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Blur Detection, Depth-of-Field, and Accommodation in Emmetropic and Hyperopic Children

Tawna L. Roberts, OD, PhD, FAAO, Scott B. Stevenson, PhD, Julia S. Benoit, PhD, Ruth E. Manny, OD, PhD, FAAO, and Heather A. Anderson, OD, PhD, FAAO

Department of Ophthalmology, Children's Hospital Medical Center of Akron, Akron, Ohio (TLR), University of Houston College of Optometry, Houston, Texas (SBS, JSB, REM, HAA), and Texas Institute for Measurement, Evaluation, and Statistics, Houston, Texas (JSB)

Abstract

Significance—Our results demonstrate that blur detection thresholds are elevated in young children compared to adults and poorer blur detection thresholds are significantly correlated with the magnitude of accommodative microfluctuations. Given that accommodative microfluctuations are greater with greater accommodative responses, these findings may have implications for young uncorrected hyperopes.

Purpose—This study investigated the association between subjective blur detection thresholds and accommodative microfluctuations in children 3 to <10 years and adults.

Methods—Blur detection thresholds were determined in 49 children with habitually uncorrected refractive error (+0.06 to +4.91D spherical equivalent) and 10 habitually uncorrected adults (+0.08 to +1.51D spherical equivalent) using a custom blur chart with 1° sized optotypes at 33cm. Letters were blurred by convolution using a Gaussian kernel (standard deviations of 0.71–11.31 arc minutes in 2 steps). Subjective depth-of-field was determined in subjects 6 years and adults. Accommodative microfluctuations, pupils and lag were measured using infrared photorefracton (25Hz).

Results—Children had greater blur detection thresholds ($p<0.001$), accommodative microfluctuations ($p=0.001$) and depth-of-field ($p<0.001$) than adults. In children, increased blur detection thresholds were associated with increased accommodative microfluctuations ($p<0.001$), increased uncorrected hyperopia ($p=0.006$), decreased age ($p<0.001$) and decreased pupil size ($p=0.01$). In a multiple linear regression analysis, blur detection thresholds were associated with accommodative microfluctuations ($p<0.001$) and age ($p<0.001$). Increased accommodative microfluctuations were associated with increased uncorrected hyperopia ($p=0.004$) and decreased pupil size ($p=0.003$) and independently associated with uncorrected hyperopia ($p=0.001$) and pupil size ($p=0.003$) when controlling for age and lag.

Conclusions—Children did not have adult-like blur detection thresholds or depth-of-field. Increased accommodative microfluctuations and decreased age are independently associated with greater blur detection thresholds in children 3 to <10 years. Larger amounts of uncorrected

hyperopia in children appear to increase blur detection thresholds because the greater accommodative demand and resulting response increase accommodative microfluctuations.

Keywords

accommodation; blur detection; hyperopia; children; depth-of-field

Blur is processed by the afferent pathway of the visual system,¹ which signals the efferent pathway to produce a change in accommodation to bring the target of regard into focus.² Once in focus, accommodation is considered to be in steady-state, however, the response oscillates at a frequency < 3 Hz,^{3, 4} known as accommodative microfluctuations.³

Accommodative microfluctuations have been studied in the context of the depth-of-focus (retinal space) and depth-of-field (object space) in adults,⁵⁻⁷ which refers to the range over which object vergence can change without being detected as blur on the retina (objective depth-of-focus),^{7, 8} or a perceived change in observed object clarity (subjective depth-of-focus).^{6, 7, 9} Accommodative microfluctuations and depth-of-field are affected similarly by factors such as luminance,^{3, 10} pupil size,^{3, 11} and spatial frequency.³ It has also been shown that as depth-of-field and accommodative microfluctuations decrease the accommodative response is more accurate, and as depth-of-field and accommodative microfluctuations increase the accommodative response is less accurate.^{7, 12}

It has been suggested that accommodative microfluctuations act as a sub-threshold blur detector in the accommodative control system (i.e.: objective depth-of-focus),^{6, 7} thus allowing the accommodative response to make appropriate adjustments without an individual perceiving blur. However, if the change in object vergence reaches the edge of the depth-of-focus without a correction by the accommodative control system, the individual detects perceptual blur (i.e. subjective depth-of-focus). While the relationship between accommodative microfluctuations and objective depth-of-focus (i.e.: accommodative control system) has previously been studied,^{6, 7} it is not clear how accommodative microfluctuations affect subjective depth-of-focus (i.e.: perceptual blur).

