Accommodation in Astigmatic Children During Visual Task Performance

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Purpose. To determine the accuracy and stability of accommodation in uncorrected children during visual task performance.

Methods. Subjects were second- to seventh-grade children from a highly astigmatic population. Measurements of noncycloplegic right eye spherical equivalent (M_{nc}) were obtained while uncorrected subjects performed three visual tasks at near (40 cm) and distance (2 m). Tasks included reading sentences with stimulus letter size near acuity threshold and an age-appropriate letter size (high task demands) and viewing a video (low task demand). Repeated measures ANOVA assessed the influence of astigmatism, task demand, and accommodative demand on accuracy (mean M_{nc}) and variability (mean SD of M_{nc}) of accommodation.

Results. For near and distance analyses, respectively, sample size was 321 and 247, mean age was 10.37 (SD 1.77) and 10.30 (SD 1.74) years, mean cycloplegic M was 0.48 (SD 1.10) and 0.79 diopters (D) (SD 1.00), and mean astigmatism was 0.99 (SD 1.15) and 0.75 D (SD 0.96). Poor accommodative accuracy was associated with high astigmatism, low task demand (video viewing), and high accommodative demand. The negative effect of accommodative demand on accuracy increased with increasing astigmatism, with the poorest accommodative accuracy observed in high astigmats ($\geq$3.00 D) with high accommodative demand/high hyperopia (1.53 D and 2.05 D of underaccommodation for near and distant stimuli, respectively). Accommodative variability was greatest in high astigmats and was uniformly high across task condition. No/low and moderate astigmats showed higher variability for the video task than the reading tasks.

Conclusions. Accuracy of accommodation is reduced in uncorrected children with high astigmatism and high accommodative demand/high hyperopia, but improves with increased visual task demand (reading). High astigmats showed the greatest variability in accommodation.

Keywords: astigmatism, accommodation, children

Eyes with regular astigmatism have two orthogonal focal planes. Unlike myopes or hyperopes, uncorrected astigmats cannot bring complex visual stimuli into full focus by adjusting accommodation or viewing distance. Most young uncorrected astigmats (i.e., those without significant myopia) can experience clear visual input for all orientations contained within complex stimuli by bringing portions of the image into focus, but all stimulus components are never simultaneously in focus. As a consequence of this persistent blur, uncorrected astigmatism can result in amblyopia, and in some cases, amblyopia for specific stimulus orientations (meridional amblyopia).[1] However, because the blur that uncorrected astigmatic children experience is dependent in part on how they accommodate, the risk for amblyopia cannot be accurately predicted by astigmatism magnitude alone.

Studies of accommodative patterns in uncorrected astigmats suggest that they may use a variety of strategies, such as accommodating to the more anterior focal plane (requiring the least accommodative response) or to the "circle of least confusion" (spherical equivalent),[2,3] and that patterns of accommodation differ depending on the demands of the visual task or stimulus (Harvey EM, et al. *IOVS* 2003;44:E-Abstract 2727).[3] Increased accommodative variability in the form of a cyclic accommodative response with increasing levels of induced astigmatism has been reported, suggesting that astigmats may vary their accommodation to bring various features of a target into focus to improve visual performance.[4] In a pilot study, we observed that some astigmats accommodated close to the anterior focal plane and others accommodated to the circle of least confusion when reading letters on an acuity chart (Harvey EM, et al. *IOVS* 2003;44:E-Abstract 2727). However, the study did not provide any insight into the factors that lead to these individual differences and the existing literature tells us little about how key factors associated with accommodative performance (e.g., astigmatism magnitude, task demand, accommodative demand) interact to elicit different accommodative responses when subjects encounter common complex visual stimuli and engage in visual tasks.

In the present study, we obtained noncycloplegic measurements of spherical equivalent (M_{nc}) to assess the accuracy and variability in accommodation under various task demand conditions to determine how uncorrected children accommodate under stimulus and task conditions commonly encountered in everyday functioning. Three task conditions were used: reading text in a letter size that is near acuity threshold (to create greater visual task demand), reading text in a letter size that is age-appropriate (to simulate reading conditions commonly encountered), and video viewing (to simulate a task that is commonly encountered but does not typically impose a high visual task demand). We predicted that accommodative accuracy would improve with greater task demand, as greater accuracy will reduce blur, resulting in improved acuity that is needed to perform the more visually demanding tasks. We also predicted that accommodative accuracy in uncorrected astigmats would be poorer than in subjects with no/low astigmatism due to the limited quality of visual feedback that results from the uncorrected astigmatism, and that this effect would be dependent on the accommodative demand (i.e., based on subject's individual refractive error and viewing distance). Additionally, we predicted that fluctuations in accommodation would be greater with increased visual task demand in astigmatic subjects as they attempt to bring the detailed targets into clear focus to perform the task (reading).

The analyses presented here represent the initial step in determining the relation between accommodative patterns and risk for development of amblyopia in astigmatic children. Here we describe the accuracy of accommodation while subjects perform common visual tasks to determine the visual experience of the children when uncorrected.

Methods

Subjects

Subjects were second- to seventh-grade children who attended school on the Tohono O'odham reservation during the 2012/2013 school year. All children in the targeted grades were eligible to participate. The Tohono O'odham have a high prevalence of large amounts of with-the-rule astigmatism.[5–9] Informed consent was obtained from a parent or guardian and assent was obtained from subjects before testing. This research followed the tenets of the Declaration of Helsinki and was approved by the Tohono O'odham Nation and the University of Arizona Institutional Review Board. This study was conducted in a manner compliant with the Health Insurance Portability and Accountability Act.

Stimuli

Measurements were made while subjects binocularly viewed stimuli at near (40 cm) and distance (2 m). Near stimuli were displayed on an iPod (Apple, Inc., Cupertino, CA, USA; display resolution 320 ppi, 10.62°w × 7.13°h at 40 cm, 147.6 cd/m^2) and distant stimuli were displayed on an iPad 3 (Apple, Inc.; display resolution 264 ppi, 4.63°w × 4.20°h at 2 m, 144.7 cd/m^2). The higher-resolution iPod display was selected for near targets, as its resolution allowed for letter stimuli (Arial font) as small as 20/20 (0.0 logMAR) to be displayed at 40 cm. The iPad was selected for distant targets because its larger display size allowed for large sentence stimuli (20/100 letters, 0.70 logMAR) to be displayed at distance in a single-line sentence format. Testing was conducted in rooms with lights lowered, but light level was not standardized, as testing was conducted on-site at several elementary schools. Stimuli used in each visual task condition are described below.

