Eye Movements, Strabismus, Amblyopia and Neuro-Ophthalmology

Objective Measurement of Fusional Vergence Ranges and Heterophoria in Infants and Preschool Children

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Purpose. Binocular alignment typically includes motor fusion compensating for heterophoria. This study evaluated heterophoria and then accommodation and vergence responses during measurement of fusional ranges in infants and preschoolers.

Methods. Purkinje image eye tracking and eccentric photorefraction (MCS PowerRefractor) were used to record the eye alignment and accommodation of uncorrected infants (n = 17; 3–5 months old), preschoolers (n = 19; 2.5–5 years), and naïve functionally emmetropic adults (n = 14; 20–32 years; spherical equivalent [SE], +1 to −1 diopters [D]). Heterophoria was derived from the difference between monocular and binocular alignments while participants viewed naturalistic images at 80 cm. The presence or absence of fusion was then assessed after base-in (BI) and base-out (BO) prisms (2–40 prism diopters [pd]) were introduced.

Results. Mean (±SD) SE refractions were hyperopic in infants (+2.4 ± 1.2 D) and preschoolers (+1.1 ± 0.6 D). The average exophoria was similar (P = 0.11) across groups (Infants, −0.79 ± 2.5 pd; Preschool, −2.43 ± 2.0 pd; Adults, −1.0 ± 2.7 pd). Mean fusional vergence range also was similar (P = 0.1) for BI (Infants, 11.2 ± 2.5 pd; Preschool, 8.8 ± 2.8 pd; Adults, 11.8 ± 5.2 pd) and BO (Infants, 14 ± 6.6 pd; Preschool, 15.3 ± 8.3 pd; Adults, 20 ± 9.2 pd). Maximum change in accommodation to the highest fusible prism was positive (increased accommodation) for BO (Infants, 1.69 ± 1.4 D; Preschool, 1.35 ± 1.6 D; Adults, 1.22 ± 1.0 D) and negative for BI (Infants, −0.96 ± 1.0 D; Preschool, −0.78 ± 0.6 D; Adults, −0.62 ± 0.3 D), with a similar magnitude across groups (BO, P = 0.6; BI, P = 0.4).

Conclusions. Despite typical uncorrected hyperopia, infants and preschoolers exhibited small exophorias at 80 cm, similar to adults. All participants demonstrated substantial fusional ranges, providing evidence that even 3- to 5-month-old infants can respond to a large range of image disparities.

Keywords: fusional vergence, motor fusion, heterophoria, hyperopia, infants, preschoolers

Binocular eye alignment is dependent upon accurate vergence responses. Classically, vergence responses are believed to consist of a weighted sum of four components described from a clinical context by Maddox[1]: tonic (a physiologic position of rest when all other cues are absent),[2] proximal (a sense of nearness, or voluntary control),[3] neurally coupled accommodative vergence,[4,5] and disparity-driven fusional vergence.[6] Disparity-driven vergence, through feedback, is considered responsible for correcting any error remaining from other components of the response.

In adults, vergence responses in binocular conditions typically are well-matched to the stimulus[7] and there is rudimentary evidence suggesting that neonates can achieve binocular alignment under naturalistic viewing conditions. Newborn infants are capable of fixating a target at a 10-inch (~25 cm) viewing distance,[8] although their vergence responses tend to be inaccurate and variable.[9] Accuracy increases with age and by approximately 3 to 5 months, studies have demonstrated grossly adult-like vergence responses[10–12] and the onset of relative disparity discriminations.[13]

A typical infant experiences a potential conflict between their vergence and accommodation demands relative to an adult, as a result of their narrow interpupillary distance (IPD) leading to reduced vergence demand[14] and their uncorrected hyperopic refractive error leading to increased accommodative demand.[15,16] For a nonstrabismic well-aligned infant or young child, these systems may reweight or recalibrate their responses to maintain alignment during development, whereas in strabismic children this compensation apparently has failed and fusional vergence cannot eliminate the remaining vergence error. The goal of the current study was to determine the role of fusional, disparity-driven vergence in alignment in typically developing 3 to 5 month olds and 2.5 to 5 year olds. It was motivated by asking how well the fusional vergence system is able to eliminate errors resulting from the combination of the other vergence components during early postnatal development, and, therefore, how tolerant the typically developing system might be to inappropriate components, such as excessive accommodative or proximal vergence. Only 20% of moderate to high hyperopes suffer refractive esotropia.[17,18] Knowledge of typical behavior will provide insight into clinical abnormality.

The magnitude of the demand on the fusional vergence system is assessed by measuring heterophoria (phoria), which is the misalignment of the visual axes when disparity information is removed, by covering one eye for example.

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The difference between this alignment in monocular viewing conditions and alignment in full cue binocular viewing is the error that fusional vergence must overcome. Mean estimates of phoria in adults range from 3 to 5 prism diopters (pd) of exophoria (divergent misalignment) at near viewing distances (33 or 40 cm), and from 0 to 1 pd for a distant target (6 m).[19–21] Children 6 to 16 years old have an average phoria ranging from orthophoria to 3 pd exophoria at near (25–40 cm) and an average of 0.6 pd esophoria to 1 pd exophoria at distance (6 m).[19–27] A limited number of studies have estimated phoria in preschool-aged children, and only at a near distance.[28–30] While Lam et al.[28] and Chen et al.[29] found most children to be orthophoric at near (25 cm reported by Chen et al.,[29] while distance not specified by Lam et al.[28]), recently, using video-based objective eye-tracking and a longer period of monocular viewing, a study from our lab[30] showed that the phoria position of children aged 2 to 7 years was typically exophoric (mean = 5 pd) for a target at 33 cm, with little change over that age range. This mean value was similar to the adult comparison group, indicating no change during childhood.

The impact of phoria on binocular function depends on the range of misalignments that fusional vergence can overcome, termed the fusional vergence range. Typical clinical fusional vergence tests gradually increase the magnitude of base-in (BI) or base-out (BO) prisms while the demand for accommodation is held constant, creating an incongruent stimulus for accommodation and vergence.[31] Due to the neural coupling between these two motor systems,[4,5] a prism-induced vergence response will drive a change in accommodative response, but studies that have measured fusional vergence typically have not made objective measures of accommodation during the fusion responses.[32–35] Fry[36] studied the interaction between accommodation and vergence by stimulating his vergence. He found that accommodation remained stable to within 0.5 diopters (D) for the initial modifications in vergence (decrease in convergence by 5° and increase in convergence by 8° from a starting position of 9°), but that it changed rapidly (by approximately 1 D) beyond a point when the target was noticeably blurred. One goal of the current study was to describe the accommodative behavior of the participants during their vergence responses, to determine whether accommodation remained steady before dissociation, or whether it shifted in relation to the vergence response. This speaks to the ability of the accommodation system to eliminate blur introduced by convergence accommodation.