Accommodative microfluctuations and blur detection have been studied extensively in adults,^{1, 3} yet only a few studies have investigated these in children.¹³⁻¹⁶ The magnitude of accommodative microfluctuations decrease with increasing age from infancy to adulthood^{13, 14} and increase with increasing accommodative response magnitude.^{7, 13, 14} Neither accommodative microfluctuations nor blur detection have been investigated specifically in children with varying amounts of uncorrected hyperopia. These children are of interest because as the accommodative demand increases with the amount of uncorrected hyperopia, larger accommodative microfluctuations may occur in relation to an increased accommodative response. Additionally, increased accommodative lag may occur due to an increased depth-of-focus which is associated with an increase in accommodative effort.^{7, 17}

If accommodative microfluctuations are operating as a sub-threshold blur detector and the magnitude of the accommodative microfluctuations is larger in individuals with higher amounts of uncorrected hyperopia, one would predict these children to have larger objective depths-of-field in terms of the accommodative control system. Increased accommodative

microfluctuations and increased objective depths-of-field may also result in increased subjective depths-of-field and poorer subjective blur detection thresholds. Thus, the purpose of this study was to determine if subjective blur detection thresholds are associated with the magnitude of accommodative microfluctuations in children 3 to <10 years with variable amounts of uncorrected hyperopia and accommodative lags. Given that blur detection thresholds are hypothesized to be significantly associated with accommodative microfluctuations, a secondary purpose of the study was to determine which variables may be related to accommodative microfluctuations, with a particular interest in the magnitude of uncorrected hyperopia. Data were also collected on adults to serve as comparison to a mature visual system.

METHODS

Study Subjects

Children 3 to <10 years and non-presbyopic adults were recruited from the University of Houston College of Optometry staff, student, and patient populations, and the local community. The study followed the tenets of the Declaration of Helsinki and was approved by the University's Committee for the Protection of Human Subjects. All subjects 18 years provided written informed consent and subjects <18 years provided assent while their parents provided written parental permission to participate in the study.

Subjects were screened for the presence of exclusion criteria: <32 weeks' gestation, birth weight of <2500 grams, history of ocular or systemic diagnoses that may affect accommodation, taking medications known to affect accommodation, history of developmental delays or behavioral diagnoses, current or previous refractive error correction, or known cycloplegic refractive error -0.50 diopters (D) spherical equivalent, anisometropia >1.00 D spherical equivalent or astigmatism >1.25 D cylinder.

All consented subjects also had a complete vision examination which included monocular visual acuity (electronic HOTV¹⁸ for subjects <8 years and ETDRS¹⁹ for subjects 8 years) presented on the M&S SmartSystem (M&S Technologies, Inc. Niles, IL). Subjects were excluded from data analysis if they did not have typical visual acuity for their age,²⁰ or were diagnosed with strabismus or amblyopia (visual acuity >2 lines intraocular difference with an amblyogenic risk factor).²¹ Three measures of cycloplegic refractive error were obtained on each eye using the Grand Seiko WAM-5500 auto-refractor (RyuSyō Industrial Co., Ltd. Hiroshima, Japan) 30 minutes after instillation of 1% cyclopentolate. The measures were transformed into spherical equivalent and averaged for each eye.

