Near Heterophoria in Early Childhood

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Purpose. The purpose of this study was to measure near heterophoria in young children to determine the impact of early growth and development on the alignment of the eyes.

Methods. Fifty young children (≥2 and <7 years of age; range of spherical equivalent refractive error −1.25 diopters [D] to +3.75 D) and 13 adults participated. Their eye position and accommodation responses, in the absence of optical correction, were measured using simultaneous Purkinje image tracking and photorefraction technology (MCS PowerRefractor, PR). The resulting heterophorias, and both accommodative convergence/accommodation (AC/A) and convergence accommodation/convergence (CA/C) ratios were then computed as a function of age, refractive error, and an alternating cover test.

Results. The mean heterophoria after approximately 60 seconds of dissociation at a 33-cm viewing distance was 5.0 prism diopters (pd) of exophoria (SD ± 3.7) in the children (78% of children > 2 pd exophoric) and 5.6 pd of exophoria (SD ± 4.7) in adults (69% of adults > 2pd exophoric; a nonsignificant difference), with no effect of age between 2 and 6 years. In these children, heterophoria was not significantly correlated with AC/A ($r = 0.25$), CA/C ($r = 0.12$), or refractive error ($r = 0.21$). The mean difference between heterophoria measurements from the PR and the clinical cover test was −2.4 pd (SD = ±3.4), with an exophoric bias in the PR measurements.

Conclusions. Despite developmental maturation of interpupillary distance, refractive error, and AC/A, in a typical sample of young children the predominant dissociated position is one of exophoria.

Keywords: heterophoria, vergence, young children, accommodation, refractive error

Dissociated heterophoria is the misalignment of the eyes relative to a target in the absence of fusional vergence. An exophoria is a divergent misalignment, while an esophoria is a misalignment in the convergent direction. Minimal to no misalignment (<2 prism diopters [pd]) is typically used as the working definition of orthophoria. Occluding one eye removes the disparity cue used by fusional vergence to correct this misalignment and results in a drift to the heterophoria position for the relevant viewing distance. This position has been well characterized in adults and older children,[1–12] but it has been difficult to measure in children less than 5 years of age due to their limited cooperation.[13,14]

In adults the average heterophoria for a distant target is 0 to 1 pd of exophoria with an SD of 2 pd[1–3,5] (1 pd is equivalent to 0.57°). This position represents the accuracy of the vergence response driven by all cues other than binocular disparity. In the language of Maddox[15] and Heath,[16] these other components are tonic vergence, proximal vergence, and coupled accommodative vergence. When an individual switches fixation to a near target, both their vergence and accommodative demands increase and so the heterophoria for the near demand is a result of the new combination of cues and responses. In adults, the average heterophoria, at a 40-cm viewing distance, is 3 to 5 pd of exophoria, or 1.7° to 2.9°.[1–3,5]

Heterophoria is of interest in early childhood for a number of reasons. Firstly, refractive error and interpupillary distance change during this period. Young children are typically uncorrected hyperopes[17–19] (mean spherical equivalent [SE] at 4 years of age was found to be +1.1 diopters [D], SD ± 0.85[18]). Uncorrected hyperopes have an increased accommodative demand, potentially leading to additional accommodative vergence and esophoria.[20,21] Young children also have a reduced interpupillary distance (IPD), of approximately 50 mm, relative to an adult value of approximately 62 mm,[22,23] and hence the angular vergence demand is actually reduced during the period of growth in IPD. Given both of these factors, do children in the first years after birth typically exhibit an esophoria (a latent over-convergence that is eliminated in binocular conditions by fusional vergence)? Secondly, approximately 20% of significant hyperopes (>3.5 D) develop a convergent strabismus during childhood that cannot be overcome by fusional vergence.[24–27] This form of strabismus has a peak onset between 2 and 4 years of age,[28] when the eyes will become permanently over-converged and esotropic with no treatment. Eighty percent of significant hyperopes remain aligned, however, in the presence of their increased accommodative demand. What is the typical near heterophoria in early childhood and, hence, what value might a clinician view as atypical and an indication for clinical concern, especially when associated with significant uncorrected hyperopia? The impact of accommodation on eye alignment in response to hyperopia partially depends upon the strength of the coupling with vergence. For example, if the gain of the accommodative convergence/accommodation (AC/A) coupling from accommodation to vergence is low, a large accommodative response will only induce a small convergence response, and possibly exophoria. The strength of the convergence accommodation/convergence (CA/C) coupling (convergence accommodation

Table 1. Mean SE Refractive Error (Rx) and IPD Across Age Bins With SD in Parentheses

	2 y	3 y	4 y	5 y	6 y	Adults
SE Rx averaged across OD and OS of each subject and then across the group, D						
Mean	1.36 (1.1)	0.96 (0.37)	1.0 (0.55)	0.96 (1.0)	0.68 (0.50)	Functional emmetropes
Minimum	0.125	0.25	0.25	−1.25	0.125	
Maximum	3.75	1.5	2.25	2.25	1.56	
Interpupillary distance at 90-cm viewing distance, cm						
Mean	4.59 (0.31)	4.62 (0.14)	4.8 (0.25)	4.85 (0.21)	5.22 (0.23)	5.5 (0.39)

per prism diopter of vergence) from vergence to accommodation[29] is also important when evaluating the effect of the heterophoria on fusional vergence, and hence accommodation.

Studies of older, school-age children have consistently reported a mean near heterophoria (at a distance of 25–40 cm) of close to orthophoria, with a mean between 3 pd of exophoria and 1 pd of esophoria,[7–12,14,30–32] and negligible to no change with age. The data regarding the variance of near heterophoria in this later childhood indicate a relatively large distribution, ranging from at least 10 pd of esophoria to 10 pd of exophoria[8,9,12] at ages 6 to 12 years.