During fusional vergence measurements, the metrics assessed in cooperative verbal patients are the prism magnitude that can be overcome with fusion when accommodative error first exceeds the depth of the focus (the blur point), the prism magnitude at which fusion can no longer be maintained (the break point), and then, as prism is reduced, the prism magnitude at which fusion is reported again (the recovery point). Mean adult fusional vergence break points, for a 40 cm viewing distance, range from 18 to 23 pd for divergence and 19 to 25 pd for convergence from the phoria position,[19,32,33,37] indicating that typical adults can routinely compensate for their phoria or fusional vergence demand (e.g., Sheard's criterion). Convergence and divergence ranges also have been well characterized in school-aged children more than 6 years old,[22,26,27,34,35,38,39] with almost adult-like mean break ranges of 11 to 21 pd for divergence and 18 to 27 pd for convergence[26,27,34,35] at a near viewing distance (40 or 33 cm). Only two studies report ranges in children 5 years or younger.[28,32] Lam et al.[28] measured heterophoria and fusional ranges at distance (6 m), and near (distance not specified), in typical children between 4.5 and 5.5 years old ($n = 162$, ≤3.5 D hyperopia, ≤0.5 D myopia). They found mean convergence and divergence break-points of 28.9 and 15.51 pd, respectively, for the near viewing distance. They also suggested that their data were similar to those of adults, although they did not test adults in their study. Wesson[32] performed a study of subjects 4 to 70 years old, but sample size was small ($n = 3$) for the youngest age range. The author reported no effect of age on fusional range. Other studies also support this finding of stability with age. However, the age ranges used were narrow and limited to older children (6–12 years), without an adult control group.[28,35]

In the current study, an objective eye-tracking approach was used to measure phoria at an 80 cm viewing distance and the range of alignments that fusional vergence can compensate for in 3- to 5-month-old infants, 2.5- to 5-year-old children, and naïve adults (20–32 years). The aim was to understand the fusional vergence demand (phoria) and range of fusional vergence around that point that can be achieved by typically developing infants and young children. The ages of 3 to 5 months and 2.5 to 5 years were studied to understand performance at the extremes of the typical developmental period of emmetropization, and at the typical age of onset of refractive esotropia.[40] The eye tracking approach was used to avoid the need for a subjective report of diplopia. We hypothesized that infants might be esophoric due to their hyperopia and small IPD and that they may need to use reflex divergence to maintain binocular alignment. In this case, we may expect to see small divergence ranges and large convergent ranges (from binocular alignment) compared to adults. Further, infants may show unstable or limited motor fusion compared to adults as a result of their immature sensory binocular system.[13]

Methods

The study was approved by the Indiana University Institutional Review Board and followed the tenets of the Declaration of Helsinki. All parents and adult subjects provided informed consent before participation in the study.

Study Participants

A total of 29 infants between 3 and 5 months of age (mean ± SD, 0.37 ± 0.08 years) were recruited from local birth records, while 20 preschool children between 2.5 and 5 years old (mean ± SD, 3.65 ± 0.90 years), and 20 prepresbyopic functionally emmetropic adults (mean ± SD, 25.47 ± 4.48 years) were recruited from the local community. Functional emmetropia was defined as uncorrected visual acuity better than 20/20 in both eyes and uncyclopleged spherical equivalent (SE) refraction between + 1 and −1 D. None of the adults wore any optical correction or reported any asthenopic symptoms suggestive of accommodative or vergence disorders.

All of the infants and children received a standard, age-appropriate eye examination that evaluated their ocular alignment, visual acuity (Teller Acuity Cards or Lea Symbols), cycloplegic refractive error using 1% cyclopentolate, and ocular health. They were all developing typically and were not taking any medications known to affect oculomotor performance. The young participants all exhibited age-appropriate refractive error (mean SE [averaged across each subject's eyes] ± SD; infants, +2.4 ± 1.2 D; preschoolers, +1.11 ± 0.64 D) and anisometropia of less than 1 D. All but two of the infants and children had astigmatism ≤1 D. Two infants had higher astigmatism of 2 and 2.25 D, which is not uncommon in young infants.[15] None of the subjects received a spectacle prescription or wore any optical correction.

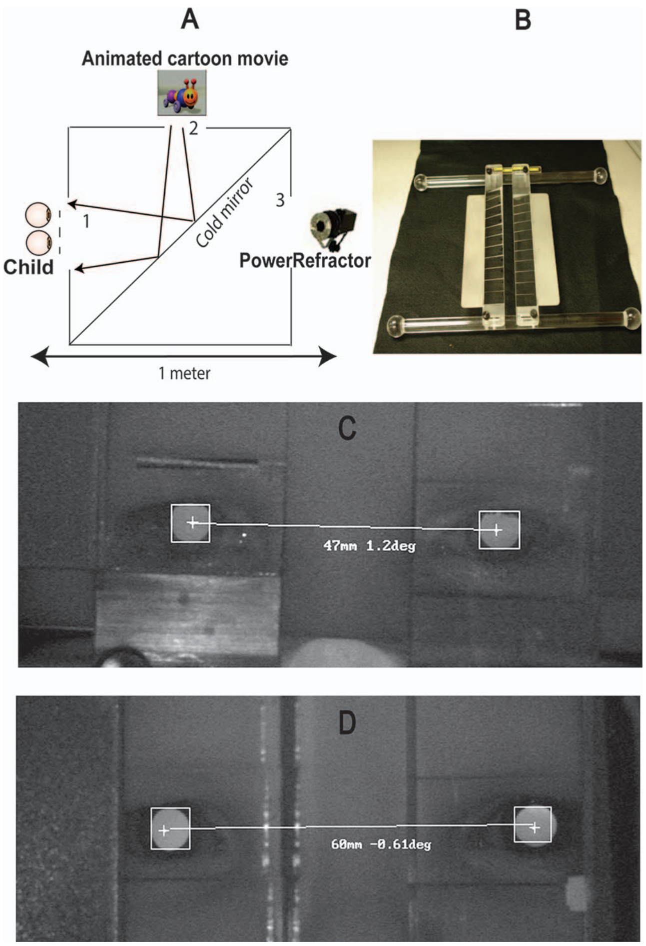

Figure 1. (**A**) A schematic of the apparatus used to measure heterophoria and fusional vergence. *Dashed line* in front of the child's eye denotes the plane where the occluder or prism bars were introduced. (**B**) The lightweight prism bar apparatus, with frosted side panels, used for measurement of fusional vergence ranges. (**C**, **D**) PowerRefractor video images displaying aligned and misaligned Purkinje images, respectively (misalignment in [**D**] is indicated by the temporal displacement of the Purkinje image in one pupil).

In an attempt to match the experience of a young infant or child, the majority of the recruited adults (15 of 20) were fully naïve participants.[41] To equate experience, only data from the naïve adults were compared to those of preschoolers and infants.