Blur Detection Experiment

Blur detection thresholds were investigated using a five-alternative forced choice method at 33cm. Custom blur charts were created with shape or Sloan letter²² optotypes using Matlab (The MathWorks Inc. Natick, MA), which applied unit area Gaussian kernels (standard deviations ranging from 0.71 arc minutes (') to 11.31' in 2 steps) to create 9 levels of blur.¹ All optotypes were 1° in size, which is sufficient to provoke an accommodative response.^{23, 24} Each row of the chart had one optotype with no added blur and four optotypes equally

blurred by one of the blur levels as seen in Figure 1. A wide span of blur levels were chosen to ensure we reached the ceiling effect in the children, as blur detection has never been done in children as young as 3 years of age. Additionally, the wide span of blur levels provided quality control and data validation as having easy and redundant levels allowed us to be confident that the subjects who participated in the task understood the task.

The rows of the blur charts were displayed on the iPad Air® (Apple Inc. Cupertino, CA, 2048×1536 pixels) using Keynote® (Apple Inc., Cupertino, CA). The investigator controlled the stimuli using an iPhone® (Apple Inc. Cupertino, CA). The iPad Air® was placed above a beam-splitter, with an optical target vergence of 33cm while refractive error and pupil size were measured in primary gaze throughout the experiment using infrared photorefractometry. Through the beam-splitter, the blurred optotypes had Weber contrasts of 60% with a background luminance of 5.9cd/m² (Contrast: Level 9=60%, 8=69%, 7=98%, 6=99%, 5 to 1=99.7%), while the clear optotypes had 99.7% contrast. The stimulus apparatus and photorefractor were covered using a curtain and the room lights were dimmed. The subjects were positioned in a headrest throughout the experiments to limit head movements.

Prior to testing, children 6 years were administered The San Diego Quick Assessment²⁵ test to estimate each child's reading level. Children unable to correctly read aloud 9/10 words at the pre-primer level viewed the shapes instead of the Sloan letters. All children <6 years were also shown the shapes.

Subjects viewed the optotypes uncorrected and binocularly in order to characterize their habitual viewing status. Subjects were instructed to tell the investigator which optotype in the row was the clearest. For the youngest children, the question "which one is not fuzzy?" was also asked. Children who viewed the shapes had a pre-test training session to ensure they understood the task of choosing the clearest shape. Of the adult subjects, 9/10 were optometry students but none had prior training in this blur detection task.

The shapes were presented one row at a time. The lowest three blur levels (0.71', 1.00', and 1.41' Gaussian standard deviation) were presented three times each to minimize frustration for the youngest children as they approached the threshold for the shape stimuli while the rest of the blur levels were presented four times. For the older participants, three rows of blur levels were displayed at one time and each blur level was presented to the subject five times. For both sets of stimuli, the subjects viewed the blur lines in order from easiest to most difficult without a time limit. Blur detection thresholds were determined using Probit analysis²⁶ with the threshold defined as 60% correct.

Subjective Depth-of-field Experiment

Subjects 6 years also participated in the subjective depth-of-field experiment. Subjects monocularly viewed either two capital letter X's placed horizontally or three capital letter Y's placed vertically and etched onto a clear piece of glass with a laser. Each letter subtended 0.21° at 33cm and was spaced 0.21° apart from one another so that if the two glass plates were on top of each other, the X's and Y's formed a cross subtending 1.4°×1.4°. The letters were displayed using an optical bench in front of the right eye while the left eye was occluded using a Kodak 89B Wratten gelatin filter. A blank, white slide (5.9cd/m²) was

displayed on the iPad Air® at 90cm in front of the subject through a beam-splitter to provide high contrast between the black fixation letters and the screen. The room lights were dimmed and the subjects were positioned in a headrest.