Near-Threshold Text Reading (THTR). Stimuli were short sentences in a letter size that was approximately 2 logMAR lines above each subject's uncorrected binocular acuity at the viewing distance (40 cm or 2 m). Pilot testing indicated that many subjects were unable to read the sentences if they were presented in the threshold letter size or 1 logMAR size greater than threshold, most likely due to a crowding effect that is generated when letters are presented closer together in word form (compared with spacing on a logMAR chart). Sentences were selected from reading passages in the DIBELS tests of Oral Reading Fluency (DIBELS; University of Oregon, Eugene, OR, USA). Sentences one grade level below each subject's grade were used so that subjects would feel comfortable and confident in performing the reading tasks (THTR and AATR [age-appropriate text reading, described below]). Sentences were presented sequentially in a single line centered on either an iPod (near) or an iPad 3 (distance) display.

Age-Appropriate Text Reading (AATR). Stimuli were identical to the THTR condition except that letter size was considered "age-appropriate." We estimated that approximately 20/100 (0.70 logMAR, 14-point type at near viewing distance)[10] was age-appropriate based on the type size used in two common tests of reading fluency in elementary school children (12 to 16 point; DIBELS and Gray Oral Reading Test, Fourth Edition [GORT-4][11]).

Video Viewing (VV). The stimulus was a video clip of a popular animated film. Size of the video frame was scaled so that the near and distant video subtended the same visual angle.

Procedures

Determination of Uncorrected Acuity at 40 cm and 2 m. Binocular uncorrected acuity was measured at the two test distances at which we obtained measurements of accommodation, 40 cm and 2 m, to ensure that subjects were capable of resolving letters in the age-appropriate font size (20/100) and to determine each subject's threshold acuity for THTR condition in which stimulus letter size was 2 logMAR lines larger than threshold acuity. The 40-cm near Early Treatment Diabetic Retinopathy Study chart (Catalog no. 2103; Precision Vision, LaSalle, IL, USA) and the 2-m distance chart (Catalog no. 2135; Precision Vision) were presented in light-emitting diode illuminator cabinets (Catalog no. 930; Precision Vision, and ESV3000; Goodlite, Elgin, IL, USA). Subjects were asked to begin at the top of each chart and read the first letter of each line. Once a letter was incorrectly identified, the tester instructed the subject to go up two lines on the chart and begin reading all five letters in each line. Threshold acuity was the logMAR value of the smallest line on which they were able to correctly identify at least three of five letters. If a subject was unable to resolve the 20/100 line at 40 cm or 2 m, he or she was excluded from analysis.

Measurement of Accommodation. The Grand Seiko Open Field Binocular Accommodation Auto-refractor/keratometer (WAM-5500) was used to obtain continuous measurements (up to five per second) of right eye refractive error while subjects performed the visual tasks. Output included M_{nc}, pupil size, and time of measurement. The WAM-5500 has been shown to be both reliable and accurate.[12] The instrument was modified to allow subjects to remain in a steady position aligned in the instrument and to speak (read sentences aloud) during measurements while viewing the stimuli placed in front of the instrument. The chin rest of the instrument was lowered so that it was out of the way. Subjects rested their forehead in the forehead rest on the instrument and rested the bridge of their nose on a pair of spectacle frames (with no lenses) that were mounted on the instrument frame below the forehead rest. This allowed two points on the child's face (forehead and bridge of nose) to be in contact with the instrument to steady the head, while still allowing mouth movement. Subjects steadied themselves by holding onto the right and left headrest mounting bars and if necessary an experimenter held the subject's head in place to reduce movement. An adjustable chair was used so that children were comfortable resting their head in the instrument.

In the THTR and AATR conditions, subjects were asked to read a series of sentences aloud for 30 seconds. One experimenter aligned the instrument and initiated the measurements and another experimenter monitored reading and triggered the presentation of a new sentence immediately after the subject read a sentence to ensure that subjects were continuously engaged in the task for the full trial duration. In the VV condition, subjects were instructed to watch an animated video clip. The order of the three task conditions was counterbalanced across subjects with the same order used for the near and distant conditions. Half of the subjects were randomly assigned to complete the near target conditions first and half were randomly assigned to complete the distant target conditions first.

Cycloplegic Refraction. Cycloplegic eye examination and autorefraction were conducted after completion of accommodation measurements or on a separate day to determine magnitude of astigmatism and spherical equivalent refractive error for determination of each subjects' accommodative demand. Cycloplegia was accomplished through use of three drops: proparacaine 0.5%, 1% tropicamide, and 1% cyclopentolate. Cycloplegic autorefraction was conducted with a Retinomax KPlus2 Autorefractor (Nikon, Inc., Tokyo, Japan) at least 30 minutes after administering eye drops. The Retinomax has been shown to provide valid and reproducible measurements in this population.[13] For each subject, a best estimate of refractive error was determined (spherical equivalent, M_c; cylinder, Cyl_c). Typically, this was the sphere determined through subjective refinement and the cylinder power and axis determined by autorefraction.

Data Analysis and Predictions

Data Point Exclusions. Before analysis, erroneous M_{nc} measurements that were likely due to eye blinks or brief lapses in target fixation or were obtained when subjects were not attending to the task, were excluded using the following criteria:

- M_{nc} measurements for which there was no concurrent pupil diameter measurement, or pupil measurement greater than 10 (missing or erroneous pupil size measurement was interpreted as an indicator of poor target fixation);
- M_{nc} measurement less than –10 or greater than +10 (i.e., measurements known to be beyond the range of values for our sample);
- M_{nc} measurements obtained during the first 2 seconds or the last 2 seconds of each 30-second trial interval. This was done to increase the likelihood that the subject was engaged in the required task during data collection, rather than getting comfortable with the instrument at the beginning or losing interest as the trial neared the end;
- M_{nc} measurements that indicated change in accommodation at a rate greater than 10 diopters (D) per second (limit of physiological possibility) for a given stimulus[14]; and
- M_{nc} measurements ± 3.00 SD (z score ≥ 3) from mean for each subject in each distance/task condition. Mean M_{nc} and SD for each subject and condition were calculated after the above data were excluded.

Once data point exclusions were applied to the data, a dataset that included the mean, SD, and n for each subject in each distance/task condition was constructed for analysis.