Apparatus and Experimental Procedure

Heterophoria and fusional vergence ranges are traditionally determined by manipulating retinal disparity with occlusion and prisms. While these observations are typically made using direct observation (for example, see prior reports[1,19,32,37]), an objective eye-tracking approach was used in this study. Purkinje image eye tracking and video-based eccentric photorefraction were used simultaneously to record vergence and accommodation responses, respectively (PowerRefractor [PR]; MultiChannel Systems, Reutlingen, Germany). The PR video camera collects images from a viewing distance of 1 m, at a sampling rate of 25 Hz. This remote working distance enables the young subject to be positioned in a relatively unrestricted setting (Fig. 1). The techniques used to estimate accommodation and eye alignment from the PR images have been described previously.[42,43] The calibration functions applied in the PR software are based on data collected from adults[42,43] and can be variable across individuals.[44] Individual calibration data were collected successfully from the adult and preschool aged subjects, using an approach detailed previously.[11,30]

During data collection, the subject was positioned in front of a large black box with 18-cm diameter circular apertures in the middle of three of the four walls (Fig. 1A, apertures 1–3). The functions of these apertures were to allow the participant to view into the box to watch the movie, present the movie at a viewing distance of 80 cm from the subject (80 cm was used based on equipment limitations), and align the photorefractor at 1 m from the subject. The subject viewed the movie stimulus using a 60-cm diameter cold mirror centered in the box (Fig. 1A). This design permitted the photorefractor and stimulus to be aligned on the same optical axis to minimize off axis measurements. The movie stimulus was an age-appropriate commercially available cartoon movie with broadband spatial frequency content. It was projected onto the rear of a screen mounted in aperture 2, with a two-dimensional Gaussian function printed on the front surface (transparent centrally and opaque peripherally). This Gaussian window reduced edge cues while providing a high contrast image subtending 6° vertically × 2.5° horizontally.

Phoria Measurement

Phoria was estimated using the differences in measured eye alignment between binocular and monocular viewing conditions, equivalent to the principle underlying a unilateral clinical cover test. Initially, the right eye was occluded using a near IR occluder (Kodak Wratten 87; Rochester, NY, USA) for 45 to 60 seconds to allow the eye alignment to drift to the steady-state phoria position.[30] Data were collected from both eyes in this condition, and then during 15 to 20 seconds of binocular viewing for comparison.

Fusional Vergence Range Measurement

Fusional vergence responses were stimulated using a lightweight prism bar apparatus (Fig. 1B) that was adjusted to the subject's interpupillary distance. The prisms were introduced in front of both eyes (Fig. 1A, dashed line), with frosted edges on either side to minimize the possibility of the subject peeking around the edges of the prism (Fig. 1B).

A baseline estimate of habitual binocular vergence position was recorded initially, and then prism-induced retinal disparity was introduced with simultaneous recording of accommodation and vergence responses for approximately 2 to 4 seconds at each step (the combined powers from two commercial prism bars were 2, 4, 8, 12, 16, 20, 24, 28, 32, 36, and 40 pd). The naïve adult participants were instructed to watch the movie and report when the target appeared blurred (their blur point) or double (their break point). The examiner then increased the disparity by two additional prism steps to ensure complete dissociation. For infants and preschoolers, two examiners monitored the Purkinje images during each prism step (Fig. 1C) and once fusion appeared to break, two additional prism steps were introduced again to ensure complete dissociation (Fig. 1D). It is important to note that the naïve adult participants were not instructed to keep the target single, which would be done in a clinical test of fusional vergence range. This was done to permit comparison with the uninstructed younger subjects.

Divergence ranges (base-in prism) were tested before convergence ranges (base-out prism) based on standard clinical practice and evidence that suggests less vergence adaptation occurs during measurement of divergence than convergence.[45,46] A second measurement of fusional vergence (BI and

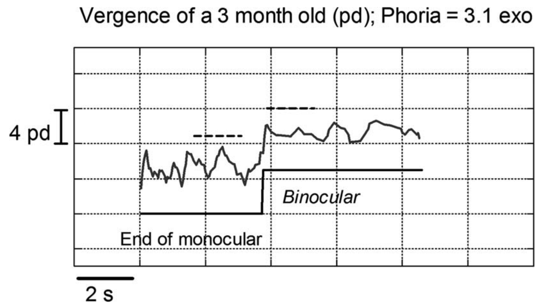

Figure 2. Example of filtered vergence data, from a 3-month-old, that were used to estimate phoria. The *black vertical line* marks the transition from monocular to binocular viewing. The *dashed horizontal lines* (shifted vertically for clarity) represent the 3.5-second averaging windows identified by an automated sliding algorithm. The difference between these mean alignments represents the phoria. Using this technique phorias could be estimated with 95% CIs of less than or equal to ±2 pd (∼ ±1°).

BO) was attempted for all subjects during the same session to test repeatability. The objective break point derived from the Purkinje image eye tracking was compared with subjective reports of dissociation (the clinical break point) in adult participants to estimate the agreement between the two techniques.

Data Analysis

The raw data obtained from the PR included noisy and physiologically implausible samples that may be attributed to, for example, blinks, aberrations from the tear film, eccentric gaze, and instrument limitations. A filtering algorithm was used to remove these outliers before further analysis, with further visual inspection used to confirm that the filtering did not introduce bias. The algorithm used known characteristics of the measurement technique and the physiology of the human visual system.[11,30] Only data that met the following combination of criteria, implemented in the instrument or applied in filtering, were included: (1) The accommodation data were within the linear operating range of the instrument (+4 to –6 D),[42] (2) pupil diameters were between 3.5 and 8 mm,[42,47] (3) accommodation velocity was <10 D/s,[48] and (4) vergence velocity was <175 pd/s.[49] Very few data points were excluded based on the requirement that the refractive data fall within the operating range of the instrument. These points were considered to be the result of measurement error, as only one subject (described below) had hyperopia capable of reaching the criterion level of refractive state and the excluded data were not sustained for a long enough period to be considered a plausible accommodative response.

A video recording collected during the experiment was used to determine the video frames at which there was a change in stimulus, for comparison with the PR data. The data analyses were performed using MATLAB (Mathworks, Natick, MA, USA), SPSS (SPSS, Inc., Chicago, IL, USA), GraphPad Prism (GraphPad Software, Inc., La Jolla, CA, USA), MacSHAPA (University of Illinois, Urbana-Champaign, IL, USA), and Microsoft Excel (Microsoft, Redmond, WA, USA).

Phoria Analysis

Estimates of monocular and binocular eye alignment were obtained by averaging eye position over 3.5-second windows. The windows were identified using an automated sliding algorithm that moved backwards in time from the end of each monocular period or forwards from the beginning of each binocular viewing period (Fig. 2). An examiner ensured that

