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The heterophoria of three to five year old children as a function of viewing distance and target type

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Abstract

Purpose—Heterophoria is the misalignment of the eyes in monocular viewing and represents the accuracy of vergence driven by all classical cues except disparity. It is challenging to assess restless children using clinical cover tests, and phoria in early childhood is poorly understood. Here we used eye tracking to assess phoria as a function of viewing distance and target in adults and young children, with comparison to clinical cover tests.

Methods—Purkinje image tracking (MCS PowerRefractor) was used to record eye alignment in adults (19–28 years, $N = 24$) and typically developing children (three to five years, $N = 24$). Objective unilateral and alternating cover tests were performed using an infrared filter while participants viewed a pseudo-randomised sequence of Lea symbols (0.18 logMAR; Snellen: 20/30 or 6/9) and animated cartoon movies at distances of 40 cm, 1 m, and 6 m. For the unilateral cover test, a 10 second binocular period preceded and followed 30 seconds of occlusion of the right eye. For the alternating cover test, a 10 second binocular period preceded and followed alternate covering of right and left eyes for three seconds each. Phoria was derived from the difference in weighted average binocular and monocular alignment. A masked prism-neutralised clinical cover test was performed for each of the conditions for comparison.

Results—Closer viewing distance resulted in greater exophoria for both children and adults ($p < 0.001$). Phorias were similar for adults and children for each viewing distance and target, with mean differences of less than 2 prism dioptres or pd. Overall, the average PowerRefractor phorias in pd (pooled across protocols) for adults were 1.3, 2.3 and 3.8 pd exophoria and for children were 0.1 pd esophoria, 0.94 and 3.8 pd exophoria for the 6 m, 1 m and 40 cm distances respectively. The corresponding clinical cover test values were 0.7, 1.9, and 4.1 pd exophoria for adults and 0, 1.5 and 3.3 pd exophoria for the children. Refractive states were also similar (± 0.5 D) for viewing the Lea symbols or movie for any protocol tested.

Conclusions—Phoria estimation can be challenging for a pre-school child. These data suggest that by three to five years of age objective eye-tracking measures in a typically developing group are adult-like at the range of distances tested, and that use of an animated movie produces similar average results to a small optotype (0.18 logMAR; Snellen 20/30 or 6/9).

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The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

Keywords

heterophoria; visual development; viewing distance; target type

Introduction

Heterophoria (phoria) is the latent ocular misalignment observed when fusional vergence is disrupted by removing retinal disparity cues (e.g. by covering one eye). This position represents the combined error in alignment from all other components of the vergence response, which must be eliminated by fusional vergence to achieve full binocular eye alignment. From this perspective, phoria measurement is an important clinical test as it indicates the demand on the fusional vergence system. A divergent misalignment is termed exophoria and a convergent misalignment is termed esophoria.

Maddox¹ originally suggested that the phoria position represents the combined contributions of tonic, proximal and accommodative vergence activity. Thus, the phoria could be influenced by factors such as the content of the visual stimulus and its viewing distance, which both influence accommodation and proximal responses,^{2, 3} or the method and time of dissociation when tonic adaptation can impact the phoria estimate.^{4–6} Other factors such as age and refractive error also play a role in determining its magnitude.^{7–9} While the impact of these factors has been studied in adults and older children (e.g.^{2–5, 7, 10}) it is poorly understood in young children at the typical ages when strabismus and clinical disorders develop. In older patients poorly controlled phorias are often associated with asthenopic symptoms such as blurred vision, eyestrain, headache, and decreased stereopsis.¹¹ They may also be related to non-strabismic binocular vision issues such as convergence insufficiency or convergence excess, which may impact academic performance in school aged children.^{12, 13}