Exclusion of Subjects. Data from subjects who met the following criteria were excluded from analyses:

- Subjects with myopia greater than 2.5 D in the most myopic meridian per cycloplegic refraction for near condition analyses and myopia greater than 0.50 D in the most myopic meridian per cycloplegic refraction for distant condition analyses (i.e., subjects who were unable to relax accommodation enough to bring stimuli into focus). A series of figures that further explain the rationale for these exclusion criteria are provided in the Supplementary Material;
- Subjects with ocular abnormalities other than high refractive error;
- Subjects with anisometropia (aniso $M_c > 1.50$ or $Cyl_c > 1.00$); and
- Subjects who have no data or have fewer than seven valid data points (as determined above) in any one of the six distance/task conditions.

Data Analysis. For analyses outlined below, subjects were categorized by magnitude of astigmatism (no/low, <1.00 D; moderate, 1.00 to <3.00 D; or high, ≥3.00 D, based on Cyl_c) and by magnitude of accommodative demand. Accommodative demand for each subject at each stimulus distance was the difference between M_c and –2.50 for 40-cm targets and the difference between M_c and –0.50 for distant targets. Subjects were categorized as having low or high accommodative demand based on the median demand for a given test distance in the sample (for near, demand ≤ 2.75 was considered low and >2.75 was considered high; for distant, demand ≤ 1.00 was considered low and >1.00 was considered high).

Dependent variables were mean M_{nc} in each distance/task condition (representing average accommodative state) and mean of the SDs of M_{nc} in each distance/task condition (representing variability in accommodative state). "Accommodative accuracy" was assessed under the assumption that accommodating to the spherical equivalent provides the best quality of stimulus input. Therefore, subjects accurately accommodating to the spherical equivalent focal plane would have a mean M_{nc} of approximately –2.50 for near and –0.50 D for distant stimuli.

Repeated measures ANOVA (RMANOVA) was used to assess the influence of task (repeated measure), astigmatism magnitude, and accommodative demand on mean M_{nc}, with age as a covariate. Separate analyses were conducted for near and distant target data. Post hoc analyses were conducted on significant main effects and interactions. The following were predicted:

1. Accommodative accuracy (M_{nc} of approximately –2.50 for near and –0.50 D for distant stimuli) will improve with increased task demand (indicated by a main effect of task, with accuracy greatest in the THTR condition) because greater accuracy would reduce blur, resulting in improved acuity needed to perform the more visually demanding task; and
2. Accuracy of accommodation will decrease with increasing amounts of astigmatism due to poorer quality visual feedback caused by the persistence of blur (main effect of astigmatism magnitude). This effect will increase with increasing amounts of accommodative demand (interac-

tion between astigmatism magnitude and accommodative demand).

Repeated measures ANOVAs were also used to assess the influence of task demand, astigmatism magnitude, and accommodative demand on mean SD of M_{nc}, with age as a covariate. Analyses were conducted separately for near and distant target data. Post hoc analyses were conducted on significant main effects and interactions. The following were predicted:

1. Accommodative variability will be higher in astigmats, as they vary accommodation to try to bring the object to best focus to perform the visual tasks (main effect of astigmatism magnitude); and
2. Accommodative variability will increase as the task demand increases and as subjects attempt to achieve best focus to perform the visual tasks (main effect of task). This effect will be greater in high astigmats (interaction between task and astigmatism magnitude).

Repeated measures ANOVAs were also conducted on data from subjects who met the criteria for both the near and distant target conditions. These analyses assessed the effects of target distance/change in accommodative demand within subjects (repeated measure) on accommodative accuracy and variability. Before analysis, mean M_{nc} data were adjusted for target distance (2.50 D for near data, 0.50 D for distance data), resulting in a measurement of accommodative error and allowed for comparison across target distance conditions.

Results

The original sample included 579 subjects. Subjects who met one or more of the following criteria were excluded from analyses: spherical equivalent anisometropia (15), astigmatic anisometropia (77), ocular abnormality (13), fewer than seven data points in any condition (170), experimenter error (28), or refusal of cycloplegia (4). For analysis of near-condition data, subjects with myopia greater than 2.50 D in most myopic meridian were excluded (77). For analysis of distant-condition data, subjects with myopia greater than 0.50 D in the most myopic meridian (198) were excluded.

The final sample for near condition analyses included 321 subjects: 166 (52%) female, average age 10.37 years (SD 1.77, 7.14–14.24 years), with M_c ranging from −2.00 to +5.88 D, Cyl_c ranging from 0 to 5.50 D, and accommodative demand ranging from 0.50 to 8.38 D. The final sample for distant condition analyses included 247 subjects: 129 (52%) female, average age 10.30 years (SD 1.74, 7.14–14.14 years), with M_c ranging from −0.50 to +5.88 D, Cyl_c ranging from 0 to 4.25 D, and accommodative demand ranging from 0 to 6.38 D. Table 1 summarizes cycloplegic refractive error, uncorrected acuity, and sample size for each condition. All testing was done without correction. However, for the near-condition sample, 29%, 94%, and 97% of subjects with no/low, moderate, and high astigmatism reported previous or current spectacle wear, with 5%, 23%, and 26% wearing spectacles on arrival on the day of testing. For the distant-condition sample, 24%, 92%, and 93% of subjects with no/low, moderate, and high astigmatism reported previous or current spectacle wear, with 3%, 17%, and 7% wearing spectacles on arrival on the day of testing. No subjects were wearing contact lenses.

Accuracy of Accommodation

Repeated measures ANOVAs were conducted separately for near (Table 2; Fig. 1) and distant conditions (Table 3; Fig. 2).

For near stimuli, there were significant main effects of task ($P < 0.001$, greater accuracy, i.e., mean closer to −2.50 D, in the THTR and AATR conditions than in the VV condition), magnitude of astigmatism ($P = 0.014$, no/low astigmatism group more accurate than high astigmatism group), and amount of accommodative demand ($P < 0.001$, subjects with lower demand more accurate). In addition, there were significant interactions between task and amount of astigmatism ($P < 0.001$) and amount of accommodative demand and amount of astigmatism ($P < 0.001$). In all three astigmatism groups, accuracy was better in the two text-reading conditions (THTR and AATR) than in the VV condition (Fig. 1; Table 2, right columns). However, accommodation in the THTR condition was more accurate than in the AATR condition only in the no/low astigmatism group. In all three astigmatism groups, accuracy was better in subjects with low accommodative demand (Table 2, bottom section), but the difference in accuracy between low- and high-demand subjects increased with increasing astigmatism (difference of 0.15 D, 0.81 D, and 1.56 D in no/low, moderate, and high astigmatism groups, respectively).

