages during (**a**, **d**) baseline monocular viewing, (**b**, **e**) binocular viewing, and (**c**, **f**) monocular viewing following decay after adaptation. Larger negative values indicate more divergence for (**a**–**c**) and more accommodation for (**d**–**f**). *Error bars* represent SEM. Vergence *y*-axis values reflect the combination of dissociated heterophoria and angle lambda.

means were –4.7 pd (SD ± 3.6) for children and –5.5 pd (SD ± 4.3) for adults.

Assessment of Vergence Adaptation

In thinking about vergence adaptation resulting from visual experience during the binocular interval, there are a number of ways to quantify the results. When separating the time and alignment dimensions, adaptation could be reflected in a longer time taken to return to a stable monocular alignment (heterophoria position) after additional vergence demand (63% time constant, τ), or it could be reflected in a difference in the final stable heterophoric alignment (y_e). The following sections describe the results required to interpret these two metrics. Only children ($n = 17$) and adults ($n = 10$) with usable data in all three conditions were included in these analyses.

63% Time Constant. The time taken to return to a stable monocular alignment (heterophoria position) was assessed using the 63% time constant. The time constant passed normality tests (Shapiro-Wilk, Kolmogorov-Smirnov) after undergoing a square root transformation, and statistical analyses were carried out on the transformed data. A two-way mixed model ANOVA (between-subjects variable was age, within-subjects variable was adaptation condition) was then conducted. There was a significant effect of adaptation condition on the time constant (Fig. 5a; Table), and Bonferroni adjustment revealed that the time constant was longer for the prism 60-second condition compared to both the 5-second condition ($P = 0.015$) and the 60-second condition ($P = 0.035$). There was no significant effect of age (children versus adults) on time constant and no interaction effect (Table).

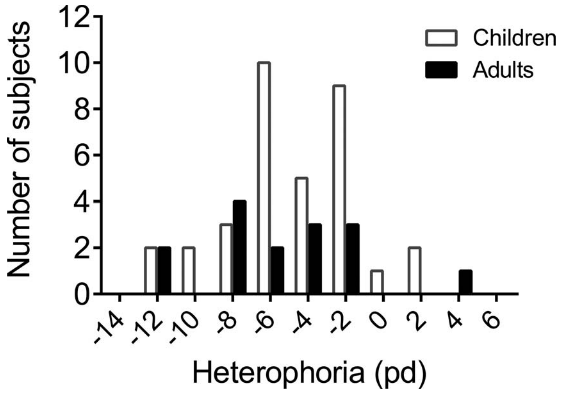

Figure 4. Distributions of baseline heterophorias in children (*white*) and adults (*black*).

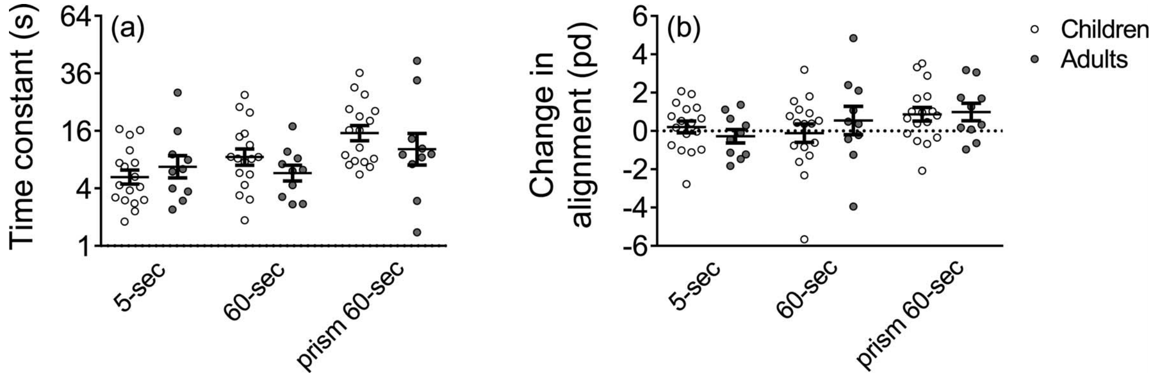

FIGURE 5. (**a**) 63% time constant in children and adults after a square root transformation. (**b**) Difference in resting alignment between the first and second monocular intervals. Positive numbers reflect a more converged alignment in the second monocular interval. Geometric mean (**a**), arithmetic mean (**b**), and SEM *error bars* (**a**, **b**) are provided.