Both the proximal and distal edges of the subjective depth-of-field were measured in a counter balanced order across subjects with a natural pupil and accommodation. For the distal edge of the subjective depth-of-field, the subject viewed the vertical “Y’s” while the investigator placed the row of the three horizontal X’s far enough from the subject such that, while maintaining focus on the “Y’s”, the subject reported the X’s were blurred. The subjects were instructed to keep the “Y’s” clear at all times but to *notice* when the “X’s” became “clear just like the “Y’s.” The investigator moved the “X’s” toward the “Y’s” at a rate of ~0.5 cm/second. The distance at which the subject reported the “X’s” were clear like the “Y’s” was recorded as the distal edge of the subjective depth-of-field. A similar testing procedure was employed for the proximal limiting condition, except that subjects viewed the “X’s” at 33cm and were instructed to keep them clear at all times while the “Y’s” were initially placed near the subject then moved away from the subject towards the “X’s” until the subject reported the “Y’s” were clear like the “X’s.” The procedure was repeated 5 times for each edge of the depth-of-field. Each subject performed practice trials to confirm comprehension of the task.

Measures of Refractive Error, Eye Alignment and Pupil Size

Infrared photorefractometry was used to measure changes in refractive error, eye alignment and pupil size in both eyes simultaneously at a sampling rate of 25Hz during the blur detection experiment and in the right eye during the depth-of-field experiment using the PowerRef II (Plusoptix Inc., Atlanta, GA). The method of infrared photorefractometry has been described in detail elsewhere.^{27, 28} Each individual underwent a trial lens calibration (plano to +4D in 1D steps) for each eye.^{27, 29} In brief, the eye being calibrated was occluded with a Kodak 89B Wratten gelatin filter. The fellow eye fixated a distance letter that subtended 0.21° at 16.5 feet. The difference between refractive measures of each eye (anisometropia) was regressed on the trial lens power and the slope of the regression used to calibrate the refractive error output from the PowerRef II obtained during experimental testing.

Photorefractometry data were filtered offline to eliminate outlying data points that are known to be outside of the working range of the PowerRef II or points that are unlikely to be physiological. Measures of refractive error were removed if the change in focus between two data points was >10D/second,³⁰ refractive error measures were <-6.00D or >+4.00D,³¹ gaze position was outside ±10° horizontally or ±5° vertically,³² and pupil size was <4mm or >8mm.³¹

The task required participants to scan across the width of the screen, and subsequent analysis revealed differences in refraction measures with gaze angle³³ (Figure 2a). There was a piecewise linear relationship between horizontal eye position and the refractive error measures obtained by the Power Ref II. The junction of the two slopes were at approximately 0° for both the right and left eyes for all subjects. As seen in Figure 2a, as the subject looks in nasal gaze with the right eye, there is a linear increase in the measure of myopia. The amount of myopic shift seen in the graph is approximately 1.5D, which is on

the high end of what was observed across all subjects, and thus the most extreme example is shown in the Figure. The erroneous myopic shift was corrected by subtracting the average error for each gaze angle (-0° or $>0^\circ$) based on a regression fit to the refractive error measures obtained by the PowerRef II versus eye position for each subject. The effect of the correction factor for a representative subject is shown in Figure 2.

Data Analysis

Refractive error data were binned every 10 seconds to minimize the chance of analyzing accommodative drifts throughout the experiment. Mean accommodative microfluctuations were defined as the square root of the average bin variance. Lag was calculated as the mean difference between the average refractive error during the experiment and the accommodative demand of 3D. The subjective depth-of-field for each subject was calculated as the difference in dioptric space between the mean measures of the distal and proximal edges of the subjective depth-of-field.

The measures of the most plus eye were used for all comparisons concerning accommodative measures from the blur detection task as that eye has the largest accommodative demand.³⁴ For most subjects, the laboratory visit was completed prior to the eye examination and thus the subjective depth-of-field experiment was conducted on the right eye of all subjects. Consequently, analyses involving the subjective depth-of-field experiment (depth-of-field and pupil size) are from the right eye.