For distant stimuli, there were significant main effects of task ($P = 0.001$, better accuracy, i.e., mean closer to −0.50 D, in the THTR and AATR conditions than in the VV condition), amount of astigmatism ($P < 0.001$, all pairwise comparisons significant, with best accuracy in the no/low astigmatism group and poorest accuracy in the high astigmatism group), and amount of accommodative demand ($P < 0.001$, subjects with lower demand more accurate) (Table 3; Fig. 2). In addition, there were significant interactions between task and amount of astigmatism ($P = 0.003$), amount of accommodative demand and amount of astigmatism ($P < 0.001$), and task and amount of accommodative demand ($P < 0.001$). Post hoc analyses indicated that in all three astigmatism groups, accuracy was better in the two text-reading conditions (THTR, AATR) than in the VV condition (Table 3, right columns). However, as astigmatism increased, the difference in accuracy between the text-reading conditions and the VV condition increased. There were no subjects who met the criteria for the high astigmatism and low-demand group. However, in both no/low and moderate astigmatism groups, accuracy was better in subjects with low accommodative demand, but the difference in accuracy between low- and high-demand subjects increased with increasing astigmatism (difference of 0.32 vs. 0.90 D in no/low versus moderate astigmatism groups, respectively) (Table 3, bottom section). Finally, for both the low- and high-demand groups, there were significant differences in M_{nc} for all pairwise comparisons between tasks, with greater differences in accuracy between the text-reading (THTR, AATR) and VV conditions. However, reduced accuracy in the VV condition (compared with text-reading conditions) was greater in the high-demand group than in the low-demand group.

For analyses comparing accuracy across near and distant target locations, we observed a significant interaction between astigmatism magnitude and target distance ($P < 0.001$, see Fig. 3). Subjects with little or no astigmatism and subjects with moderate astigmatism had significantly better accuracy at distance than at near (P values < 0.001). Subjects with high astigmatism did not differ significantly in accuracy across target distance, but on average showed significantly poorer accuracy than subjects with no/low and moderate astigmatism (P values < 0.001). There was also a significant interaction between target distance, task, and astigmatism magnitude ($P = 0.003$). The three-way interaction reflects the finding that the magnitude of the difference in accuracy between astigmatism groups varied by distance/task condition, but accuracy was consistently best in subjects with no/low astigmatism and poorest in subjects with high astigmatism.

Investigative Ophthalmology & Visual Science

Table 1. Summary of Cycloplegic Refractive Error (Spherical Equivalent [M_c] and Astigmatism [Cyl_c]), Uncorrected Acuity, and Sample Size by Target Distance, Astigmatism Magnitude, and Accommodative Demand

Variable	Amount of Astigmatism, D	Low Demand Mean	Low Demand SD	Low Demand *n*	High Demand Mean	High Demand SD	High Demand *n*	Total Mean	Total SD	Total *n*
Near target										
Mean M_c	<1	−0.21	0.51	116	0.98	0.80	93	0.32	0.88	209
	≥1 and <3	−0.45	0.53	41	1.68	0.94	40	0.60	1.31	81
	≥3	−0.36	0.41	10	1.91	1.18	21	1.18	1.46	31
	Total	−0.28	0.52	167	1.29	0.97	154	0.48	1.10	321
Mean Cyl_c	<1	0.31	0.27	116	0.30	0.26	93	0.31	0.26	209
	≥1 and <3	1.64	0.54	41	1.81	0.65	40	1.73	0.60	81
	≥3	3.68	0.71	10	3.70	0.59	21	3.69	0.62	31
	Total	0.84	0.99	167	1.16	1.28	154	0.99	1.15	321
Mean binocular uncorrected acuity at 40 cm, logMAR	<1	0.02	0.15	116	0.02	0.15	93	0.02	0.15	209
	≥1 and <3	0.17	0.13	41	0.16	0.14	40	0.16	0.14	81
	≥3	0.28	0.06	10	0.32	0.11	21	0.31	0.10	31
	Total	0.07	0.17	167	0.10	0.18	154	0.08	0.17	321
Distant target										
Mean M_c	<1	0.10	0.26	116	1.17	0.86	69	0.50	0.76	185
	≥1 and <3	0.27	0.23	14	1.89	0.87	34	1.42	1.05	48
	≥3	—	—	0	2.55	0.87	14	2.55	0.87	14
	Total	0.12	0.26	130	1.54	0.99	117	0.79	1.00	247
Mean Cyl_c	<1	0.27	0.25	116	0.32	0.27	69	0.29	0.26	185
	≥1 and <3	1.18	0.32	14	1.91	0.64	34	1.70	0.65	48
	≥3	—	—	0	3.57	0.44	14	3.57	0.44	14
	Total	0.37	0.38	130	1.17	1.21	117	0.75	0.96	247
Mean binocular uncorrected acuity at 2 m, logMAR	<1	−0.05	0.11	116	−0.02	0.13	69	−0.04	0.12	185
	≥1 and <3	0.09	0.16	14	0.18	0.14	34	0.15	0.15	48
	≥3	—	—	0	0.34	0.06	14	0.34	0.06	14
	Total	−0.03	0.13	130	0.08	0.18	117	0.02	0.16	247

—, no data.

Variability of Accommodation

Repeated measures ANOVAs were conducted separately for near (Table 4; Fig. 4) and distant conditions (Table 5; Fig. 5) with SDs of M_{nc} as the dependent variable.