There are several other variables that may influence the 63% time constant in children. The following analyses evaluated the effect of IPD, spherical equivalent refractive error, age, and heterophoria on the time constant from the prism 60-second condition. A multiple linear regression model revealed that none of these variables was a significant predictor in these typically developing children (all P values > 0.4), and Figure 6 demonstrates the weak relationships, with correlations (r values) of 0.03, –0.03, 0.16, and –0.15 for age, heterophoria, IPD, and spherical equivalent, respectively. There was a moderate but insignificant correlation between heterophoria and the 63% time constant for adults ($r = -0.40$, $P = 0.22$, $n = 11$) (Fig. 6b).

Final Stable Monocular Position (y_e). The final stable monocular position, measured at the end of the second monocular interval, was compared to the baseline alignment measured at the end of the first monocular interval. A three-way mixed model ANOVA was performed; between-subjects variable was age, and within-subjects variables were adaptation condition and viewing interval (i.e., first monocular interval versus second monocular interval). There were no main effects of adaptation condition, viewing interval, or age, and none of the interactions were significant. P values were greater than 0.10 for the main effects of adaptation condition and age group, and for the interactions between adaptation and age, interval and age, and adaptation and interval and age. The P values were less than or equal to 0.10 for the main effect of viewing interval ($P = 0.10$, $F = 3.0$, $\eta_p^2 = 0.11$; Fig. 5b) and the interaction between adaptation condition and viewing interval ($P = 0.08$, $F = 2.7$, $\eta_p^2 = 0.10$). Thus the results indicate that the participants had returned to their baseline heterophoric alignments by the end of the second monocular interval (i.e., after 60 seconds), although the prism 60-second condition was the closest to exhibiting a more convergent position after the adaptation period, and the adaptation condition by viewing interval interaction was the closest to significance.

DISCUSSION

For a viewing distance of 33 cm, and varying amounts of stimulus to adaptation, the group of 2- to 7-year-old children demonstrated comparable levels of adaptation to adults. More specifically, when viewing the near target through 10-pd base-out prisms for 60 seconds, young children and adults showed a significant increase in their mean 63% recovery time constant compared to the 5-second condition. This result is significant as it confirms that, as a group, young children exhibit adaptation during a period when the vergence demand for the developing visual system is changing with the increase in distance between the eyes.[3,4,41]

These results are consistent with the finding that older children (age 5.5–15 years) also show evidence of vergence adaptation.[26,42] While Sreenivasan et al.[27] measured vergence adaptation during the adaptation interval, Wong et al.[26] quantified the magnitude of the vergence shift several seconds after a 5-minute adaptation period. Our study, like that of Wong et al.,[26] measures the decay of the vergence position in recovery, following an adaptation interval. We also summarized complete decay function using the 63% time constant for duration and the final monocular position after 60 seconds of occlusion. Using these measures, the children tended to have a longer time constant than the adults in the prism condition (Fig. 5), but we did not find statistically or clinically significant differences between the 2- to 7-year-old children and adults. This result provides evidence of adaptation in these younger children; but the impact of different adaptation tasks and durations, and different analysis metrics, on the difference between young and adult observers' adaptation will need to be determined.

Evidence of vergence adaptation in the form of the 63% time constant suggests that the adaptation was making the vergence position more appropriate for the task undertaken during the adaptation period. Base-out prism was used to loosely mimic the increasing convergence demand experi-

TABLE. Two-Way ANOVA for the 63% Time Constant

	ANOVA Results	Geometric Mean
Adaptation condition	$F(2,50) = 6.8$, $P = 0.003$, $\eta_p^2 = 0.21$	5-s: 5.3 s, 95% CI 3.8–7.5 60-s: 7.1 s, 95% CI 5.1–9.9 Prism 60-s: 11.5 s, 95% CI 7.7–17.1
Age group	$F(1,25) = 0.7$, $P = 0.42$, $\eta_p^2 = 0.03$	
Interaction	$F(2,50) = 1.5$, $P = 0.24$, $\eta_p^2 = 0.06$	