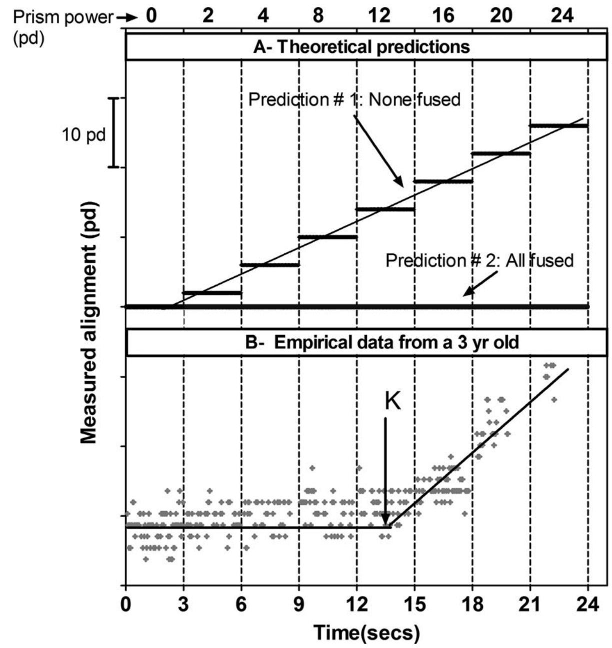

Figure 3. Theoretical predictions (**A**) and an empirical example (**B**) from a 3 year old viewing through BI prisms, which drove a divergent response. The first 3 seconds of alignment data at each prism step are plotted as a function of prism power/time. (**A**) Zero prism power (pd) represents the binocular alignment before the introduction of prism, serving as a reference. Then in prediction 1, in the absence of motor fusion (i.e., a dissociated state), the alignment follows the optical shift induced by the prism (a step function). In prediction 2, where motor fusion is maintained through the prisms, the measured alignment would match the reference as depicted by the *horizontal line*. (**B**) The empirical data were fitted with a bilinear function (*black lines*) to determine the objective break point. The horizontal linear fit represents the fused state while the diagonal fit denotes dissociation (*break*). The intersection (*K*, marked with an *arrow*) indicates the last prism step that was fused. The subsequent prism step was considered the objective break point or limit of the fusional vergence range.

the monocular and binocular alignments obtained from the automated algorithm agreed with visual observation of the trend seen in the data. This algorithm retrieved the first 3.5-second interval of data that had a 95% confidence interval (CI) for the estimate of the mean that was less than ±1 pd and a minimum of 20 usable frames. If the 95% CI was greater than 1 pd, or the number of usable frames was less than 20 throughout the trial, the subject's data for this condition were excluded. The final phoria then was calculated as the difference in mean alignments between the monocular and binocular positions with a confidence interval of ≤ ±2 pd (∼1°). Recently, a study from our lab used a similar technique to estimate heterophoria in children, which showed good agreement with a clinical cover test (Mean difference ± SD = 2.4 ± 3.4 pd exophoria).[30]

Fusional Vergence Analysis

For the fusional vergence analysis, the most prism for which a participant achieved fusion was determined using a least-squares fitting approach. Three parameters were determined (Fig. 3): (1) the mean binocular vergence response measured before the introduction of the prism, which served as an estimate of the fused/aligned position; (2) the time at which the alignment became dissociated; and (3) the slope of the dissociated phase. The intersection between the fused and dissociated phases (K in Fig. 3) indicated the most prism that

TABLE. Details of the Subjects in Each Group, With the Number of Subjects Providing Usable Data as a Proportion of Those Providing Any Data

	Number Recruited	Mean ± SD		Number of Usable Subjects/ Number Providing Any Data		
		SE Refraction, D	IPD, cm	Phoria	Divergence	Convergence
Infants, 3–5 m	29	2.4 ± 1.2	4.1 ± 0.2	17/22	17/19	14/17
Preschool, 2.5–5 y	20	1.1 ± 0.6	4.9 ± 0.2	18/20	19/19	19/19
Naïve adults, 20–32 y	15	Functional emmetropes*	6.0 ± 0.2	14/15	14/15	13/15

* Functional emmetropia was defined as uncorrected visual acuity better than 20/20 in both eyes and uncyclopleged spherical equivalent refraction between +1 and −1 D.

was apparently fused. The objective break point then was defined as the next prism value, equivalent to the clinical protocol of asking when the patient first sees double. This approach resulted in good agreement with subjective reports of break (diplopia) in adult subjects (see Results section). Some conditions were excluded (three infants in convergence testing and two infants in divergence testing) due to poor data quality resulting in a poor fit. In this analysis, convergence was represented with a positive sign and divergence with a negative sign, while the zone of alignment was defined as the full range between the break points.

RESULTS

Usable data were collected from at least 46 of 64 subjects for each condition (see Table; most exclusions were due to an inability to record any data from the subject, resulting from poor attention or cooperation, while the others did not meet the data quality criteria). The infant group produced the lowest number of included subjects, as a result of restlessness and reduced cooperation (only 17–22 provided any data for the conditions tested) or poor data quality that did not meet the inclusion criteria listed above (2–5 subjects were excluded). Previous studies of infant accommodation and vergence have experienced similar data loss.[10,11,50]

Heterophoria

Figure 4 presents the phorias measured at the 80 cm viewing distance after extended occlusion, as a function of age. The mean did not differ significantly with age (Adults, 1.0 ± 2.7 pd exophoria; Preschoolers, 2.43 ± 2.0 pd exophoria; Infants, 0.79 ± 2.5 pd exophoria; $F(2,46) = 2.7$; $P = 0.1$), demonstrating that the younger subjects tended to exhibit adult-like phoria at this intermediate viewing distance, even in the presence of their hyperopia. The mean adult value is consistent with the literature.[19–21,37]

It is important to note that this analysis uses the default calibration function in the PR software for all study groups, as we were unable to perform individual calibration on several infants due to lack of cooperation. We believe this is acceptable as the data are interpreted at the group rather than individual level, and the Hirschberg ratio does not vary dramatically with age.[51] Furthermore, the mean phoria in the preschooler and adult groups that provided individual calibration was not significantly different from the values obtained using the default calibration slopes from the PR (mean phoria using individual calibration; Preschoolers, 3.1 ± 3.0 pd exophoria; paired *t*-test, $P = 0.4$; Adults, 1.6 ± 3.8 pd exophoria; paired *t*-test, $P = 0.8$).

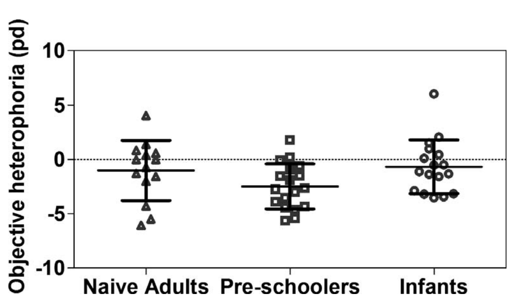

FIGURE 4. Individual and mean phoria values for the 80 cm viewing distance, as a function of age. *Negative values* denote exophoria. *Error bars*: standard deviation.

Fusional Vergence Ranges

The primary goal of this experiment was to determine the capacity of the young vergence system to respond to increased retinal disparity introduced using prisms. Before comparing the ranges across groups, a comparison with conventional subjective reports of diplopia was performed for 12 naïve adults. Figure 5 shows an average bias of −2.1 pd for adults (SD ± 2.3) for divergence and 3.0 pd (SD ± 3.4) for convergence testing. Due to the sign convention, the opposite sign biases indicated that the eye-tracking approach was more sensitive to the motor misalignment than the subjective reports. Most subjects displayed differences of zero or one step on the prism bar (most steps equaled a change of 4 pd).

The first 3 seconds of alignment through each prism are presented in Figure 6, for each subject. All subjects, including infants, were on average able to overcome the prism-induced disparity within approximately 1 second. The infants and preschoolers displayed a wide range of objective break points, that were similar to naïve adults for BI (Fig. 6, top) and BO (Fig. 6, bottom) testing. These data suggested that even the youngest participants were capable of responding to convergent and divergent demands in the absence of instruction. Two infants (marked with an asterisk) stopped cooperating with data collection before they provided evidence of dissociation while viewing through BO prisms. In these cases, the objective break point was considered conservatively to be the prism step after the final recording indicating fusion.