Interestingly, the only studies to have included younger children[13,14] have both suggested a mean heterophoria of very close to orthophoria and that the variance is lowest in the youngest groups (aged 2–6 years). Lam et al.[13] measured heterophoria at near in typical children between 4.5 and 5.5 years of age ($N = 162$, ≤ 3.5 D of hyperopia, ≤ 0.5 D myopia). Using the alternate prism cover test they found that 96.9% of the children were orthophoric at near. Chen et al.[14] used a subjective technique (Modified Maddox Wing) to measure heterophoria position at 25 cm in 2- to 15- year-old emmetropic children ($n = 268$, excluding any myopia or hyperopia $> +1$ D). They found that 100% of 2- to 3-year-old and 98% of 4-year-old emmetropes were orthophoric. Neither of these studies provided their working definition of orthophoria, but, while a mean position of orthophoria in these young children is comparable to estimates from school-aged children,[9–12,30,31] the lack of variability in the younger measurements is somewhat surprising. Wong et al.[33] have found that older children (mean age = 9.8 years) show stronger adaptation (take longer to dissociate) to a near stimulus than adults and therefore, one plausible explanation for the lack of variance found by Lam et al.[13] and Chen et al.[14] is that the children were not fully dissociated. If so, what is the heterophoria once a longer decay or drift has occurred? And, what does that position mean for the role of fusional vergence during development?

The goal of the current study was to use an objective assessment of near heterophoria that requires minimal cooperation from young children to understand maturation of heterophoria between 2 and 6 years of age. We hypothesized that the youngest children might be esophoric due to their narrow IPD and uncorrected hyperopia. Their eye alignment was measured over a relatively long period of monocular viewing to determine the time course of dissociation, and, in conjunction with measures of accommodation, to derive AC/A and CA/C ratios to gain insight into the relationship between the coupling ratios and heterophoria during early childhood.

Methods

Subjects

A total of 13 adults (age range, 20.0–35.8 years, mean 25.9; by report, 11 of European Caucasian and 2 of Hispanic/Latino ethnicity, and all of white race) and 50 children (age range, 2.36–6.98 years, mean 4.5 years; by parental report, 44 of European Caucasian, 4 of Hispanic/Latino, and 2 of Asian ethnicity, with 47 of white, 2 of Asian, and 1 of African American race) participated in the study. Typically-developing children (by parental report; no evidence of developmental delays or intervention for a condition impacting the child's development) were recruited from the local community while adults were recruited from the academic department. All of the children received an eye examination that revealed no evidence of strabismus or abnormality beyond uncorrected refractive error. The examination included an age appropriate assessment of visual acuity, ocular alignment, refractive error, and ocular health. Refractive error was determined with cycloplegic retinoscopy using one drop of 1.0% cyclopentolate in each eye. The clinician was masked with regard to the eye-tracking and photorefraction data collected for the study. Adult participants were functionally emmetropic, requiring no refractive correction, and prepresbyopic. The children typically had a low hyperopic refractive error (Table 1; mean cycloplegic SE averaged across eyes of +1.0 D, SD ± 0.8 D (Refs. 34, 35; note that those studies typically report SE of worse eye) low astigmatism (averaged across eyes: 0.46 D, SD ± 0.21), and low anisometropia (all < 1 D). None of them had been prescribed any optical correction at the time of their visit. Written informed consent was obtained from adult participants and from the parents of the children tested. The study was approved by the local Indiana University institutional review board and adhered to the tenets of the Declaration of Helsinki.

Data Collection

The data were gathered using simultaneous Purkinje image tracking[36] and photorefraction technology.[37,38] The video-based PowerRefractor (PR; Multi Channel Systems, Reutlingen, Baden-Württemberg, Germany) was used to collect continuous accommodation and vergence measurements at 25 Hz. Previous studies of heterophoria in children have used the alternate cover test and modifications of the Maddox Rod test, which do not permit the continuous recording of both accommodation and vergence and have a subjective component. The Purkinje image tracking approach provides an objective recording that is analyzed offline to determine heterophoria.[36,39,40] The only disruption to the child during testing is the presence of a near infra-red (IR) filter in front of one eye while they view a cartoon movie (the filter provides occlusion as used in a clinical cover test, while permitting data collection from both eyes). These eye position recordings have a resolution of less than 2 pd, which is the smallest deviation detected under ideal conditions with the clinical cover test.[41]

The PR uses a population-average defocus calibration based on data collected from adults.[38,42] Similarly, a population-average Hirschberg ratio is used to calculate gaze position and vergence.[42,43] In this study, individual relative defocus and eye position calibrations were performed on all participants in order to confirm the changes in accommodation and vergence.

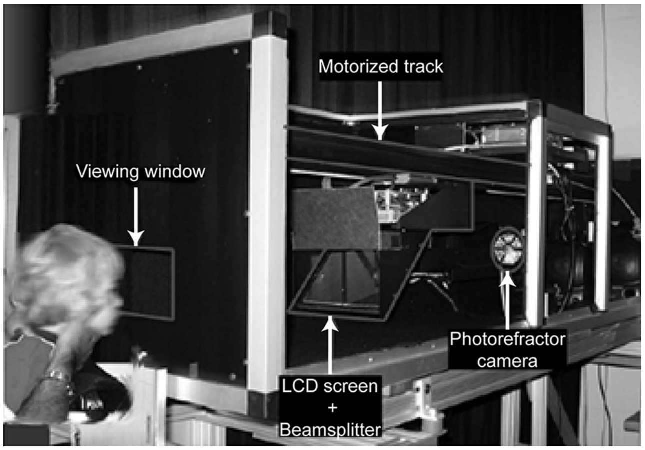

Figure 1. Experimental equipment. Subjects viewed a cartoon movie displayed on a horizontally mounted LCD screen via a beam splitter, while the PR camera (at 1 m) measured eye alignment and refraction. The LCD screen and the beam splitter were mounted on a motorized track and placed at a viewing distance between 33 and 90 cm depending on the condition.