In adults the mean distance phoria, for a target at a viewing distance of 6 m or 20 ft, ranges from 0 to 1 prism dioptre (pd) exophoria (SD around 2 pd), while the mean near phoria, for a target at 33 or 40 cm, is typically exophoric and ranges between 3 and 6 pd.^{14–16} Phoria has also been well characterised in older school aged children (>six years) with mean values ranging from 1 pd esophoria to 1 pd exophoria at distance and orthophoria to 3 pd exophoria at near.^{17–21} In children under six years of age, Chen *et al.*²² and Lam.²³ showed a high prevalence of orthophoria (no misalignment) at near using subjective Maddox wing and alternating cover test respectively. Babinsky *et al.*⁶ showed adult-like exophorias in young children at 33 cm using objective testing and a longer period of dissociation. Using similar objective eye tracking techniques we recently confirmed that even three to five month old infants on average showed small exophoria at an 80 cm viewing distance, similar to preschool children and adults.²⁴ The differences between these studies (albeit small) may be attributed to several factors such as the type of fixation target, technique used to measure phoria and the duration of dissociation.

Although several techniques are available to quantify the magnitude of heterophoria in the absence of a strabismus,²⁵ the alternating cover test is commonly performed by clinicians. In this test, patients are asked to fixate a 0.18 logMAR (20/30 or 6/9 Snellen) target at distance

and near.²⁵ However, it is challenging to persuade restless young children to pay attention to this small target for assessment with the conventional approach. Animated cartoon movies are more interesting to young children and represent a naturalistic image with broadband spatial frequency content,²⁶ unlike the small Optotype targets. With the clinical importance of collecting meaningful data from small children, the current study asks whether useful estimates of phoria can be collected with different combinations of viewing distance, cover protocol, and type of stimulus, and uses both clinical and objective approaches to gathering the data, to provide a deeper understanding of phoria and its assessment in the early years when clinical abnormality can become manifest.

Methods

The study was approved by the Indiana University IRB and followed the tenets of the Declaration of Helsinki. Adult subjects and all parents provided informed consent prior to their participation in the study.

Study population

Twenty four typically-developing children (mean age 4.7 years, SD 0.8, range 3.0–5.8) and 24 adults (mean age 23.8 years, SD 0.8, range 19–29) participated in the study. Typically-developing children were recruited from the local community while the majority of the adults (23 out of 24) were recruited from the academic department. All children received an eye examination that showed typical cycloplegic refractive error (mean spherical equivalent 1.28 D (SD 0.95); astigmatism ≤ 1 D; anisometropia ≤ 1 D), with no evidence of amblyopia, strabismus or other ocular health issues. None of the children had any optical correction prescribed at the time of the study. All the adult subjects were either emmetropic ($n = 11$) or habitually wore spherical soft contact lenses to correct them to functional emmetropia ($n = 13$; mean spherical equivalent -3.35 D (SD 2.36); anisometropia ≤ 1 D).

Equipment

Purkinje image tracking (Multi Channel Systems PowerRefractor; www.multichannelsystems.com) was used to record eye alignment at 25 Hz while accommodation was measured simultaneously from the same video using the principle of eccentric photorefraction. Detailed descriptions of the techniques can be found in prior publications.^{27, 28} The instrument uses default average calibration functions based on data collected from adults, but these calibration factors have been found to be variable across subjects.²⁹ For this reason, individual calibrations of refractive state (lens calibration) and gaze (prism calibration) were performed for all subjects using a technique described elsewhere.^{6, 30} The mean relative calibration slopes were similar for adults and children (*Prism calibration*: Adults: -0.80 ± 0.20 ; Children: -0.92 ± 0.28 ; *Lens calibration*: Adults: 1.11 ± 0.22 ; Children: 1.04 ± 0.24). The default instrument calibration (relative slope = 1) was used for three adults and two children because insufficient calibration data were obtained from them.