The distributions of divergence and convergence fusional break points are summarized in Figure 7A. A 2-way mixed model ANOVA (absolute value of convergence versus divergence break point as the within-subject variable and age group [naïve adults, preschoolers and infants] as the between-subject variable) revealed no significant main-effect of age ($F[2,40] = 1.9$, $P = 0.1$) on the fusional ranges, a main effect of direction with the convergence range being greater than the divergence range ($F[1,40] = 13.5$, $P = 0.001$), and no significant interaction ($P = 0.22$). Figure 7B shows the total range of fusion (defined as the absolute sum of the convergence and divergence break points) as a function of age. While the mean total vergence range was marginally higher in naïve adults compared to preschoolers and infants, this effect was only approaching significance (1-way ANOVA, $F[2,42] = 2.86$, $P = 0.06$).

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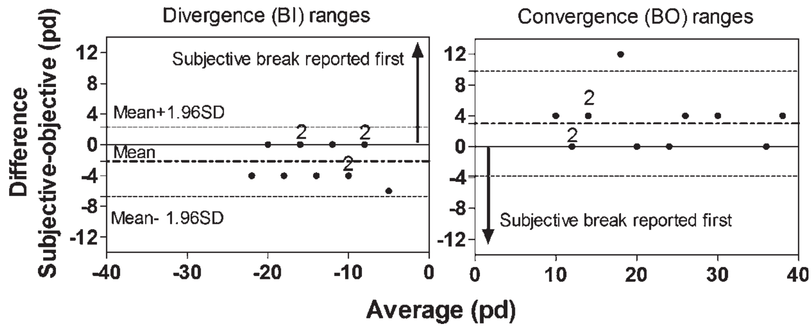

Figure 5. Comparison of the subjective report of double vision (break point) with the objective estimate of misalignment obtained using Purkinje image eye-tracking in naïve adult subjects. The values above individual *symbols* denote the number of subjects that share that value.

Effect of Expertise

A small group of expert adult observers (defined as observers with knowledge of oculomotor function; $n = 5$) were recruited for comparison with the naïve adult subjects ($n = 15$; Fig. 7 expert adults versus naïve adults). While divergence ranges were statistically similar in naïve adults and experts (means ± SD, Expert = 15.2 ± 5.9 pd; Naive = 11.8 ± 5.2 pd; Unpaired *t*-test, $t = 0.89$, $P = 0.38$), the convergence ranges were significantly larger in experts than naïve participants (means ± SD, Expert = 38.4 ± 2.1 pd; Naive = 20 ± 9.2 pd; Unpaired *t*-test, $t = 4.33$, $P = 0.0005$).

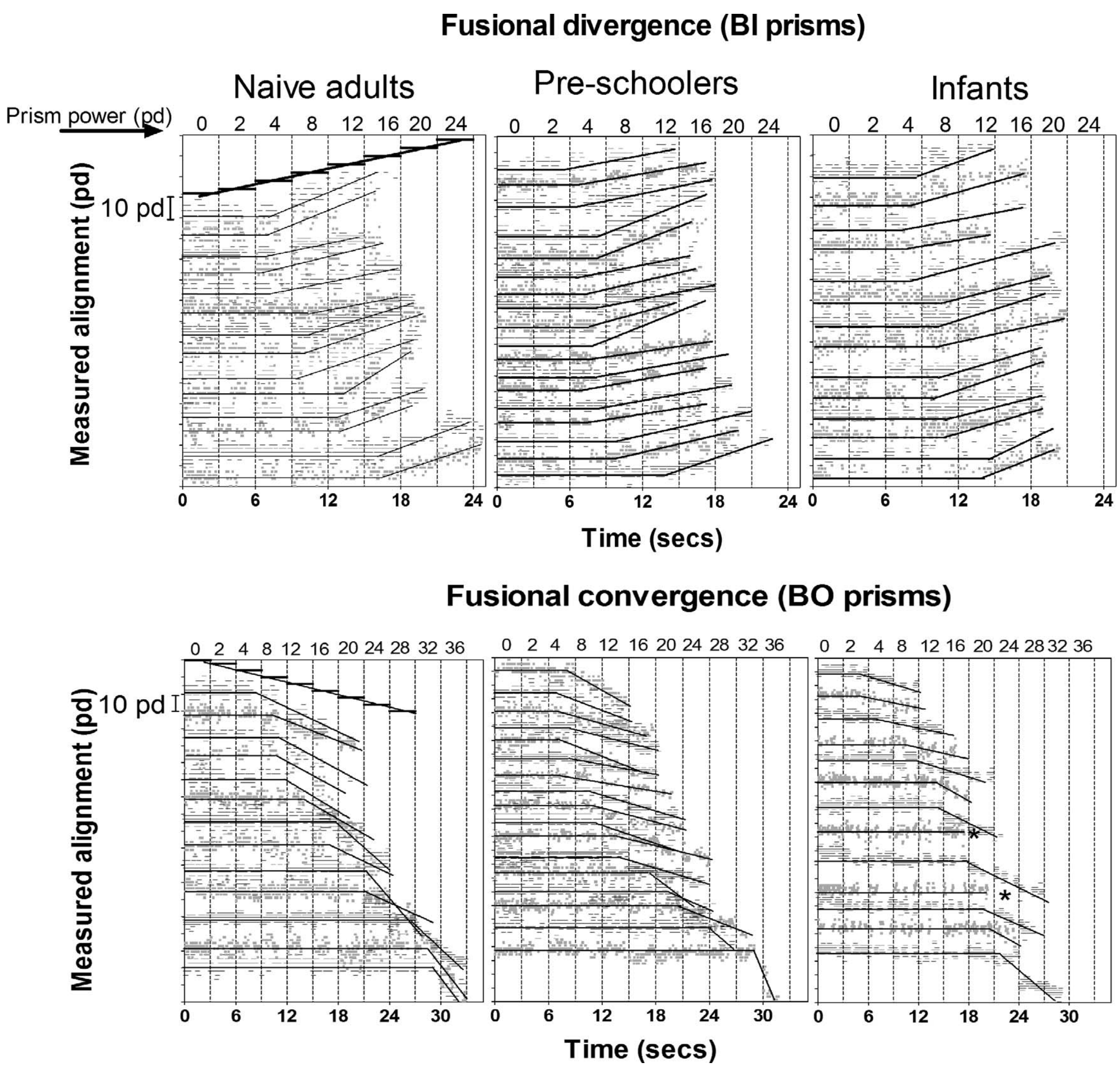

Figure 6. Empirical data and bilinear fits from all subjects who provided usable data for BI (*top*) and BO (*bottom*) testing. The data from each subject have been shifted vertically for clarity. Infants show a similar range of performance to adults and preschoolers. *Two infants did not provide evidence of dissociation while viewing through BO prisms. The theoretical predictions if the subjects did not fuse the images are provided at the top of the adult panels for comparison.