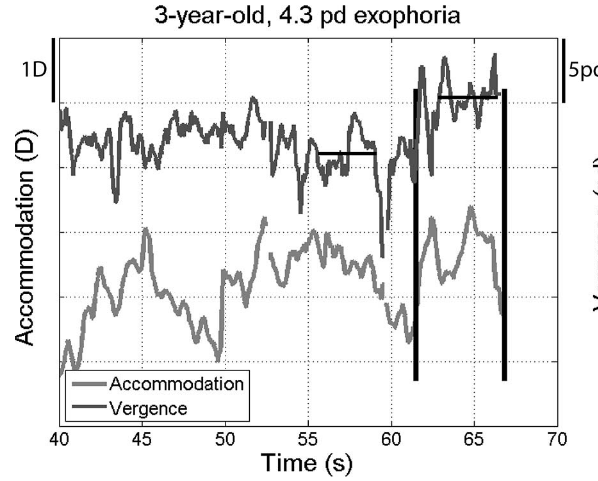

Figure 2. Representative vergence and accommodation responses for the measurement of the heterophoria (accommodation shifted vertically for clarity). The end of the approximately 60-second occlusion period is marked by the *left vertical black bar* while the end of the binocular interval is marked by the *right vertical black bar*. The *horizontal black bars* represent the intervals used for the measurement of the phoria and their relative position on the *right-hand y*-axis reflects the averaged vergence responses.

A relative calibration was performed by occluding vision in one eye with the near IR filter (Kodak Wratten filter # 87; Rochester, NY, USA) and placing lenses and prisms of different powers over the filter.[44] The calibration factor for defocus was determined by introducing five lenses (+1, 2, 3, 4, −2 D) in front of the occluded eye and deriving the slope of the linear function relating difference in PR reading between the eyes to lens power. Similarly, an estimate of the slope of the vergence function was determined by optically shifting the Purkinje image of the occluded eye using base-out prisms (4, 8, 12, 16 pd). The occluded eye does not respond to the lens or prism, and thus it was possible to compare the effect of each lens or prism relative to the other, uncovered eye to control for consensual changes in accommodation or version eye movements.[45]

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. The image from the LCD screen was reflected from a beamsplitter to the subject while the apparatus was moved on a motorized track (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 noted from the PR image with the stimulus screen at 90 cm at the start of the experiment. The distance of the screen varied with condition. It was set to 90 cm for the calibration and 33 cm for the heterophoria estimate. The participant's accommodative convergence/accommodation (AC/A) and convergence accommodation/convergence (CA/C) ratios were estimated by moving the screen between 90 and 35 cm (a 1.75 D or meter angle [MA] stimulus). This method mimics the clinical calculated ratio, rather than the gradient ratio, as it incorporates proximal cues.

Heterophoria Estimation

An individual's near heterophoria was determined by measuring the difference in eye alignment between monocular and binocular viewing (disparity open- and closed-loop, respectively). This measurement is comparable to the clinical unilateral cover test where the fusional vergence movement is used to estimate dissociated heterophoria. Calculating the relative difference between monocular and binocular viewing eliminates the need to measure absolute fixation direction, which would require an estimate of angle lambda.

At the start of the measurement, the right eye was covered with the near IR filter for 60 to 80 seconds to allow the alignment to settle into the heterophoria position.[46,47] The eye was then uncovered for a binocular period that lasted at least 5 seconds. The heterophoria was defined as the difference in vergence between these intervals (Fig. 2). Most heterophoria measurements were made in the morning but appointment times ranged from 9 AM to 4 PM. The subjects were likely to have undertaken a range of visual tasks during their journey to the lab, but they were primarily engaged in nondemanding tasks at intermediate viewing distances during the 15 minutes before data were collected (sitting with a parent during the signing of the consent form or playing with toys primarily). At least two heterophoria measurements were obtained within a visit for 28 of the 50 children. Repeatability between visits was also obtained from 11 children, with at least 1 week between visits.

Heterophoria Analysis

Data analyses were performed using MacSHAPA (University of Illinois, Urbana-Champaign, IL, USA), MATLAB (Mathworks, Natick, MA, USA), Microsoft Excel (Microsoft, Redmond, WA, USA), SPSS (IBM, Armonk, NY, USA), and GraphPad Prism software (GraphPad Software, Inc., La Jolla, CA, USA). Video of each experimental session was recorded and analyzed offline using MacSHAPA to determine the frames when a lens, prism, or near-IR filter was introduced and removed. These marked frames formed a stimulus profile and were used as a reference when analyzing accommodation and vergence responses (Fig. 2).

Raw accommodation and vergence data from the PR were multiplied by the calibration factor for the individual subject, and 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 D to −6 D), (2) Pupil size was less than 3 mm or greater than 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) accommo-

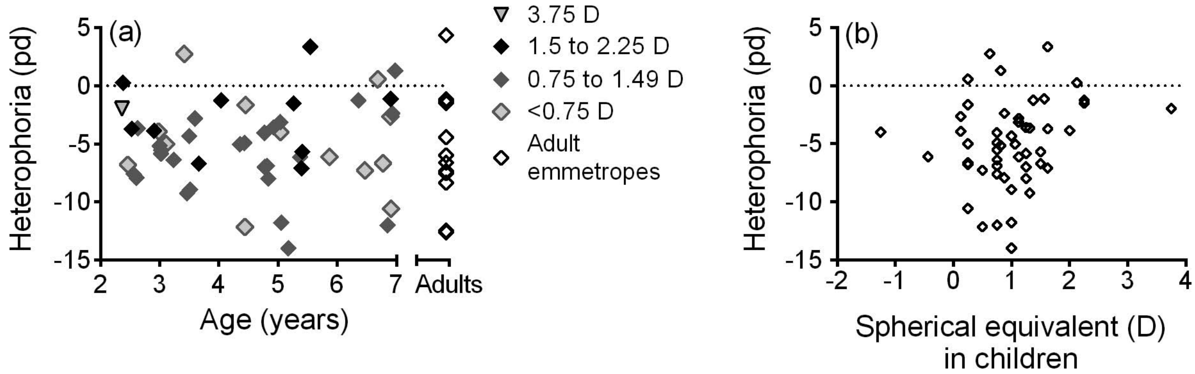

FIGURE 3. (a) Heterophoria as a function of age, categorized by SE refractive error. Positive values greater than 2 pd represent esophoria and negative values less than –2 pd represent exophoria. Heterophoria did not change significantly with age. Spherical equivalent refractive error did change significantly with age (see text). (b) Heterophoria as a function of SE refractive error in children.