For near stimuli, there was a significant main effect of amount of astigmatism ($P = 0.001$, no/low astigmatism group significantly less variable than moderate and high astigmatism groups). In addition, there were significant interactions between task and amount of astigmatism ($P = 0.006$) and task

Table 2. Mean M_{nc} by Task, Astigmatism Magnitude, and Magnitude of Accommodative Demand for Near Stimuli

Near Task	Amount of Astigmatism, D	Low (≤2.75 D) Mean	Low (≤2.75 D) SD	Low (≤2.75 D) *n*	High (>2.75 D) Mean	High (>2.75 D) SD	High (>2.75 D) *n*	Total Mean	Total SD	Total *n*
THTR	<1	−2.11	0.22	116	−2.01	0.30	93	−2.07	0.26	209
	≥1 and <3	−2.35	0.52	41	−1.58	0.64	40	−1.97	0.70	81
	≥3	−2.74	0.90	10	−1.11	1.05	21	−1.64	1.25	31
	Total	−2.21	0.41	167	−1.77	0.64	154	−2.00	0.57	321
AATR	<1	−2.07	0.26	116	−1.95	0.34	93	−2.02	0.30	209
	≥1 and <3	−2.31	0.44	41	−1.56	0.63	40	−1.94	0.66	81
	≥3	−2.78	0.73	10	−1.24	1.10	21	−1.74	1.22	31
	Total	−2.17	0.40	167	−1.76	0.63	154	−1.97	0.56	321
VV	<1	−1.77	0.53	116	−1.56	0.54	93	−1.67	0.54	209
	≥1 and <3	−1.78	0.52	41	−0.85	0.97	40	−1.32	0.90	81
	≥3	−2.07	0.73	10	−0.55	0.95	21	−1.04	1.13	31
	Total	−1.79	0.54	167	−1.24	0.84	154	−1.52	0.75	321
Total	<1	−1.98	0.28	116	−1.84	0.36	93	−1.92	0.33	209
	≥1 and <3	−2.15	0.45	41	−1.33	0.71	40	−1.75	0.72	81
	≥3	−2.53	0.76	10	−0.97	1.00	21	−1.47	1.18	31
	Total	−2.06	0.39	167	−1.59	0.67	154	−1.83	0.59	321

Mean value of −2.50 would indicate accurate accommodation to the spherical equivalent plane.

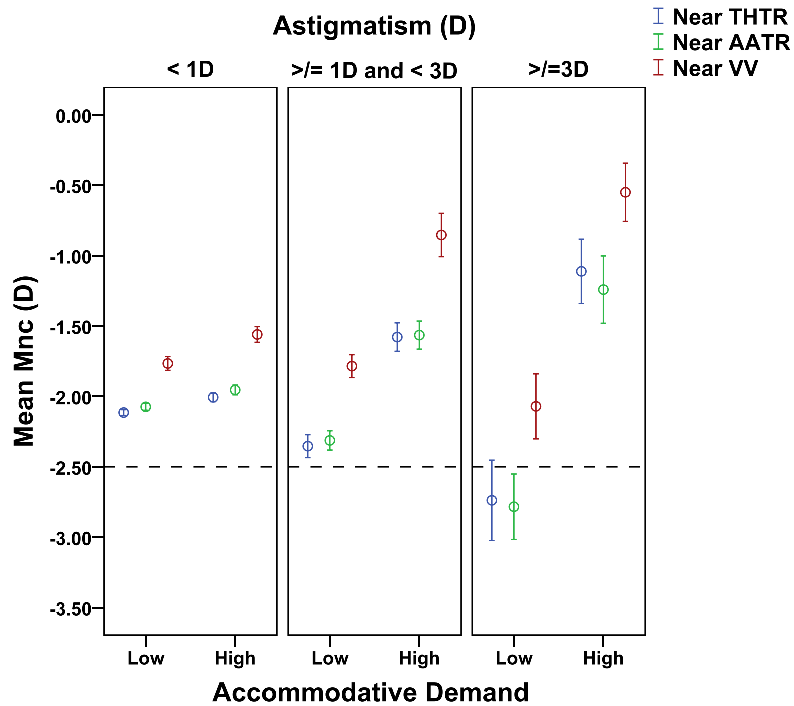

Figure 1. Mean M_{nc} by task, astigmatism magnitude, and magnitude of accommodative demand for near stimuli. Mean value of −2.50 (*dashed line*) would indicate accommodation to the spherical equivalent plane. Accommodative demand less than or equal to 2.75 was considered low and greater than 2.75 was considered high. *Error bars* are ± 1 SE.

and amount of accommodative demand ($P = 0.002$). Variability was higher in the VV task than for the text-reading tasks (THTR, AATR) in no/low and moderate astigmatism groups only (Table 4, right columns). Variability was higher in the VV condition than in the text-reading conditions in subjects with high accommodative demand. There were no differences in variability across tasks in the low-demand group.

For distant stimuli, there was a significant main effect of amount of astigmatism ($P = 0.02$) with the no/low astigmatism group showing significantly less variability than the moderate astigmatism group. There were no statistically significant interactions.

For analyses comparing variability across near- and distant-target conditions, there was no significant interaction between magnitude of astigmatism and target distance/accommodative demand. There was a significant interaction between target distance, task, and astigmatism magnitude ($P = 0.018$). Post hoc analyses indicated that there was lower variability in the no/low astigmatism group compared with the moderate astigmatism group only for the VV task ($P = 0.019$) and THTR task ($P =$

Table 3. Mean M_{nc} by Task, Astigmatism Magnitude, and Magnitude of Accommodative Demand for Distant Stimuli

		Distant Demand								
		Low (≤1.00 D)			High (>1.00 D)			Total		
Distant Task	Amount of Astigmatism, D	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*
THTR	<1	−0.49	0.20	116	−0.26	0.38	69	−0.40	0.30	185
	≥1 and <3	−0.49	0.27	14	0.27	0.64	34	0.05	0.65	48
	≥3	—	—	—	1.36	0.55	14	1.36	0.55	14
	Total	−0.49	0.21	130	0.09	0.71	117	−0.22	0.59	247
AATR	<1	−0.55	0.23	116	−0.21	0.47	69	−0.42	0.38	185
	≥1 and <3	−0.49	0.33	14	0.34	0.68	34	0.10	0.71	48
	≥3	—	—	—	1.29	0.63	14	1.29	0.63	14
	Total	−0.54	0.24	130	0.13	0.74	117	−0.22	0.63	247
VV	<1	−0.25	0.37	116	0.16	0.53	69	−0.09	0.48	185
	≥1 and <3	−0.18	0.36	14	0.93	0.80	34	0.60	0.86	48
	≥3	—	—	—	2.00	0.91	14	2.00	0.91	14
	Total	−0.24	0.37	130	0.60	0.91	117	0.16	0.80	247
Total	<1	−0.43	0.24	116	−0.10	0.44	69	−0.30	0.36	185
	≥1 and <3	−0.39	0.31	14	0.51	0.67	34	0.25	0.72	48
	≥3	—	—	—	1.55	0.64	14	1.55	0.64	14
	Total	−0.42	0.24	130	0.28	0.76	117	−0.09	0.65	247

Mean value of −0.50 would indicate accurate accommodation to the spherical equivalent plane.