Two-sample t-tests and multiple linear regression were used to compare spherical equivalent, blur detection thresholds, accommodative microfluctuations, depth-of-field and pupil size between children and adults. The remainder of the analyses pertain to the children. Due to the hypothesis that subjective blur detection thresholds may be associated with increased accommodative microfluctuations we investigated the associations between blur detection thresholds and accommodative microfluctuations as well as other confounding variables in our sample population that may affect our outcome variables. We were specifically interested in variables which may affect accommodative microfluctuations as the microfluctuations are thought to be associated with increased blur detection. Spearman correlation was chosen over Pearson as a more robust assessment of all bivariate relationships. Multiple linear regression was used to assess the relationship between outcome variables blur detection thresholds and accommodative microfluctuations while adjusting for potential confounders age, spherical equivalent, lag, and pupil size. Data analysis was performed using Stata version 12.1.

RESULTS

Seventy-six subjects (66 children and 10 adults) were recruited to participate in the study. Of the 66 children recruited, 17 were excluded from data analysis (3-missing cycloplegic refractive error; 1-missing calibration; 9-did not understand the task or were uncooperative; 2-amblyopia; 1-astigmatism $>1.25D$; and 1-born <32 weeks gestation). Forty-nine subjects between 3 to <10 years and 10 subjects between the ages of 23 to <32 years met the inclusion criteria and were included in the analysis for the blur detection task whereas 20 children ≥ 6 years and all 10 adults were able to complete the depth-of-field experiment.

Summary characteristics of age, spherical equivalent, blur detection thresholds, accommodative microfluctuations, lag, pupil size, and subjective depth-of-field are found in Table 1.

Data were analyzed for quality control to ensure children understood the task. All children correctly identified the clear shape or letter 100% of the time for row 9 (most blurred) and at least 75% of the time for the shapes or letters for rows 6–8. This suggests that all children included in the analysis understood the task.

Refractive Error, Pupil Size, and Blur Detection Threshold Comparisons between Children and Adults

Among children, spherical equivalent decreased significantly with age ($n=49$, $r=-0.32$, $P=0.03$). Children had significantly higher mean spherical equivalent ($+1.63\pm1.18$ D vs. $+0.82\pm0.40$ D, $P<0.001$) than adults (Table 1). Children also had significantly larger pupils (6.3 ± 0.7 mm vs. 5.1 ± 0.6 mm, $P<0.001$) than adults during the blur detection task (Table 1).

Mean blur thresholds were compared between the children and adults. Seven of the 10 adults identified at least 80% correct on all blur levels tested, making their blur detection thresholds below the blur levels generated for this experiment. For comparison purposes, those 7 adults were assigned a threshold value of 0.71' (lowest level of blur). The blur detection threshold of children ($n=49$) was significantly higher ($P<0.001$) than the adults ($n=10$). To ensure the difference was not due to the higher spherical equivalent in children, the analysis was repeated with children who had a similar upper limit spherical equivalent as the adult subjects ($<+1.51$ D). The children ($n=27$) still had higher blur detection thresholds than the adults ($P<0.001$). During the blur detection task, accommodative microfluctuations were also significantly higher in children ($n=49$) than adults ($n=10$) when comparing all children ($P=0.001$), or when comparing the subset of children ($n=27$) with a similar upper limit spherical equivalent as the adults ($P=0.04$) (Table 1).

Given that pupil size was free to vary during the task, the comparisons between the children and adults were adjusted for pupil size. The children still had significantly larger blur detection thresholds ($P<0.001$; 95% CI = $-1.24, -0.57$) than the adults for both the entire group and when only including the children with a similar range in refractive error to adults ($P=0.001$; 95% CI = $-1.16, -0.30$). The children also had significantly larger microfluctuations than the adults when comparing all children ($P<0.001$; 95% CI = $-0.24, -0.07$), or when only comparing children with similar range of refractive error to adults ($P=0.001$; 95% CI = $-0.25, -0.07$).