dation velocity was greater than 12.5 D/s,[48] and (5) vergence velocity was greater than 175 pd/s.[49]

The heterophoria was estimated by comparing eye alignment during 3.5 seconds of stable monocular and binocular viewing. The 3.5 seconds of monocular data were taken from the end of the monocular period just before the start of the binocular interval (Fig. 2). The 3.5 seconds of binocular data were taken 1.5 seconds after the start of the binocular period. Specific criteria had to be met for the inclusion of these intervals: (1) during the monocular period, accommodation had to be within 1.5 D of the mean accommodation measured in the binocular interval (accommodative stability criterion), and (2) the 3.5 seconds of eye position data had to have a 95% confidence interval (CI) for the estimate of the mean (1.96 × SEM) of less than or equal to ±1 pd. A high SD and/or a low number of samples in the 3.5 seconds could both increase the calculated SEM, and lead to data being excluded. The criterion of a 95% CI less than or equal to ± 1 pd permitted an estimate of heterophoria with a ± 2 pd CI.

AC/A and CA/C Ratio Estimation

The calculated AC/A and CA/C ratios were measured by manipulating the visual information available to participants while they viewed the movie. One eye was covered during AC/A testing (disparity open-loop) and participants viewed a blurred version of the movie binocularly during CA/C testing (blur open-loop). Proximal cues were still available in both conditions. Particularly in the AC/A condition, the motivation for including proximal information was to determine the naturalistic visual demand that vergence must overcome, when both blur and proximal information are included. High spatial frequencies were removed in the CA/C condition by inserting a low-pass spatial filter material, with a difference of Gaussian (DOG) printed on it, in front of the LCD screen. In addition, the DOG was multiplied by a Gaussian function to generate a slow transition to an opaque mask in the periphery. This approach removed all visible edges from the stimulus. During AC/A and CA/C measurements, the movie screen moved between 90 and 35 cm (a 1.75 D or MA change), maintaining the stable position at the far and near points for 8 seconds prior to moving in the opposite direction. Between 8 and 10 stable responses were recorded per condition.

AC/A and CA/C Analysis

After the calibration factors had been applied and the data had been filtered to remove outliers, 2 seconds of stable data were identified from each 8-seconds interval at 90 or 35 cm. Responses from a particular interval were excluded if (1) the change in response of the closed-loop system (vergence in the CA/C condition and accommodation in the AC/A condition) was less than 0.5 MA or D, and (2) the 95% CI for the mean vergence or accommodation response (1.96 × SEM) was more than ±0.15 D or MA (reflecting poor data acquisition or unstable behavior). There were between 1 and 10 (mean = 3.9, SD ±2.3) usable pairs of distance and near responses per condition.

The stable accommodation and vergence responses were then averaged for each distance and the difference in responses between distances was calculated to provide the final estimates of the accommodation and vergence change for the 1.75 D or MA stimulus movement. The convergence-induced accommodation (CA) change was divided by the vergence change for the CA/C ratio, and the accommodation-induced vergence (AC) change was divided by the accommodation change for the AC/A ratio.

Cover Test

Objective heterophorias from the PR were compared with clinical estimates from 32 children. An alternating cover test[50] was performed by a residency-trained clinician at 33 cm. The clinician was masked to the results of the eye tracking condition. In this technique, fusional vergence is disrupted by occluding one eye while the other eye fixates an accommodative target. The covered eye is expected to move to its heterophoric position. The amplitude of the refixation movement when the occluder is moved to the other eye provides the magnitude of the heterophoria. This value was quantified using prism neutralization unless a child was restless and the heterophoria was estimated by observation. Approximately 25% of children had an estimation of their alignment by observation, and those children were mostly 2 to 3 years of age.

RESULTS

Heterophoria

We hypothesized that the youngest children might be esophoric due to their narrow IPD and uncorrected hyperopia. In fact, we found a preponderance of exophoria for this viewing distance, target, and period of occlusion (Fig. 3). Overall, the mean heterophoria for the 33-cm distance was –5.0 pd (exophoria; SD ±3.7) in the children and –5.6 pd (exophoria; SD ±4.7) in adults (unpaired t-test: $t(1, 61) = 0.45$, $P = 0.65$). In the children, heterophoria ranged from –14.0 pd

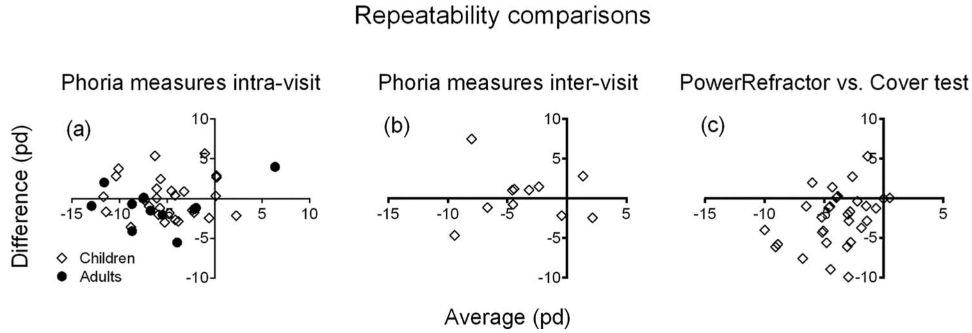

Figure 4. Repeatability of heterophoria measurements (**A**) intravisit, (**B**) intervisit, and (**C**) compared with a cover test. Differences were calculated in (**C**) by subtracting cover test measures from PR measures.

to 3.4 pd, and in adults, it ranged from −12.6 pd to 4.4 pd (Fig. 3a). Seventy-eight percent of the children and 69% of the adults were exophoric (defined as exophoria of > 2 pd), whereas only 20% of children and 23% of adults were orthophoric (between 2 pd exophoria and 2 pd esophoria). Only one adult and one child were esophoric (more than 2 pd of esophoria; Fig. 3a).