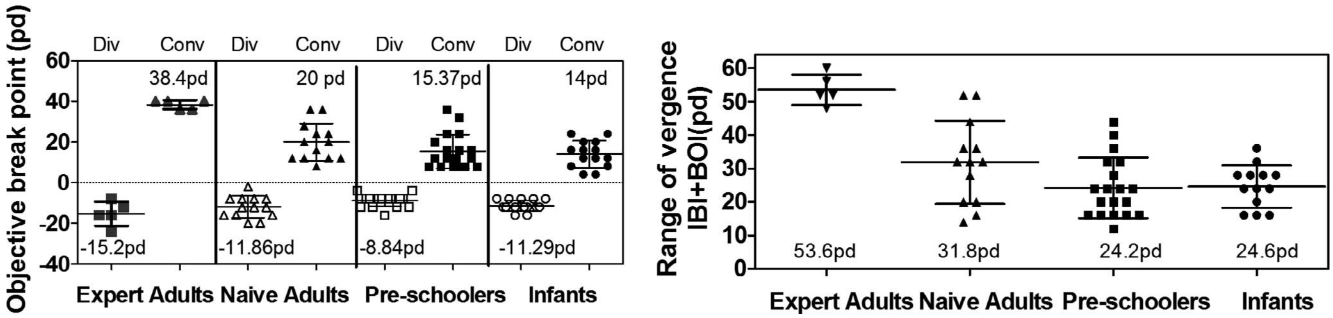

FIGURE 7. (**A**) Mean divergence and convergence fusional break points as a function of age and expertise. (**B**) Total range of fusional vergence (absolute magnitude of convergence + divergence break points) as a function of age and expertise. The mean values are provided for each group. *Error bars* denote standard deviation.

These results are consistent with a previous study[41] showing differences in vergence and accommodation responses between naïve and expert observers. Based on these results it appears that the convergence ranges of naïve adult subjects, preschoolers, and infants may have been larger if they could be instructed successfully to keep the target single.

Repeatability of Fusional Vergence Ranges

At least 31 subjects provided repeatability data when viewing through BI or BO prisms, as shown in Figure 8. No systematic bias was observed between the first and second trials for any group (paired *t*-tests, all $P > 0.2$), and, therefore, there was no obvious effect of learning, fatigue, or adaptation across trials. The largest mean bias between first and second recording was 3.2 pd, observed in naïve adults during convergence testing, which still was less than 1 prism step value. The coefficient of repeatability (COR; $1.96^{*}SD_{bias}$) indicated greater variability for convergence in all groups (COR, Adults = ±17.7 pd; Preschoolers = ±13.3 pd; Infants = ±22.5 pd) compared to divergence ranges (COR, Adults = ±7.6 pd; Preschoolers = ±6.5 pd; Infants = ±3.3 pd). The previous literature shows a COR of ±8 pd for near divergence and ±15 pd for near convergence for instructed young adult subjects tested using a prism bar.[52] In the current study, the COR for a similar group of expert subjects was 0 pd for divergence and ±8 pd for convergence when tested using the objective PR technique.

Relationship Between Refractive Error, Phoria, and Fusional Ranges

The correlation between refractive error and phoria was insignificant in preschoolers ($r = -0.07$, $P = 0.7$) but approached significance in infants ($r = 0.46$, $P = 0.06$) as a result of one infant with high hyperopia. The correlation

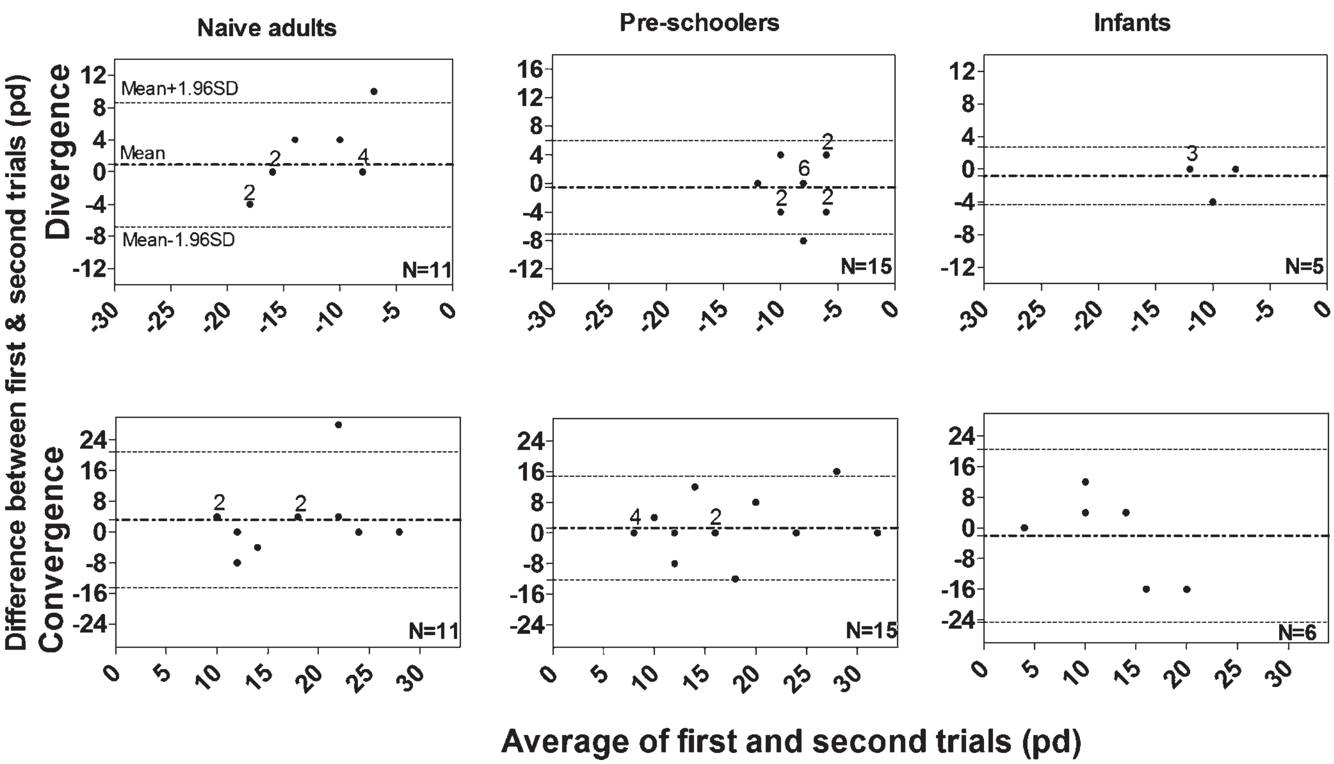

FIGURE 8. Repeatability of objective break points for divergence stimulation with BI (*top*), and convergence stimulation with BO prism (*bottom*). The values above individual *symbols* denote the number of subjects that share the value.