Blur Detection Thresholds and its Associations with Accommodative Microfluctuations, Spherical Equivalent, Age, Lag and Pupil Size in Children

Accommodative microfluctuations ($r=0.60$, $P<0.001$), age ($r=-0.48$, $P<0.001$), spherical equivalent ($r=0.39$, $P=0.005$) and pupil size ($r=-0.36$, $P=0.01$) were each significantly associated with blur detection thresholds whereas a significant association between blur detection thresholds and lag was not detected ($r=-0.11$, $P=0.46$) (Figure 3). The results for the multivariable linear regression for outcome blur detection threshold is presented in Table

2. Poorer blur detection thresholds were significantly associated with increased accommodative microfluctuations ($P<0.001$) and decreased age ($P<0.001$).

Association between Accommodative Microfluctuations, Spherical Equivalent, Age, Lag and Pupil Size in Children

Accommodative microfluctuations were significantly associated with spherical equivalent ($r=0.40$, $P=0.004$) and pupil size ($r=0.42$, $P=0.003$). A significant association was not detected between accommodative microfluctuations and age ($r=-0.13$, $P=0.39$), or lag ($r=-0.15$, $P=0.29$) (Figure 4). The results for the multivariable linear regression for outcome accommodative microfluctuations are presented in Table 3. Accommodative microfluctuations were independently associated with increased spherical equivalent ($P<0.001$) and decreased pupil size ($P=0.003$).

Association between Spherical Equivalent and Lag

A significant relationship between spherical equivalent and accommodative lag was not detected (Figure 5, $r=0.22$, $P=0.12$) during the blur detection task. However, the children with $>+2.50$ D of uncorrected hyperopia were all in the top 25 percent of children for largest accommodative lag.

Subjective Depth-of-Field Experiment

Twenty of the 31 children 6 years and all 10 adults were able to complete the subjective depth-of-field experiment. The results are found in Table 1. The mean depth-of-field of the children was significantly larger than the adults ($P<0.001$). The children also had significantly larger mean accommodative microfluctuations than the adults ($P<0.001$) during the proximal and distal measures of the depth-of-field. Because the subjects were not cyclopleged during the experiment, the analyses were repeated on a subset of subjects whose mean accommodative response as measured by the PowerRef II during each of the proximal and distal measures were within 0.75 D of one another to increase the likelihood that the subjects were repeatedly accommodating to the same place during testing. The subset of the thirteen children still had significantly larger subjective depths-of-field ($P=0.004$) and accommodative microfluctuations ($P=0.001$) than the 9 adults.

Because depth-of-field is influenced by pupil size,¹¹ the difference in depth-of-field between the children and the adults were adjusted for pupil size. Despite the children having significantly larger mean pupil size than the adults during the depth-of-field experiment ($P=0.006$, Table 1), the difference in depth-of-field between the children and the adults remained significant when adjusted for pupil size ($P=0.002$, 95% CI=-1.33, -0.34).

DISCUSSION

The children in this study had poorer blur detection thresholds, larger subjective depths-of-field and larger accommodative microfluctuations than the adults. In the children, increased accommodative microfluctuations and younger age were found to be independently associated with increased blur detection thresholds in multivariable analysis when adjusting for spherical equivalent, lag and pupil size. Uncorrected hyperopia and pupil size were found

to be independently associated with accommodative microfluctuations when adjusting for age and lag.

It has been shown in adults that accommodative microfluctuations can act as sub-threshold blur detectors, and that the magnitude of the accommodative microfluctuations are less than both the objective and subjective depths-of-field in the same eyes.^{6,7} A similar relationship between accommodative microfluctuations and the subjective depths-of-field was found in the present study in both the children and the adults, as the accommodative microfluctuations for each participant were less than their measured subjective depth-of-field as shown in Table 1.

In the blur detection threshold experiment, 7 out of 10 adults were able to distinguish the clear letter from the lowest level of blurred letters, indicating not all adults reached their thresholds. However, the purpose of including the adults in the study was to determine if children had adult-like blur detection abilities and while the difference between children and adults may be even larger than was found, a significant difference between the two groups was still detected despite the majority of adults not reaching their thresholds. The differences in blur detection thresholds between the children and the adults were not due to the children having larger amounts of uncorrected refractive error, as the difference remained significant when the analysis was restricted to children with a similar upper limit spherical equivalent as the adults. It is unknown if the discrepancies between the adults and children lie in true biological differences, behavioral differences, or a combination of the two. Three children had lower blur detection thresholds than the adult with the highest threshold, suggesting that adult-like blur thresholds are possible in some older children, but were not typical in the study sample.