Ordinary least-squares linear regressions revealed that while IPD ($R^2 = 0.47$, slope = 0.15, $F(1, 48) = 43.1$, $P < 0.001$) and SE refractive error ($R^2 = 0.09$, slope = −0.16, $F(1, 48) = 4.69$, $P = 0.035$) changed significantly with age in children, the mean heterophoria did not change significantly with age between 2 and 6 years ($R^2 < 0.01$, slope = 0.05, $F(1, 48) = 0.02$, $P = 0.88$; Fig. 3a). The correlation between heterophoria and SE refractive error was also not significant ($r = 0.21$, $P = 0.15$) for the range of refractive errors tested, although the reduction in variance suggested that there was less exophoria as hyperopia increased to higher dioptric levels (>+1.5 D; Fig. 3b).

Accommodation Responses During Heterophoria Measurements

The use of simultaneous photorefraction and Purkinje image tracking enabled accommodation performance to be assessed during the heterophoria measurements. A two-way mixed model ANOVA (between-subjects variable was age, within-subjects variable was condition) revealed that mean binocular accommodation was significantly greater than mean monocular accommodation ($F(1, 61) = 48.0$, $P < 0.001$). While the between-subject comparison between children and adults was not significant ($F(1, 61) = 0.47$, $P = 0.5$), a borderline significant interaction effect revealed that the change in accommodation between monocular and binocular viewing was larger in children than adults ($F(1, 61) = 4.1$, $P = 0.048$).

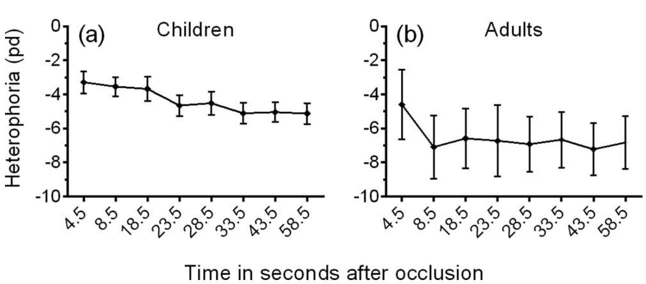

Figure 5. The effect of occlusion duration on the calculation of PR heterophoria in children and adults. *Error bars* equal SEM. Only the children and adults with data in both the first and last bin are included (45 of 50 children, 8 of 13 adults).

Overall, the response in children was greater (more myopic) by a little more than 0.5 D during binocular viewing than during monocular viewing (median increase = 0.69 D, 95% central range −0.18 to 1.46; adult median increase = 0.34 D, 95% central range −0.38 to 1.15). The largest increase in accommodation between monocular and binocular viewing for a child was 1.49 D and for an adult was 1.27 D. There was a moderate correlation between the accommodative change and heterophoria in both children ($r = -.44$, $P = 0.002$, $n = 50$) and adults ($r = -.54$, $P = 0.056$, $n = 13$). Larger magnitudes of exophoria were associated with greater changes in accommodation between monocular and binocular viewing.

The stability of the accommodation response during a heterophoria measurement, assessed using a two-way mixed model ANOVA (between-subjects variable was age, within-subjects variable was condition), revealed that the SD of the 3.5 seconds accommodation sample was larger in children than adults ($F(1, 61) = 15.9$, $P < 0.001$) but there was no significant difference in SD between monocular and binocular viewing ($F(1, 61) = 0.20$, $P = 0.65$) and no interaction ($F(1, 61) = 1.0$, $P = 0.31$). The mean accommodation SD in monocular viewing was 0.34 D in children and 0.21 D in adults, and in binocular viewing it was 0.37 D in children and 0.20 D in adults. These values are in good agreement with Candy and Bharadwaj.[51]

Repeatability of Heterophoria Measurements

The repeatability of the PR heterophoria measurements was determined within and between visits for children. Intravisit estimates were gathered from 28 children (Fig. 4a: mean difference = 0.07 pd (SD = ± 2.54), 95% Limits of Agreement −4.9 to 5.0 pd). Intervisit measurements were gathered from 11 children (Fig. 4b: mean difference = 0.37 pd (SD = ± 3.21), 95% Limits of Agreement −5.9 to 6.6 pd). Intravisit estimates for 12 adults revealed a mean difference of 0.93 pd (SD = ± 2.49) with 95% Limits of Agreement of −3.9 to 5.8 pd.

The heterophoria measurements from the PR were also compared with measurements obtained from the cover test for 32 children (Fig. 4c). The mean difference between these measurements was −2.4 pd (SD = ± 3.4), with 95% Limits of Agreement of −9.1 to 4.3 pd and an exophoric bias in the PR measurements. One possible explanation for a bias between measurements is that the PR measurement was calculated after approximately 60 seconds of monocular occlusion compared with only a few seconds during the typical cover test. In our PR calculations, the mean length of occlusion was 68.6 sec (SD ±10.4) and a monocular measurement was made on average at 58.8 seconds (SD ±11.2). As shown in Figure 5a, the length of occlusion can have an effect on the calculated heterophoria. A repeated-measures ANOVA of the heterophoria calculated