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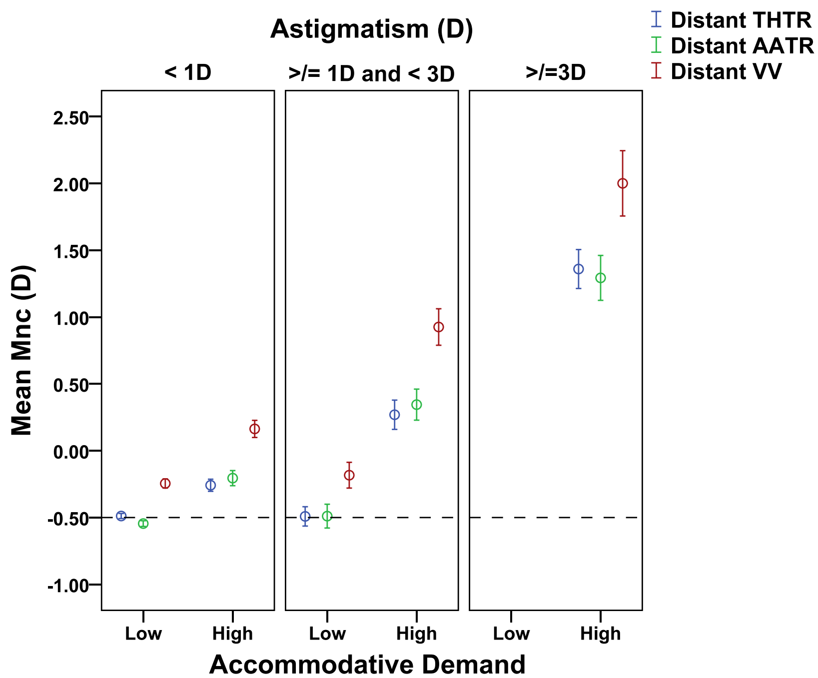

FIGURE 2. Mean M_{nc} by task, astigmatism magnitude, and magnitude of accommodative demand for distant stimuli. Mean value of –0.50 (*dashed line*) would indicate accommodation to the spherical equivalent plane. Accommodative demand less than or equal to 1.00 was considered low and greater than 1.00 was considered high. *Error bars* are ± 1 SE.

0.026) at near, and for the AATR ($P = 0.001$) and THTR task ($P = 0.010$) at distance.

DISCUSSION

Few studies have examined accommodative strategies in uncorrected astigmats (Harvey EM, et al. *IOVS* 2003;44:E-Abstract 2727).[2–4] The present study assessed the influence of astigmatism as well as other key variables (task demand, accommodative demand) on accommodation in a large sample of children, many of whom have visually significant astigmatism.

Results indicated that children tend to underaccommodate relative to the circle of least confusion, but the extent of this underaccommodation is dependent on several factors. The high astigmatism group showed poorest accuracy (greatest amount of underaccommodation) compared with subjects with no/low or moderate astigmatism. This indicates that, on average, children with high astigmatism tend to focus toward the anterior focal plane. Greater accommodative accuracy was

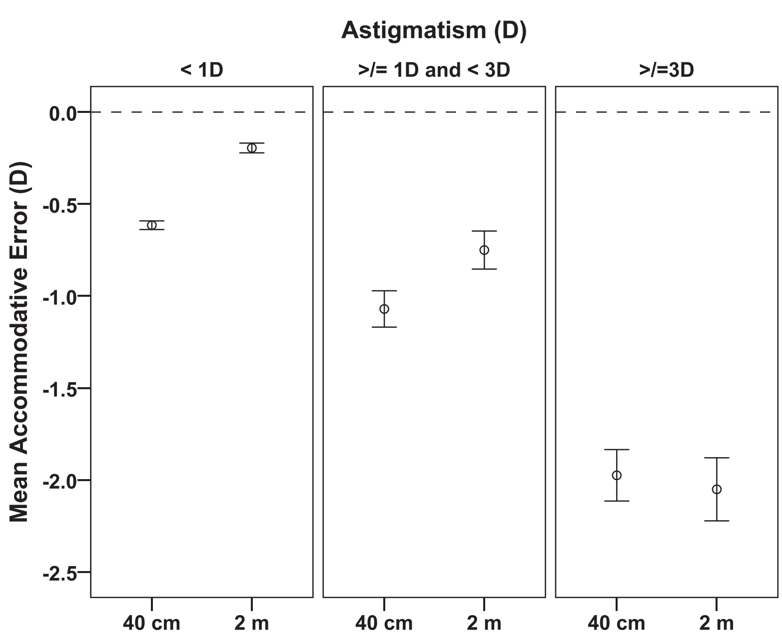

FIGURE 3. Mean accommodative error by astigmatism magnitude and target distance. *Error bars* are ± 1 SE. Accommodative error was determined by adjusting M_{nc} data for target distance (2.50 D for near data, 0.50 D for distance data) to allow for comparison across target distance conditions.

Table 4. Mean of SDs of M_{nc} by Task, Astigmatism Magnitude, and Magnitude of Accommodative Demand for Near Stimuli

		Near Demand								
		Low (≤1.00 D)			High (>1.00 D)			Total		
Near Task	Amount of Astigmatism, D	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*
THTR	<1	0.25	0.23	116	0.27	0.23	93	0.26	0.23	209
	≥1 and <3	0.34	0.30	41	0.37	0.29	40	0.35	0.29	81
	≥3	0.40	0.28	10	0.39	0.31	21	0.39	0.30	31
	Total	0.28	0.25	167	0.31	0.27	154	0.30	0.26	321
AATR	<1	0.28	0.20	116	0.31	0.25	93	0.30	0.23	209
	≥1 and <3	0.31	0.26	41	0.32	0.17	40	0.31	0.22	81
	≥3	0.59	0.46	10	0.39	0.25	21	0.46	0.34	31
	Total	0.31	0.25	167	0.33	0.23	154	0.32	0.24	321
VV	<1	0.32	0.23	116	0.38	0.26	93	0.35	0.25	209
	≥1 and <3	0.33	0.18	41	0.50	0.24	40	0.41	0.23	81
	≥3	0.39	0.13	10	0.44	0.27	21	0.42	0.23	31
	Total	0.33	0.21	167	0.42	0.26	154	0.37	0.24	321
Total	<1	0.29	0.17	116	0.32	0.19	93	0.30	0.18	209
	≥1 and <3	0.33	0.21	41	0.40	0.18	40	0.36	0.20	81
	≥3	0.46	0.23	10	0.41	0.24	21	0.42	0.23	31
	Total	0.31	0.19	167	0.35	0.20	154	0.33	0.19	321