The children in this study had significantly larger subjective depths-of-field and significantly larger accommodative microfluctuations than the adults even when adjusting for pupil size. Of the 20 children who were included in the analysis, 7 of them did not meet the accommodative repeatability criterion and all but one of the seven children had the largest subjective depths-of-field. The lack of children ($n=7$) meeting the accommodative repeatability criterion could be secondary to the children not understanding the task, or that those children do indeed have larger subjective depths-of-field and their accommodation varied within that range during the experiment resulting in more variable accommodative responses between trials. Accommodative microfluctuations in children were still significantly higher (Table 1) than the adults after imposing the accommodative repeatability criterion. Our results are in general agreement with the idea that accommodative microfluctuations and subjective depth-of-field are related,^{6,7} however additional confirmation of the relationships in children will require further investigation with a larger number of children.

Despite only a few children having a spherical equivalent $>+3.00\text{D}$ in the current study, there was a marginal, yet significant association between spherical equivalent and blur detection thresholds (Figure 3). However, spherical equivalent was not found to be significant in the adjusted analysis (Table 2). Given that increased spherical equivalent was significantly associated with increased accommodative microfluctuations in both the correlations and

adjusted analyses (Table 3) a post-hoc mediation analysis was performed to determine if spherical equivalent may be affecting blur detection thresholds through accommodative microfluctuations. The mediation analysis (not shown) suggested that there is a small yet significant indirect effect (95% CI: 0.028, 0.14) of spherical equivalent on blur detection thresholds through accommodative microfluctuations.

The source of the increase in accommodative microfluctuations in children with uncorrected hyperopia is likely to be the motor system (e.g.: a greater accommodative response and thus greater accommodative microfluctuations - Figure 4), however, there may be some contribution from the sensory system (e.g.: greater defocus due to larger accommodative lags) as the children with $>+2.50\text{D}$ of uncorrected hyperopia were all in the top 25 percent of children for largest accommodative lag (Figure 5). However, this cannot be determined until the children's hyperopia is corrected to equate accommodative demand, and presumably accommodative response, to determine whether accommodative microfluctuations decrease under these conditions.

If children with larger amounts of uncorrected hyperopia experience increased blur from either under-accommodating,^{35,36} or from increased accommodative variability, the increased exposure to blur may result in blur adaptation. It is important to remember that in many studies, it is assumed that the stimulus remains "clear" during experiments and that the definition of "clarity" is similar across subjects, but it has been shown that adaptations are unique to an individual's own aberrations³⁷ and consequently blur may be perceived and acted upon differently across individuals. Thus, further work is needed to better understand blur detection and accommodative variability in a larger sample of children with moderate to high amounts of uncorrected hyperopia and the possible role of blur adaptation in these children.

It is thought that increased levels of lag may result in increased defocus, which could affect one's ability to detect blur.³⁸ The lack of association between blur detection thresholds and accommodative lag in this study may be the result of various factors. The magnitude of lag does not always correlate to levels of perceived blur (Figure 3).¹⁷ Additionally, it has also been shown that there is a "dipper" effect in which the threshold for blur detection slightly improves when the reference blur (e.g.: the clear letter) is also out of focus.¹ Thus, if subjects had lags of accommodation during the task such that all letters were blurred, they may have still been able to identify the non-blurred optotype as they would be choosing the least blurred letter. Lastly, it is unknown as to whether the individuals in the study have adapted to their own optical blur, which may affect the relationship between lag and blur thresholds.