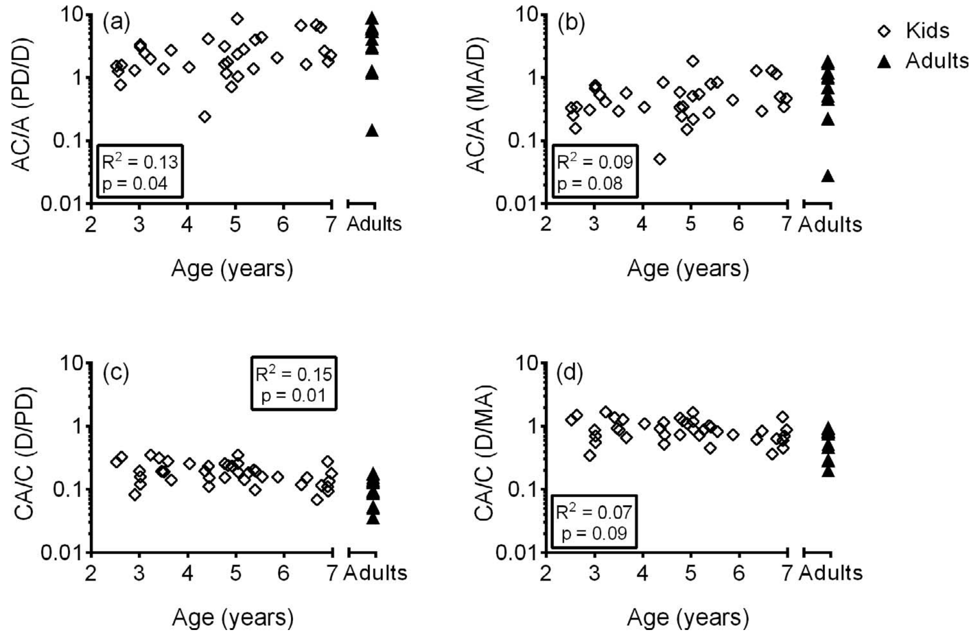

FIGURE 6. Ratios and age; (**a**) AC/A in prism diopters/D, (**b**) AC/A in meter angles/D, (**c**) CA/C in D/prism diopters, and (**d**) CA/C in D/meter angles.

using monocular viewing at 4.5 and 58.5 seconds of occlusion (averaging the prior 3.5 seconds in each case) revealed a significant change in phoria over this interval ($F(1, 51) = 9.0$, $P = 0.004$; Fig. 5) and no age effect between children and adults ($F(1, 51) = 0.9$, $P = 0.34$). In children, the phoria changed from −3.3 pd (SD ±4.4) at 4.5 seconds of occlusion to −5.1 pd (SD ±4.2) at 58.5 seconds of occlusion. Forty-four percent of the children displayed an increase in exophoria of greater than 2 pd over this time interval while only 10% of the children showed an increase in esophoria (>2 pd).

AC/A and CA/C Ratios

AC/A and CA/C ratios were measured in most children and adults ($n = 34$ children and 12 adults for AC/A and 40 children and 13 adults for CA/C). The other subjects either did not meet data inclusion criteria (5 children and 1 adult for AC/A, 4 children for CA/C) or did not cooperate with the protocol (11 children for AC/A, 6 children for CA/C). An increased AC/A ratio might contribute to a more convergent near heterophoria, whereas an increased CA/C ratio might reduce the blur-driven accommodative demand and be associated with a more divergent heterophoria.

The ratios passed normality tests (Shapiro-Wilk, Kolmogorov-Smirnov) after undergoing logarithmic transformations and statistical analyses were carried out on the transformed data. The CA/C ratios, but not the AC/A ratios, differed significantly between children and adults when measured in prism diopters and meter angles (Fig. 6). In prism diopters, geometric mean AC/A was 2.1 pd/D (95% CI 1.6–2.7) in children and 3.1 pd/D (95% CI 1.5–6.5) in adults (unpaired *t*-test, $t(1, 44) = 1.3$, $P = 0.19$; Fig. 6a). In meter angles, geometric mean AC/A was 0.43 MA/D (95% CI 0.34–0.55) in children and 0.56 MA/D (95% CI 0.27–1.2) in adults ($t(1, 44) = 0.9$, $P = 0.36$; Fig. 6b). Geometric mean CA/C in prism diopters was 0.18 D/pd (95% CI 0.16–0.20) in children and 0.10 D/pd (95% CI 0.07–0.14) in adults ($t(1, 51) = 4.0$, $P < 0.001$; Fig. 6c). Geometric mean CA/C in meter angles was 0.86 D/MA (95% CI 0.75–0.97) in children and 0.57 D/MA (95% CI 0.41–0.77) in adults ($t(1, 51) = 3.0$, $P < 0.01$; Fig. 6d).

The AC/A ratio increased significantly with age in children in pd (linear regression; $R^2 = 0.13$, $F(1, 32) = 4.6$, $P = 0.04$, Fig. 6a) while the CA/C ratio in children in pd decreased significantly (linear regression; $R^2 = 0.15$, $F(1, 38) = 6.6$, $P = 0.01$, Fig. 6c). As might be predicted based on the IPD changes as a function of age, the linear regressions only approached significance in meter angles (AC/A: $R^2 = 0.09$, $F(1, 32) = 3.2$, $P = 0.08$, Fig. 6b, and CA/C: $R^2 = 0.07$, $F(1, 38) = 3.1$, $P = 0.09$, Fig. 6d).

Relationship Between Heterophoria, Refractive Error, and Ratios

The correlations between the ratios and heterophoria and SE refractive error are provided in Table 2. None of the correlations in children were significant and the correlation between AC/A and heterophoria was the closest in both meter angles ($r = 0.28$, $P = 0.13$) and prism diopters ($r = 0.25$, $P = 0.15$; Table 2, Figs. 6a, 7a). The correlation between AC/A and heterophoria in adults was borderline significant for meter

TABLE 2. Correlation Matrix for Ratios in Children and Adults

	AC/A (PD/D)	AC/A (MA/D)	CA/C (D/PD)	CA/C (D/MA)
Children				
Phoria	$r = 0.25$, $P = 0.15$	$r = 0.28$, $P = 0.13$	$r = 0.12$, $P = 0.45$	$r = 0.13$, $P = 0.42$
SE refractive error	$r = -0.11$, $P = 0.53$	$r = -0.09$, $P = 0.63$	$r = -0.08$, $P = 0.64$	$r = -0.11$, $P = 0.52$
Adults				
Phoria	$r = 0.56$, $P = 0.06$	$r = 0.58$, $P = 0.048$	$r = -0.45$, $P = 0.12$	$r = -0.49$, $P = 0.09$