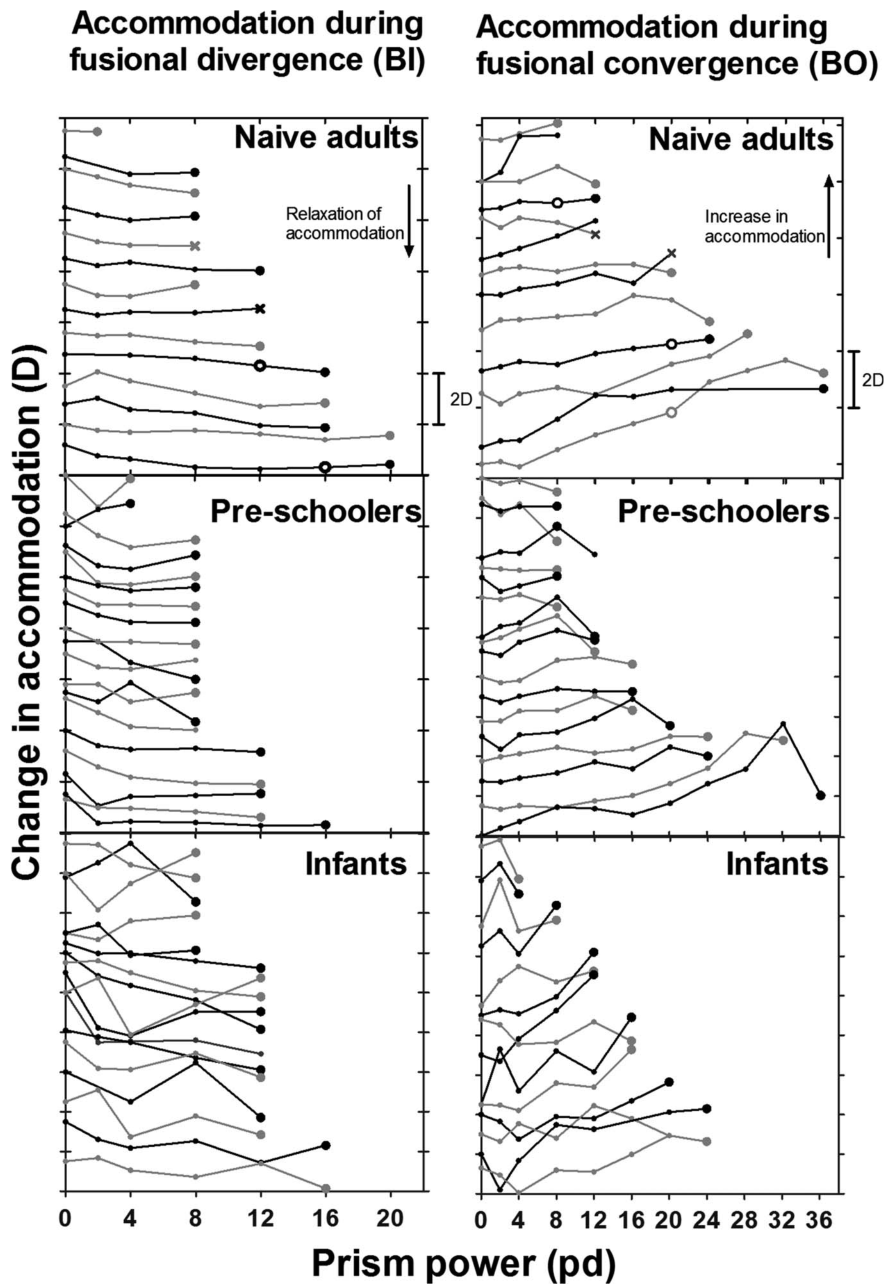

FIGURE 9. Accommodative behavior of individual subjects during measurement of divergence and convergence fusional ranges. The data from each subject have been shifted vertically and coded with alternating color for clarity. Subjects showed increases in accommodation during convergence stimulation and decreases in accommodation during divergence stimulation. *Large filled circles* denote each subject's objective breakpoint obtained from the PR. *Large open circles* denote subjective blur points when they were reported in naïve adults. *Cross symbols* indicate that the subjective blur and objective break points occurred at the same prism step.

became weak and insignificant ($r = 0.01$; $P = 0.96$) without this infant. The correlations between refractive error and fusional ranges also were not significant for either age group (BI: Preschoolers, $r = -0.13$, $P = 0.5$; Infants, $r = 0.10$, $P = 0.7$; BO: Preschoolers, $r = -0.39$, $P = 0.09$; Infants, $r = -0.27$, $P = 0.3$). Further, there was no evidence of a trend in BI or BO fusional range around phoria in adults or in younger subjects ($r < \pm 0.3$ and $P > 0.29$). It is important to note that the objective break points presented above are the ranges of convergence and divergence relative to binocular alignment with no compensation for the response required to overcome the subject's phoria. Overall, the range of reflexive fusional vergence responses around the phoria appeared consistent across age groups.

Accommodation During Measurements of Fusional Vergence Range

The accommodation data collected during fusional vergence testing are presented for each subject in Figure 9. The data from each subject were shifted vertically and coded with alternating color for the sake of clarity. Therefore, each function shows the change in accommodation relative to the baseline zero prism power. The left column shows the typical

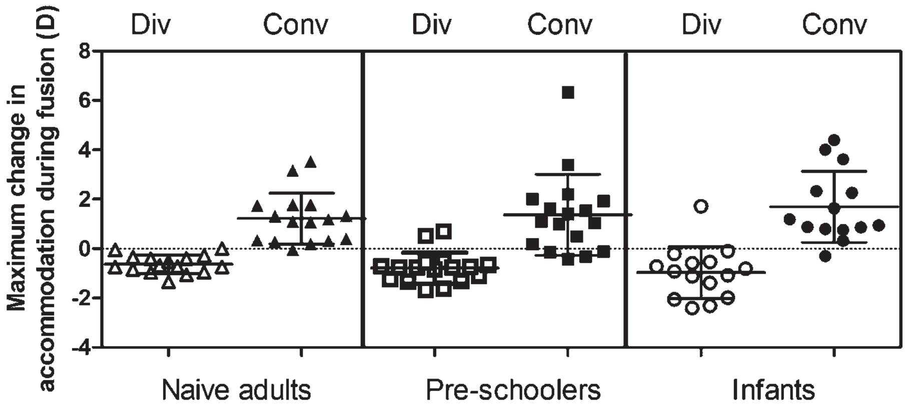

FIGURE 10. Comparison of changes in accommodation during the fused divergent and convergent phases. *Positive sign* denotes increase in accommodation with the introduction of prism. *Error bars* denote standard deviation.

disaccommodation induced by the BI prism stimulating divergence. The rate of change in accommodation appears different among subjects, with some showing minimal change (0.5–1 D) and others producing a steady shift. These results agree with those observed by Fry.[36] Similarly, the right column shows the typical increase in accommodation when BO prisms stimulated convergence. The full change in accommodation with increase in prism power, to the last fused prism before the breakpoint, is summarized in Figure 10. An ANOVA demonstrated that these responses were statistically similar across age groups (main effect of age, $F[2,44] = 0.905$; $P = 0.41$; main effect of vergence direction, $F[1,44] = 8.66$; $P = 0.005$; Interaction, $F[2,44] = 0.037$; $P = 0.96$).