A schematic of the equipment is shown in Figure 1 (*Panel A*). The PowerRefractor was positioned at an optical path distance of 1 m from the subject using a beam-splitter. Targets

were presented in free space at 40 cm, 1 m and 6 m, in an order pseudo-randomised across individuals. Both children and adults were positioned at the appropriate viewing distance using a head and chin rest. Two types of targets were presented to all subjects: 1) Single Lea symbols (Size = 0.18 logMAR; Snellen = 20/30 or 6/9; Angular subtense = 0.125 degree) as conventionally used during a typical clinical assessment of phoria for children and 2) An age-appropriate cartoon movie (angular subtense = 10 degrees) that contained naturalistic broadband spatial frequency content. Both targets were scaled to have a constant angular subtense at each distance. At the distances of 40 cm and 1 m, the movies and Lea symbols were displayed on an Apple Mac Book Pro with a 13.3" Retina Display (2560 × 1600 pixel resolution). At 6 m, the movies and symbols were projected onto a white projector screen using a Powerless Home Cinema 705 HD Projector (1280 × 720 pixels resolution).

Procedure

To understand the role of viewing distance, target type, and cover protocol on the phoria position of young children, we collected eye alignment and accommodation data while subjects viewed targets at three viewing distances, using two types of visual stimuli and two cover protocols (Fig 1, *Panel B*). The order of testing was pseudo-randomised across subjects to avoid any systematic bias.

In all cases, objective phoria was determined by measuring the difference in eye alignment between monocular and binocular viewing conditions. The use of an infrared filter (Kodak Wratten filter #87; Rochester, NY, USA <http://www.edmundoptics.com/optics/optical-filters/color-dichroic-filters/kodak-wratten-filters/54518/>) for the monocular occlusions permitted the measurement of gaze position from both eyes while blocking vision of the occluded eye (Fig 1, *panel A, top insert*). The cover protocols differed in measurement time during binocular and monocular viewing. For the unilateral cover test, a 10 second binocular period preceded and followed approximately 30 seconds of occlusion of the right eye. For the alternating cover test, a 10 second binocular period preceded and followed six alternate coverings of the right and left eyes for approximately three seconds each, equivalent to the principle underlying a clinical alternating cover test. The eye was occluded manually using the time provided in the PowerRefractor image (min: secs: msec).

After the eye-tracking data were collected for all conditions, conventional prism-neutralized clinical alternating cover tests were performed by a trained clinician for the whole set of conditions, to compare with the objective phorias measured using the PowerRefractor. For this technique, the subject was instructed to fixate the target while the examiner alternately covered each eye for approximately three seconds (with no video confirmation) to disrupt fusional vergence. The amplitude of the re-fixation movement was quantified using a commercially available prism bar (Bernell, <http://www.bernell.com/product/4676/290>). The highest prism power that induced no movement was recorded as the end point. If a neutral endpoint was not seen using the available prism steps, the endpoint was defined as an average of the last prism power that elicited the re-fixation movement and first prism power that resulted in reversal of the movement.

The clinician was masked to the phoria results obtained from the PowerRefractor, but completed the clinical tests in the same order as the prior eye-tracking measurements.

Analysis

Data analyses were performed using Matlab (Mathworks, Natick, USA), Openshapa/Datavyu (Databrary Project, New York University. URL <http://datavyu.org>), Stata (StataCorp, College Station, TX) and Excel (Microsoft, Redmond, WA, USA). Monocular and binocular data intervals were labelled using the video recording of each condition. Calibration factors were applied to the raw refractive and eye position data obtained from the PowerRefractor and these calibrated data were filtered to remove non-physiological outliers using criteria described in earlier studies^{6, 24}

The phoria position was derived from the difference in the weighted average of 3.5 second intervals of binocular and monocular eye positions as described below (Figure 2). For both unilateral and alternating protocols, 3.5 seconds of binocular data were obtained at least one second after the start of the binocular period. The analyses differed between protocols in terms of the monocular data. In the case of the unilateral cover protocol, two estimates of phoria position were obtained by selecting different monocular time points. The first estimate simulated a clinical cover test where one eye is typically covered for a short duration of approximately two to three seconds. This phoria estimate was termed “Unilateral short cover”, when 3.5 secs of monocular eye position data were averaged after three seconds of occlusion. A second estimate of phoria termed “Unilateral long cover” was obtained by averaging 3.5 secs of stable monocular eye position data near the end of the 30 s occlusion to permit the alignment to settle to a phoria position. For the alternating cover test, 1.8 sec of stable monocular data were averaged for each pair of right and left eye occlusions (total monocular viewing time = 3.6 sec in each case). The calculation of the overall weighted average then consisted of an average of all of the estimates in the trial, each weighted by their standard error.