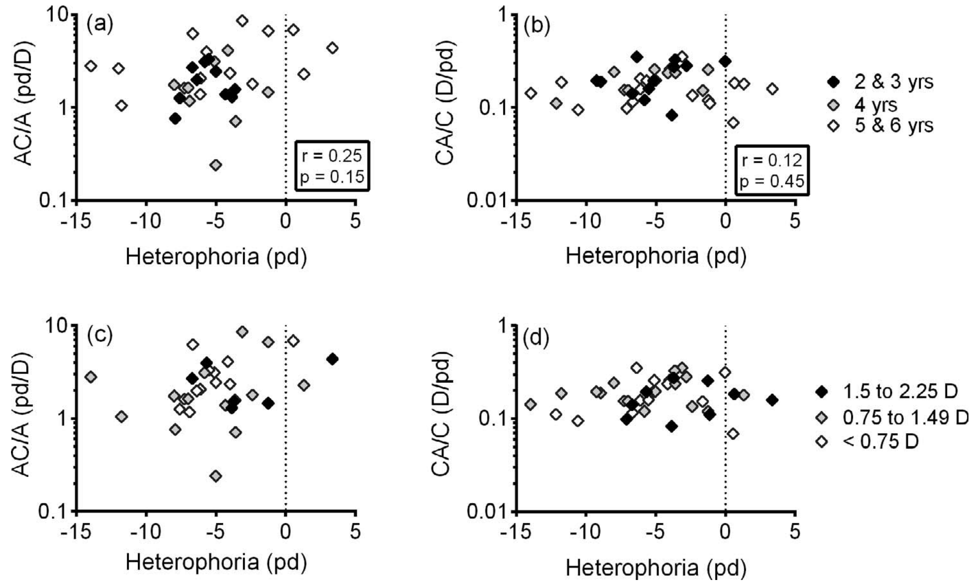

Figure 7. The relationship between the ratios and heterophoria in children as a function of age (plots a and b) and refractive error (plots c and d).

angles ($r = 0.58$, $P = 0.048$). The significance of these correlations is not adjusted for multiple comparisons.

Discussion

Previous reports found that the youngest children tested (2- to 6-year olds) appeared to be predominantly orthophoric at a near distance with little variance across individuals.[13,14] That finding is qualitatively different from the literature regarding adult subjects, which finds exophoria at near with a relatively broad range across individuals. Do these apparent differences between age groups suggest a fundamentally different alignment in early childhood than adulthood? One might predict a tendency for the youngest children to be esophoric relative to adults, due to their uncorrected hyperopia and narrower IPD.

Using a fully objective and longer duration technique, the children in the current study were typically found to be exophoric rather than orthophoric. The mean heterophoria after approximately 60 seconds of occlusion was –5.0 pd with a SD of ±3.7 pd, and 78% of the children tested had more than 2 pd of exophoria, at a 33-cm viewing distance. After a more typical duration of 4.5 seconds of occlusion, the average heterophoria was –3.3 pd with a SD of ±4.4 pd.

There are several possible explanations for this difference in mean heterophoria from the previous literature. (1) Firstly, the monocular periods analyzed in this study are longer than typical methods of heterophoria estimation and, as demonstrated in Figure 5, the data collected during the prolonged occlusion period revealed relatively longer duration of drift in exophoria in young children. Based on previous studies of vergence in adults, the change in heterophoria can be attributed to the decay of slow fusional vergence from an adapted level,[47,52–55] which is consistent with the data of Wong et al.[33] for older children, aged 5.5 to 11.7 years, compared with adults. None of the children in this study participated in any near-work in the 15 minute interval before the start of the experiment. Nonetheless, 44% of the children tested showed more than a 2-pd increase in exophoria over the 60-second occlusion period. This may explain the observation of approximate orthophoria in the previous studies of younger children[13,14] as these techniques may have incorporated a limited dissociation time. We found that 20 seconds of dissociation was typically required for the heterophoria to reach a stable position. More time may be required if children have performed near-work prior to the measurement. (2) Secondly, the difference could result from the nature of the visual target. A cartoon movie with naturalistic spatial amplitude spectra was used as the target in the current study, while clinical cover tests typically recommend using a small detailed target to encourage and maintain accommodative accuracy. If the subjects in the current study did not generate fully accurate accommodation and maintained an accommodative lag, they would be expected to generate less accommodative vergence and therefore be more exophoric than a subject accommodating accurately. The motivation for using the naturalistic target in this study was two-fold. The primary goal was to understand the likely oculomotor status of these subjects during their habitual daily activities, and the secondary goal was to mimic the clinical target that might be used for a young child who is not capable of attending to a small and detailed target. (3) A final explanation for the differences in heterophoria is that different viewing distances were used. Here heterophoria was measured at 33 cm. Measurements for farther viewing distances should appear less exophoric if the subject has an AC/A ratio of less than their IPD in centimeters. For example, many clinical measurements are made at 40 cm, which is 0.5 MA less demand than for the current stimulus. Using calculations based on IPD and AC/A ratio, this would typically equate to a change in heterophoria of 3 pd or less for children and most adults (assuming the proximal response stays constant between 33 and 40 cm). Such an effect may be evident when comparing our results with other studies. For example, a distance of 40 cm was used by Letourneau and Giroux,[9] Walline et al.,[10] and Lyon et al.[12] for children aged 5 to 8 years and they found children were less exophoric at near than children in our study with mean values ranging between 0.49 and 1 pd. However, testing distance may not explain the orthophoria found by Lam et al.[13] and Chen et al.[14] in young children as they tested at 35 and 25 cm, respectively.

Irrespective of the magnitude of the heterophoria, we found that most children displayed an exophoric alignment of the eyes when dissociated. This could not result from errors in the calibration of the PR as the direction of the fusional movement of the eye would not be affected by a calibration factor. The actual heterophoria estimate after 60 seconds of