also associated with higher task demand and lower accommodative demand (due to presence of myopia or low hyperopia). There were also interactions between these factors. In all three astigmatism groups, accuracy was better in subjects with low accommodative demand, but the effect of demand increased with increasing astigmatism (see Fig. 1, the difference in accuracy between low- and high-demand groups was greatest in the high astigmatism group and lowest in the no/low astigmatism group). Accuracy was also better in the more visually demanding reading-task conditions (THTR, AATR) than in the video-viewing condition. However, the most visually demanding THTR task only elicited significantly better accuracy than the AATR task at near and only in subjects with no/low astigmatism. This may be because there was often little difference between the two reading conditions (THTR, AATR) for subjects with high astigmatism because the near-threshold letter acuity used to determine the letter size displayed in the THTR task was close to the 20/100 letter size used in the AATR task, whereas subjects with no/low astigmatism generally had threshold letter acuity near 20/20.

When comparing across target distance (Fig. 3), we found that moderate and high astigmats did not differ significantly in accuracy across target distance, indicating that within individual subjects, changes in accommodative demand due to changes in target distance did not influence accuracy of accommodation in astigmatic children. However, as noted

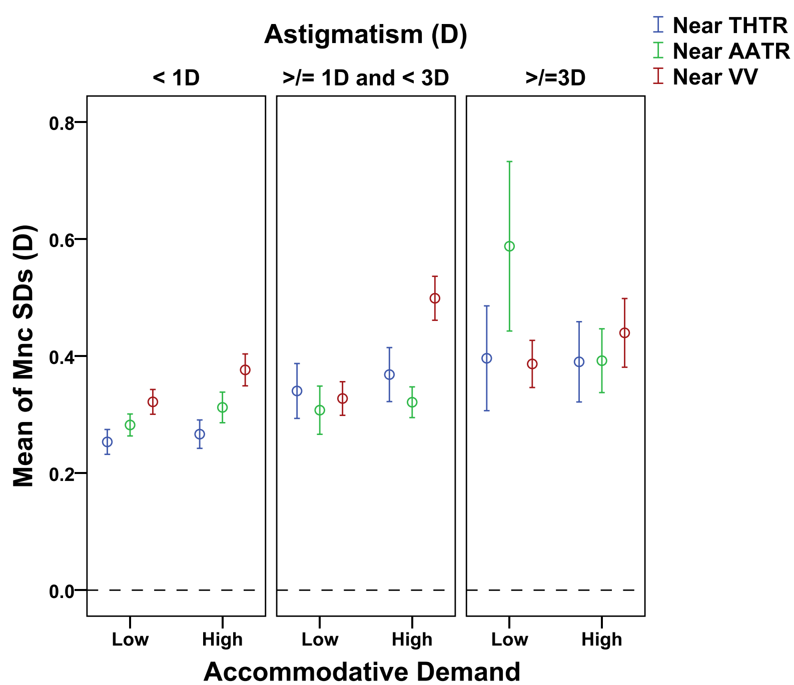

Figure 4. Mean of SDs of M_{nc} by task, astigmatism magnitude, and magnitude of accommodative demand (≤2.75 was considered low) for near stimuli. *Error bars* are ± 1 SE.

Table 5. Mean of SDs of M_{nc} by Task, Astigmatism Magnitude, and Magnitude of Accommodative Demand for Distant Stimuli

		Distant Demand								
		Low (≤2.75 D)			High (>2.75 D)			Total		
Distant Task	Amount of Astigmatism, D	Mean of SDs	SD	*n*	Mean of SDs	SD	*n*	Mean of SDs	SD	*n*
THTR	<1	0.19	0.16	116	0.19	0.10	69	0.19	0.14	185
	≥1 and <3	0.28	0.19	14	0.24	0.11	34	0.25	0.14	48
	≥3	—	—	0	0.24	0.14	14	0.24	0.14	14
	Total	0.19	0.17	130	0.21	0.11	117	0.20	0.14	247
AATR	<1	0.22	0.17	116	0.25	0.17	69	0.23	0.17	185
	≥1 and <3	0.32	0.32	14	0.38	0.43	34	0.36	0.40	48
	≥3	—	—	0	0.29	0.15	14	0.29	0.15	14
	Total	0.23	0.19	130	0.29	0.28	117	0.26	0.24	247
VV	<1	0.26	0.32	116	0.29	0.17	69	0.27	0.27	185
	≥1 and <3	0.32	0.28	14	0.35	0.15	34	0.34	0.19	48
	≥3	—	—	0	0.32	0.17	14	0.32	0.17	14
	Total	0.26	0.32	130	0.31	0.16	117	0.28	0.26	247
Total	<1	0.22	0.17	116	0.24	0.12	69	0.23	0.16	185
	≥1 and <3	0.31	0.20	14	0.32	0.17	34	0.32	0.18	48
	≥3	—	—	0	0.28	0.13	14	0.28	0.13	14
	Total	0.23	0.18	130	0.27	0.14	117	0.25	0.16	247

previously, subjects with greater accommodative demand due to high hyperopia showed poorer accommodative accuracy than subjects with lower accommodative demand due to low amounts of hyperopia or myopia (Fig. 1). Taken together, these results suggest that poorer accuracy is not necessarily dependent on the amount of accommodation required for a given task, but rather that astigmatic subjects with higher amounts of hyperopia who are required to make more of an accommodative effort in general tend to have poorer accuracy.