In addition to the eye position data, the simultaneously collected weighted averages of binocular and monocular refractive state were analysed to determine whether accommodative performance differed across the different phoria measurement protocols.

Results

Of the 24 children and 24 adults recruited for the study, 17 children and 23 adults provided usable data in at least one of the six phoria conditions (two target types by three distances). Data from seven children were excluded due to lack of attention (four participants) or poor data quality (small pupil size for two participants and poor image contrast in the images for one participant), while one adult’s data were excluded due to poor data quality (small pupil size).

As indicated earlier, this study was designed to understand the effect of viewing distance, target type, cover protocol, and length of occlusion on phoria estimates for adults and children. Two mixed model analyses were performed to analyse these data to account for correlation within a subject and permit the inclusion of subjects with missing data. Phoria estimate was the dependent variable in one model and refractive state in the other. In each case, the null model with inter-subject differences as a random intercept resulted in a lower Akaike’s Information Criterion (AIC) and a significant likelihood ratio test when compared

with a linear regression model (Phoria model: AIC = 3768; LR test $\chi^2(1) = 249.5$; $p = 0.00$); Accommodation model: AIC = 3314; LR test $\chi^2(1) = 327$; $p = 0.00$). The addition of age, viewing distance, target type and phoria condition as fixed effects and viewing distance as a random coefficient effect improved the model further (Phoria model: AIC = 3446; Accommodation model: AIC = 1507).

Comparison between the clinical and PowerRefractor alternating cover test results

Overall, the mean phorias measured using the alternating clinical cover test (pooled across targets) at a 6 m viewing distance were 0.0 (SD 1.4) for the children and 0.7 pd (SD 1.8) of exophoria for the adults. At the 1 m distance they were 1.5 pd (SD 1.3) of exophoria for the children and 1.9 pd (SD 2.6) of exophoria for the adults, and at the 40 cm viewing distance they were 3.3 pd (SD 1.7) of exophoria for the children and 4.1 pd (SD 2.6) of exophoria for the adults (Figure 3).

The mean phorias obtained using the clinical cover test were no different from the objective alternating cover protocol from the PowerRefractor (Mixed model: Mean difference = 0.0 pd (SE 0.1); $p = 0.89$; Lower bound 95% CI = -0.3 pd; Upper bound CI = 0.3 pd). The bias (mean difference) across viewing distance between the alternating clinical and PowerRefractor estimates was less than 1 pd for the Lea and movie targets in adults and children, with no systematic trend in these data (Figure 4). These results establish that the PowerRefractor provides similar alternating cover test values to the clinical technique used for measuring phoria.

Effect of viewing distance, age and target type on eye-tracking phoria estimates

Figure 5 plots the PowerRefractor based phoria data as a function of viewing distance and age for all protocols. At an individual subject level, the range of the phoria measurements across the different protocols and distances tested was, on average, 4 pd. As expected, the phoria became more exophoric with closer viewing distance for each target type and cover protocol tested in both adults and children (Figure 5). The mixed model with phoria value as the dependent variable showed a significant fixed effect of viewing distance (with the phoria becoming 2.9 pd (95% CI -3.6: -2.3 pd) more exophoric at 0.4 m relative to 6 m, $p = 0.000$). The fixed effect of age showed a statistically significant but small change in phoria between adults and children (Mean difference = 1.1 pd; $p = 0.01$; 95% CI = 0.2–2.1 pd). There was no fixed main effect of target type such that a movie target resulted in similar phoria values compared to a Lea optotype conventionally used to measure phoria in the clinic (Mean difference between Lea and movie = 0.1 pd; $p = 0.30$; 95% CI = -0.1–0.3 pd). Furthermore, it is evident from Figure 5 that differences in phoria at any given viewing distance are less than approximately 2 pd between children and adults for both lea and movie targets. These differences are not clinically significant³¹.