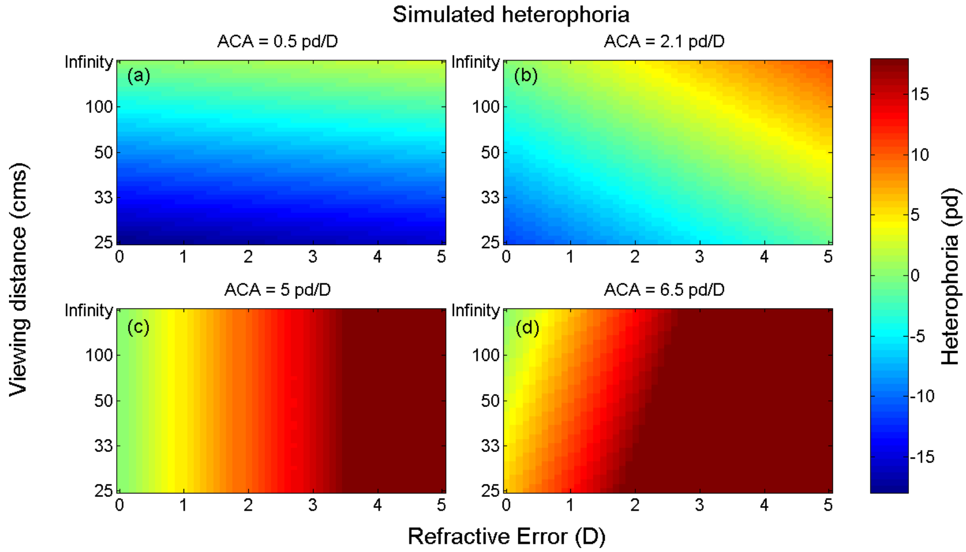

FIGURE 8. Simulation of the effect of refractive error and AC/A ratio on heterophoria as a function of viewing distance (from 0–4 MA or D), assuming the individual accommodates to the target, and that they are orthophoric when accommodation is fully relaxed. Heterophoria was calculated as follows: Heterophoria $_{(\text{in pd})}$ = (viewing distance $_{(\text{D or MA})}$ + refractive error $_{(\text{D})}$) × AC/A $_{(\text{pd/D})}$ – (viewing distance $_{(\text{D or MA})}$ × IPD $_{(\text{cm})}$) where the IPD is 5 cm, and negative heterophoria corresponds to exophoria. (**a**) An AC/A ratio of 0.5 pd/D leads to exophoria at near. (**b**) An AC/A ratio of 2.1 pd/D leads to the typical heterophorias found here for refractive error of +1D, while larger refractive errors actually predict greater esophoria at distance than near. (**c**) An AC/A ratio of 5.0 pd/D, matching the IPD in cm, results in no change in alignment with viewing distance. (**d**) An AC/A ratio of 6.5 pd/D results in greater convergence at near than distance. If it were able, fusional vergence would be required to compensate for these heterophorias using disparity cues to achieve alignment in binocular conditions.

dissociation was not influenced by age, uncorrected refractive error, the AC/A ratio, or the CA/C ratio at this sample size. It is possible that there was no effect of refractive error because a limited range of refractive error was tested. The average spherical equivalent across the two eyes in the sample varied between +3.75 and −1.25 D, with the majority of children lying between +2 and 0 D. The relationship between heterophoria and refractive error will need to be explored further in individuals with increased amounts of both. Given the consistency of the heterophoria position across age and moderate refractive error, it appears that this exophoria may be a robust state settled upon by the vergence system to serve binocular vision at near.[5,7,56,57] These data suggest that there is no qualitative difference between adults and young children, either in terms of the direction or range of values found. The apparent exophoria could perhaps be a position that the visual system even adapts to, given the range of interpupillary distances and refractive errors typically found with age.[58]

The simultaneously recorded accommodative response tended to increase from monocular to binocular viewing, by a range of amplitudes across subjects. Larger amounts of exophoria were correlated with larger increases, as found previously in adults[59,60] and in older children,[61] highlighting the importance of understanding the role of accommodation in maintaining binocular alignment. This correlation between the motor responses likely reflects the underlying neural coupling between the two systems.[62]

Clinical Implications

The children tested in this study did not display levels of hyperopia that would put them at high risk for refractive esotropia (i.e., all subjects ≤ +3.75 D of SE).[24–26] On average, these children had AC/A ratios somewhat lower but not significantly different from adults (Figs. 6a, 6b). Between 2 and 6 years of age, however, the AC/A ratio, in prism diopters, increased (Fig. 6a). In children, the geometric means of the response ratios, including proximity cues, were 1.25, 2.39, 1.35, 2.72, and 3.38 pd/D at 2, 3, 4, 5, and 6 years of age, respectively. These values can be compared with Turner et al.[63] who reported a ratio of 3.45 pd/D (after conversion from MA/D) in children (n = 9) between the ages of 2 years 11 months and 4 years 1 month, which is higher for younger children than found here, and comparable with adult values. Candy and Bharadwaj[51] also reported a ratio of approximately 2.0 to 3.0 pd/D for three- to four-year-olds (their Fig. 4). Overall, smaller AC/A ratios than the corresponding interpupillary distances in cm at these ages (see Table 1) allows for some under-convergence relative to the demand if the subject accommodates fully. A young child with low hyperopia, but an AC/A in pd/D that is close to or larger than their IPD in centimeters would be predicted to have an esophoria at near if they accommodate fully, but very few of the current subjects had high AC/A response ratios of greater than 5 pd/D (for simulations see Fig. 8).[5,64,65] In attempting to understand the clinical path of young hyperopic children who develop refractive esotropia, the classical theory would be that they drive excessive convergence through the accommodative convergence coupling and therefore experience an esophoric position that they cannot overcome with fusional divergence. Additional studies are required, but given the prevalence of exophoria in the current study, moderate esophoria at near in a young child wearing no optical correction and looking at a naturalistic target would warrant further investigation to test for moderate to high hyperopia or an increased AC/A ratio.

Summary

Between 2 and 6 years of age, the vergence and accommodation systems experience changing demands; refractive error is typically decreasing while interpupillary distance is increasing. Despite these changes, the mean heterophoria at near was found to be relatively invariant over this age range and comparable to the adult exophoric position. Seventy-eight percent of children and 69% of adults had exophoria greater than 2 pd after 60 seconds of dissociation, with a range of approximately −13 to 4 pd in both age groups. In our normative sample of children, heterophoria was weakly and insignificantly correlated with refractive error and AC/A ratio. If exophoria is an important resting alignment for near vision, a logical next step is to evaluate the association between more clinically significant refractive errors, the AC/A ratio, and heterophoria measured using this objective and increased duration technique. The current data revise our understanding of the typical range of heterophoria at near in early childhood and inform our predictions about when heterophoria becomes atypical and/or predictive of binocular vision problems. The question of duration of dissociation also has implications for tests used during clinical examinations, as noted by Wong et al.[33]

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