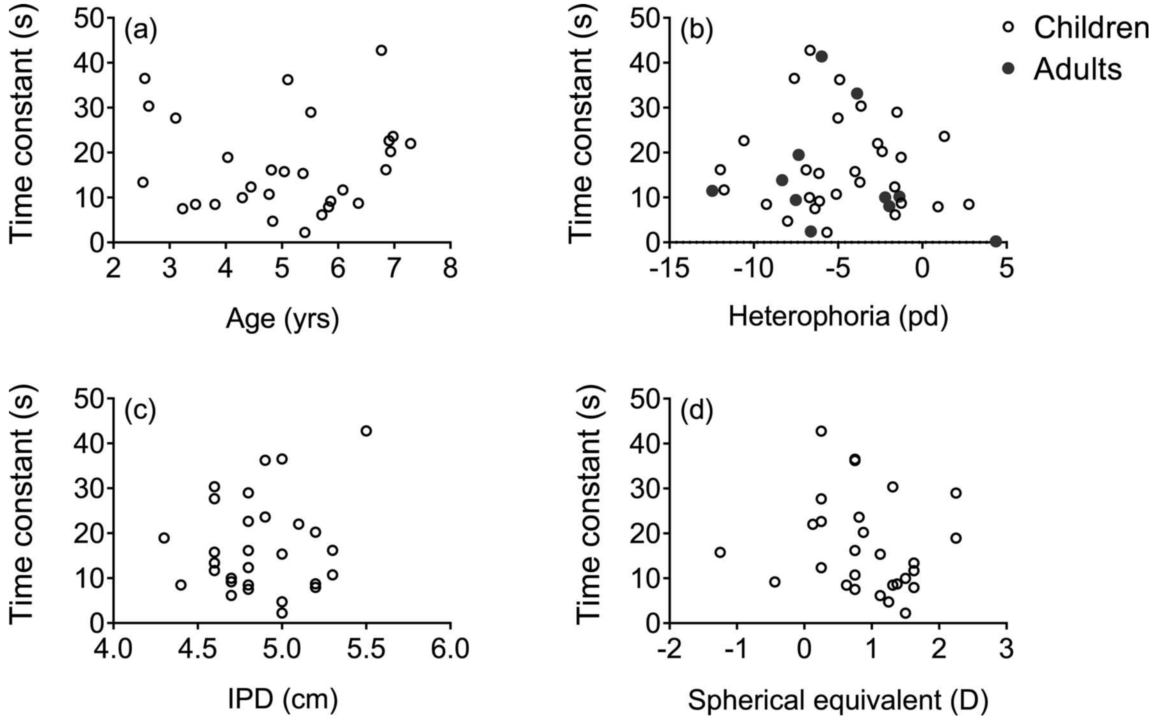

Figure 6. Relationship between 63% time constant from the prism 60-second condition and (**a**) age in children, (**b**) heterophoria in children and adults, (**c**) IPD in children, and (**d**) spherical equivalent in children.

enced with growth of the head, as the IPD changes approximately 6 mm between 2 and 7 years of age (4.7-5.3 cm).[4] It also tested adaptation in the direction required to overcome typical near exophoria. In effect, the prism represents an additional demand beyond the current state of adaptation. At least some of even the youngest children were able to undergo this additional adaptation, as an analysis of age within the children showed no difference in 63% time constant in the prism 60-second condition (Fig. 6a). This is important as it may allow them to compensate not only for growth of the head but also for changes in the mechanics of eye rotation, visual demands, and potentially excessive accommodative vergence resulting from hyperopia during emmetropization.

Young children typically view objects at many distances. While they are not yet doing extensive near work in school, they do have different oculomotor demands from adults, imposed by their developmental immaturities. Nonetheless, after allowing approximately 1 minute for dissociation, heterophoria is relatively constant with age (Fig. 4),[25] and therefore something other than classical rapid fusional vergence appears to be adapting to these changing immaturities. When considering classical components of the vergence response,[43] the data collected in this project were not collected under fully open-loop conditions (where focus, disparity, and ideally proximity cues would be uninformative). It is, therefore, not possible to interpret the adaptation mechanism in any further detail currently, although the results provide little evidence of changes in closed-loop accommodation with vergence adaptation (Figs. 3d–f), and the protocol held the proximity cue constant throughout testing.

It is possible that adaptation is involved in the development of pediatric clinical disorders such as refractive strabismus, if a patient is unable to employ it effectively to compensate for other challenges to binocular function. The current study tested a relatively limited range of typical refractive errors, and therefore this question was not addressed directly here. Previous studies have shown abnormal vergence adaptation in adults experiencing asthenopic symptoms[18] and in those with binocular vision disorders such as convergence insufficiency.[36,44–46] Similarly, children with uncorrected hyperopia (>3.5 D) who are unable to adapt to increased accommodative convergence may break down into refractive strabismus. This additional factor may help explain why only approximately 20% of children with higher hyperopia develop refractive esotropia while the other 80% remain binocularly aligned.[47–50]

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