Subjects with higher amounts of astigmatism tend to demonstrate greater fluctuation in accommodation during task performance for both distant and near stimuli. Variability in high astigmats was uniformly high across task conditions. In no/low and moderate astigmatism groups, variability was lower in the text-reading tasks (THTR, AATR) than in the VV task at near (Table 4). This pattern suggests that at near, subjects show less variability in accommodation while performing tasks that require better focus (reading), but with high amounts of astigmatism, this strategy breaks down, perhaps due to the generally poor quality of visual feedback due to blur. Task demand also interacted with accommodative demand. At near, variability was higher in the VV condition than in the text-reading conditions (THTR, AATR) in subjects with high accommodative demand. There were no differences in mean variability across tasks in the low-demand group, and amount of variability was similar to that seen in the text-reading

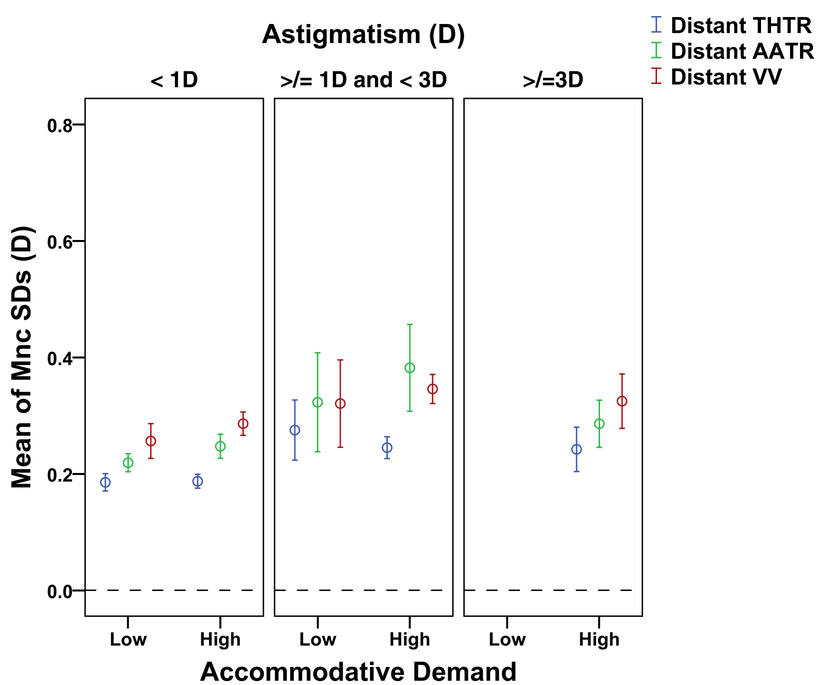

Figure 5. Mean of SDs of M_{nc} by task, astigmatism magnitude, and magnitude of accommodative demand (≤1.00 was considered low) for distant stimuli. *Error bars* are ± 1 SE.

conditions (THTR, AATR) in the high-demand group. The high variability in accommodation in the VV condition may result from changes in the level of detail contained in the video or level of attention to the video over time. However, because we did not correlate accommodative response with individual segments of the video, we cannot test this hypothesis.

This experiment provides a novel analysis of accommodation in children during visual task performance. However, the study has some limitations. First, the study population is unique in terms of their high prevalence of with-the-rule astigmatism, and therefore it is not clear to what extent these findings can be generalized to other populations. However, it is likely that with-the-rule astigmats, regardless of race or ethnicity, would use similar strategies to compensate for their uncorrected astigmatism. Second, sample sizes across astigmatism and accommodative demand conditions were unequal, and no subjects met the criteria for the high astigmatism/low accommodative demand group. This limited the statistical power to assess effects in some groups. Third, the altered WAM-5500 experimental setup (use of spectacle frame rather than chin rest to stabilize the subject's head) may have influenced accuracy or reliability of measurements, although data were carefully reviewed to eliminate erroneous measurements due to misalignment or movement. If there were any effects on measurements, it is not likely that the effects varied across experimental condition, and therefore it is not likely that the overall results would be influenced. Fourth, different autorefractors were used to obtain accommodation measurements and measurements of cycloplegic refractive error. The Retinomax instrument was used to determine cycloplegic refractive error because these refraction data were also used as part of a long-term study of this population in which the Retinomax is used as the gold-standard measurement of refractive error. However, studies comparing the Retinomax to the Grand Seiko WR5100K autorefractor (which is essentially the same as the WAM-5500 when used in static measurement mode per the manufacturer; AIT Industries, Bensenville, IL, USA) found good agreement between the two instruments in cycloplegic measurement of spherical equivalent and astigmatism (Clifford CE, et al. *IOVS* 2003;44:ARVO E-Abstract 2793).[15] Fifth, in high astigmats, the stimulus letter size that was used for the THTR (size based on uncorrected acuity) and AATR (20/100 letters) tasks was similar or identical for many subjects and therefore comparisons between the two conditions in high astigmats adds little additional information. A final limitation of the study is that magnitude of accommodative demand was not systematically manipulated across subjects (i.e., for each subject, test distance was not manipulated to achieve specific levels of accommodative demand based on their M_c). As a result of this design, accommodative demand was confounded with spherical equivalent refractive error. Our experimental design included target distances that represented common stimulus distances for reading and for viewing at distance. This design was purposefully chosen because the aim of the experiment was to determine how astigmatic subjects perform under conditions that best resemble everyday viewing and visual task performance. As a result, our data provide insight into the everyday visual experience of uncorrected astigmats. In subsequent analyses, we will assess the relation between the blur that subjects experience during visual task performance and their best-corrected grating acuity to determine the relation between accommodative strategies and risk for amblyopia.

In conclusion, the findings presented here add to our understanding of the factors that influence accommodative patterns in children. The results of the present study have important implications for prescribing recommendations and risk for development of amblyopia in children with astigmatism. Our findings suggest that the child's visual needs (task demands) as well as their spherical equivalent refractive error (accommodative demand) significantly influence their ability to accommodate accurately in the absence of correction. Previous studies on this population have found evidence of meridional amblyopia in myopic/mixed astigmats. In contrast, on average, hyperopic astigmats did not show meridional amblyopia, but did show equally reduced best-corrected acuity (amblyopia) across stimulus orientation.[16,17] One possible explanation for the absence of meridional amblyopia in hyperopic astigmats is that some may accommodate to the circle of least confusion/spherical equivalent when uncorrected, thus experiencing equivalent blur for anterior and posterior focal planes. From the results of the present study, we would predict that meridional amblyopia may be more likely to develop in astigmats with high accommodative demand/more hyperopia who tend to underaccommodate (accommodate closer to the anterior focal plane) and less likely to develop in astigmats with low accommodative demand/less hyperopia who tend to accommodate close to the circle of least confusion/spherical equivalent) (Fig. 1). In further investigations, we will test these predictions by examining the relation between the meridional blur that children experience during visual task performance when uncorrected and their best-corrected grating acuity for horizontal and vertical stimuli.

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