Influence of cover protocol (alternating vs. unilateral) and occlusion time on phoria measurements

Typically, the phoria magnitude is measured in the clinic by performing an alternating cover test when the paddle is quickly alternated between covering the right and left eyes. Here the magnitudes measured using unilateral short and long duration occlusion were compared with

the alternate occlusion protocol. The unilateral short cover protocol showed a small albeit significant esophoric shift in phoria compared to the alternating protocol (Mean difference between the protocols = 0.4 pd; $p = 0.02$; 95% CI = 0.0–0.8 pd). The long duration cover protocol, on the other hand, resulted in an exophoric shift in phoria compared to the alternating version (Mean difference between the protocols = –0.6 pd; $p = 0.02$; 95% CI = –1.0 pd to –0.2 pd). The difference between the unilateral short and long cover protocols is greatest at a viewing distance of 40 cm (approx. 2 pd) for both target types in children (Figure 5).

Accommodation during phoria measurements

Figure 6 shows refractive state during the phoria measurements for the unilateral long duration cover test protocol. The other protocols resulted in similar values. The mixed model built with refractive state as the dependent variable indicated, as expected, that there was a significant main effect of viewing distance with more myopic refractive state/ accommodation at viewing distances closer than 6 m (Mean change between 6 m and 0.4 m = –1.9 D [95% CI –2.0 to –1.6 D]; $p = 0.000$). The main effect of target type, age and viewing condition were statistically significant but the mean differences were small (–0.5 D) in each case (Mean difference between movie and Lea = 0.07 D [95% CI = 0.02 to 0.11 D], $p = 0.002$; Mean difference between children & adults = 0.5 D [95% CI = 0.18 to 0.89 D], $p = 0.003$; Mean difference between binocular and monocular viewing = 0.1 D [95% CI = 0.05 to 0.2 D]; $p = 0.00$). There was no main effect of measurement protocol (all mean differences were less than 0.2 D; $p > 0.7$).

Discussion

The heterophoria magnitude is considered to represent the demand on the fusional vergence system in achieving binocular alignment. Large uncontrolled phorias may lead to poor visual comfort¹¹ and impact academic performance in school-aged children.^{12, 13} Given the importance of the phoria in the visual health of young children, this study was designed to ask how different measurement approaches impact the estimates made. To our knowledge this is the first study to determine the impact of viewing distance, target type and assessment protocol on the results of phoria testing in typically-developing preschool children, with comparison of the clinical protocol and objective eye-tracking estimates and assessment of accommodative status.

Using the eye tracking approach, the mean phoria in children was found to be within 2 pd of adult values at all viewing distances. The mean position became more exophoric with closer viewing distance for all protocols. This result is consistent with the adult literature that shows larger exophoria at near viewing distances^{3, 16}, and with studies of older children that measured phoria at distance and near.^{17, 19–21} Despite any visual immaturities at three to five years of age (e.g. in interocular distance [approximately 47 mm compared to adult value of 60 mm³²]) preschool children consistently exhibit almost adult-like heterophoria values.

When fixation changes from a distant to a near target, proximal, accommodative and tonic responses can all impact phoria position. The role of accommodation is hard to ascertain during typical clinical assessments, as clinical cover tests do not provide an estimate of

refractive state during phoria measurement. With the use of simultaneous photorefractive and Purkinje image eye tracking, accommodation could be tracked during the various cover protocols tested using the PowerRefractor. As expected, accommodation increased with closer viewing distance under both monocular and binocular viewing conditions (Figure 6). There was no qualitative difference between the behaviour of the young children and adults in any of the conditions tested.