DISCUSSION

During the developmental period when IPD is increasing and hyperopia is typically decreasing, the visual system requires reweighting or recalibration of its vergence responses to maintain alignment of the eyes. How well is fusional vergence able to eliminate small to moderate phorias or changes in phoria while this adaptation or recalibration occurs? Heterophoria and reflex fusional ranges were measured objectively to determine the range of misalignments that can be overcome typically during infancy and early childhood. To our knowledge, this study provides the first documented estimates of phoria and fusional ranges in infants. These results describe typical behavior for an 80-cm viewing distance and provide insight into clinical abnormality.

Using an extended duration Purkinje image eye-tracking approach, infants and young children exhibited small exophorias at 80 cm that were comparable in magnitude to adult values. The similarity of phorias between infants and adults is somewhat surprising, as the infants displayed typical amounts of uncorrected hyperopia (mean SE = +2.4 D versus functionally emmetropic adults) and smaller IPDs than the adults (mean 4.1 vs. 6 cm). Uncorrected hyperopia necessitates increased accommodative effort if the infants are to focus on a target accurately. Increased accommodation may then lead to additional accommodative convergence and esophoria if the gain of the neural coupling from accommodation is adult-like (accommodative convergence per diopter of accommodation [AC/A]). Reduced IPD also may result in overconvergence of the visual axes, if the tonic, proximal, and accommodative components of the vergence response are adult-like in angular units. Interestingly, the majority of infants displayed an exophoric position, which may be attributed to four possible factors. First, infants may have a smaller AC/A ratio compared to adults, and thus, despite accommodating accurately to the target, the vergence driven by accommodation will not push them into esophoria. Two studies (Ref. 50 and Teel D, et al. *IOVS* 2010;51:ARVO E-Abstract 1837) have suggested that the AC/A ratio is, indeed, smaller in infants compared to adults. Recently, a study from our lab[30] used simulations to illustrate that AC/A ratios in pd/D that are smaller than the IPD in cm may result in underconvergence (exophoria) in young children even in the presence of accurate accommodation at near. A second possible factor is that infants may not be exerting accurate accommodation and, therefore, may show exophoria due to the reduced input from accommodative vergence. The third explanation is related to the duration of occlusion used in this study. Phoria measurements were taken after a mean occlusion time of 57, 47, and 63 seconds in adults, preschoolers, and infants, respectively, and previous evidence suggests that prolonged occlusion reveals greater exophoria in young children[30] and adults.[53] Lastly, the combined weighting of the other components of vergence, specifically the proximal and tonic components, could influence the phoria. These factors alone or in combination appear to have resulted in an exophoric position in infants.

The similarity in phoria across age groups suggests that the demand on the fusional vergence system is similar across age for typical binocular conditions. The infants, preschoolers, and adults also were capable of maintaining motor fusion through a similar range of convergent and divergent prism-induced disparities. These results suggest that fusional ranges of 3- to 5-month-olds are coarsely adult-like around the classical age of onset of sensitivity to relative disparity.[13,54,55] Interestingly, the fact that the infants were exerting fusional vergence to overcome phorias on the order of 2 pd confirms that their motor system is sensitive to image misalignment on the order of 1° at 3 to 5 months of age, consistent with a recent study that measured their vergence sensitivity.[56]

While numerous studies have reported fusional ranges in adults,[19,32,33,37] the current results should not be compared quantitatively to previous studies for two reasons. First, fusional ranges typically are measured by providing instructions, such as "keep this target single as long as possible,"[31] which may invoke additional voluntary vergence. Though the majority of the previous studies did not provide details about the precise instructions given to the participants,[19,32] it is likely that these instructions influenced the results. The present study only compared the naïve adult subjects, who were uninstructed, to the younger participants. Consistent with this, expert adults generated larger fusional ranges during convergence stimulation than naïve subjects (Fig. 7). These results are in agreement with a previous study that reported differences in accommodation and vergence accuracy between expert and naïve adults.[41] Secondly, the viewing distance used in this study was different from that of earlier studies. Standard clinical estimates typically are collected either at 6 m or 40 cm, whereas at this 80 cm distance (used based on instrument limitations), the demand for accommodation and vergence was 1.25 D or MA, approximately halfway between the 0.12 (6 m) and 2.5 (40 cm) D or MA demands. Though direct comparisons are difficult, the mean vergence ranges for this intermediate distance fall between the distance and near norms predicted by the literature.[19,32,33,37]

Fusional vergence ranges are measured when accommodation and vergence mechanisms receive feedback and, therefore, are active. Most studies have not recorded the changes in accommodation during vergence testing with prisms, but have documented the subjective report of blur.[19,22,26,27,32–35,38,39] The use of simultaneous Purkinje image eye tracking and eccentric photorefraction permitted recording of accommodation in this study. Based on the presence of the neural coupling from vergence to accommodation,[5] the expectation would be that accommodation would increase during convergent stimulation with BO prisms and decrease during divergent stimulation with BI prisms. Figures 9 and 10 demonstrate that the results are consistent with these predictions. This evidence that the CA/C coupling is present in infants is consistent with the literature, which suggests that their CA/C ratios are greater than those of adults[12,57] when accommodation is measured in open loop conditions.

The absence of a test for suppression of one eye's image was a limitation of this study. The inability to assess infants' percepts prevents this, but the fact that their vergence alignment was consistent with binocular viewing suggests there was motor fusion (Figs. 6, 7). A second limitation was that the commercially available prism bars only permitted limited resolution, with 4 pd steps in total prism power. Smaller steps may have provided greater resolution, or may have revealed small differences between the age groups. However, these steps would have increased the testing time with restless infants and increased the potential for vergence adaptation during the task.[45,46,58,59] A final limitation was related to the axial position of the prism bars. The prism bar apparatus was held between approximately 3 and 10 cm from the corneal apex. According to Thompson and Guyton,[60] this might result in an overestimation of the induced disparity and response amplitude. The effect of vertex distance was tested here using an approach similar to that of Thompson and Guyton. The results suggested that an extreme vertex distance of 11 cm would reduce the effective prism power by 15%. This equates to a 3 pd reduction for the highest mean fusional ranges observed in the study, which is less than one prism step size.

Potential Clinical Significance

The clinical measurement of fusional vergence ranges typically requires subjective reports of blur or diplopia, which are not possible with preverbal children. However, it is important to understand fusional vergence ranges in this age range as binocular alignment can decompensate into strabismus during early childhood.[40] The majority (approximately 80%) of moderate hyperopes (>3 D) remain binocularly aligned despite their increased accommodative demand, while the remaining approximately 20% have esotropia.[17,18] The reasons for this decompensation into strabismus are poorly understood, as it appears that refractive esotropes are able to maintain alignment for some months or years after birth before decompensating, even though the accommodation and vergence systems are typically quite active by approximately 3 months of age.[11,61]

The current study only included one infant with significant hyperopia (SE, +6.5 D). This infant displayed the only moderate esophoria (6 pd; Fig. 4) while the fusional divergence break point relative to alignment was well matched to the other infants, indicating some ability to overcome the esophoria. It would be interesting to determine whether fusional ranges can be predictive of refractive strabismus in children with moderate to high hyperopia, and the current study has identified a novel technique that would facilitate such measurements in preverbal children.

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