In the absence of strabismus, phoria magnitude is typically measured using an alternating cover test, during which an occluder alternately covers each eye to disrupt fusional vergence.²⁵ In this study, three cover protocols were compared: an alternating cover test, a unilateral short cover protocol and a unilateral long cover protocol. On average, there was less than 1 pd difference in the phoria magnitude between the alternating and the unilateral short cover protocol, while the unilateral long cover revealed larger phorias especially at the closest viewing distance in both adults and young children. These results agree with previous studies showing larger phorias after prolonged dissociation^{4-6, 10}. This change in heterophoria with duration has been attributed to the decay of slow fusional vergence and so these results suggest that young children are capable of undergoing adaptation of their tonic vergence, supporting the results of other recent studies.^{33, 34}

A small optotype is typically recommended as the target for phoria assessment with young children. However, this type of target is frequently not interesting and stimulating to a young child. Here, it was asked whether an animated movie with broadband naturalistic spatial frequency content²⁶ could be used. The results demonstrated that the movie, subtending 10 deg of visual angle, produced a similar mean accommodative response and phoria position on average when compared to a conventional 20/30 Lea symbol (0.18 logMAR). These data supported an anecdotal observation that the children were more attentive to the movie than the Lea symbols. Of the children who provided incomplete measurements of phoria ($n = 6$ at 6 m viewing distance; $n = 9$ at 1 m; $n = 7$ at 40 cm), none had missing values for only the movie targets. About 50% of the children with missing values had missing data for the Optotype targets only (3/6 at 6 m; 4/9 at 1 m & 3/7 at 40 cm) and the remaining children had a mix of missing data for both Lea and movie targets. It appears, therefore, that a small movie or cartoon target can be used to assess phoria in these children with typical visual systems. These targets have an additional advantage in that they present naturalistic spatial information to help reveal the oculomotor status of children during their habitual activities. Eye movements that occur while watching a somewhat larger movie may make clinical cover test assessment of phorias challenging, however. Testing may require multiple measurements to achieve appropriate confidence with a restless child.

Conclusions

This study used clinical and laboratory based eye-tracking methods to measure the heterophoria of young children (three to five years) with different combinations of viewing distance, cover protocol, and target type. The conclusions were as follows: i) Animated cartoon movies produced similar average phoria results compared to conventional optotypes and may be more interesting to young children. ii) Clinicians can expect similar variations in phoria and accommodation as a function of viewing distance for adults and preschool

children. iii) As is sometimes recommended for older patients, occlusion durations of longer than three seconds may uncover larger phorias for these typically developing children.

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Figure 1.

Schematic of the experimental setup (Panel A) and the protocols tested (Panel B). The insert in panel A shows a child viewing through an IR filter that blocked visible light to that eye, but permitted the measurement of eye positions in monocular and binocular viewing for estimation of the phoria position.

Figure 2.

Examples of eye alignment and accommodation data collected from the PowerRefractor to estimate phoria in the unilateral and alternating cover protocols. The black lines indicate the transition between the binocular & monocular viewing conditions. The horizontal grey lines represent the windows identified in the different protocols to estimate phoria (see text for more information). The data have been separated vertically for clarity.

Figure 3. Mean clinical cover test phorias as a function of viewing distance and target type in adults and children. Error bars denote standard deviation. The values above the X-axis present the average phoria for each group.

Figure 4. Comparison of alternating cover test phoria data obtained using the clinical and PowerRefractor protocols. The horizontal lines present the mean bias and 95% Limits of Agreement. The bias (mean difference) was less than 1 pd for the Lea and movie targets in adults and children.

Figure 6.

Monocular and binocular viewing refractive states during phoria measurement using the unilateral long cover protocol for adults and children. Numbers above the X-axis represent averages for each group.