While this study has shown that higher levels of blur detection thresholds among children are associated with both higher magnitudes of accommodative microfluctuations and younger age, it is unknown whether the associations are due to immaturities in the young visual system or the significant associations are secondary to neural deficits regarding blur detection. It is not surprising that blur detection thresholds decreased with age as the young behavioral visual system (e.g.: contrast sensitivity) continues to mature up to 8 years and above.³⁹ However, increased accommodative microfluctuations remained independently

associated with increased blur detection thresholds when adjusting for age in this sample population ($p<0.001$), suggesting that some children have increased blur detection thresholds that are unrelated to visual immaturities due to age.

Study Limitations

There are limitations to this study. One limitation is that data from only 49 children were eligible to be analyzed and there were few subjects with spherical equivalent $>+3.00$ D in the study. The relatively small sample with high refractive errors in children constrains the ability to determine the effect of uncorrected hyperopia on blur detection thresholds when adjusting for confounding factors such as accommodative microfluctuations, age, lag and pupil size. Despite the low number of children in the study with $>+3.00$ D spherical equivalent, the magnitude of uncorrected hyperopia was still independently associated with higher accommodative microfluctuations, which affect blur detection thresholds. In addition to the low number of subjects recruited with $>+3.00$ D hyperopia, the children recruited for this study appear to be relatively unaffected by their hyperopia and thus our results may differ if we were to include children that had more difficulty with their accommodative demand. An additional limitation regarding refractive error is that the study restricted recruitment to children with uncorrected hyperopia and thus the results are not generalizable to subjects with refractive errors that fall outside the eligibility criteria (i.e.: myopia, high astigmatism, etc.). Another limitation to the study is that we did not recruit adults with a wider range of uncorrected refractive error and thus the adult data are only representative of adults with up to $+1.51$ D spherical equivalent uncorrected refractive error.

Our study also measured blur detection thresholds under binocular viewing rather than monocular viewing, which introduces possible limitations in our interpretation of the data due to the potential of differing optics between the two eyes. While we attempted to limit differences in refractive error by employing anisometropia criteria and controlling for pupil size in analyses, other factors such as higher order aberrations may have differed between the two eyes. The purpose of the study was to determine blur detection thresholds under viewing conditions that children with a range of uncorrected hyperopia, who inherently have a higher accommodative demand during normal viewing conditions. Thus, performing the experiment under monocular viewing or with fixed pupils would have removed natural aspects of the task.

Another limitation to the study is that neither the blur detection threshold experiment nor the subjective depth-of-field experiment was performed under cycloplegia. For the blur detection experiment, we are unable to differentiate whether the individuals with poorer blur detection have neurological deficits in the afferent pathway resulting in decreased ability to detect blur or if their higher blur detection thresholds were simply due to noise in the signal due to increased accommodative microfluctuations. Further investigation of blur detection thresholds in children under cycloplegia is needed to differentiate the neural blur detection thresholds from the functional blur detection thresholds in children given the strong association between accommodative microfluctuations and blur detection thresholds in the children in this sample population. For the depth-of-field experiment, we accounted for variability of the accuracy of the accommodative response by performing the analysis with

and without an accommodative repeatability criterion. The overall results did not change with the criterion in that the children still had larger depth-of-field than the adults. The adult measures of subjective depth-of-field were similar to other depth-of-field measures found in other studies^{9, 11} particularly when measuring depth-of-field on an accommodating eye.⁴⁰ Depth-of-field measures have not been explored in children and thus there are no comparative studies.

In terms of the calculation of lag, it should be noted that while relative lens calibrations were performed to account for inter-subject variability in the luminance slope change per diopter, absolute calibrations (absolute off-set) were not performed, which introduces a limitation to our data analysis. Previous authors have analyzed accommodative lag using photorefractometry by calculating a relative change in accommodation from one distance to another. However, this approach relies on the assumption that the subjects fully relax accommodation at the distance stimulus. Given that we were specifically recruiting children with uncorrected hyperopia, it would be incorrect to assume that the children relaxed accommodation for distance, or even had accurate focus to the distance stimulus, making it difficult to perform an absolute calibration. Thus, we accepted the limitation of calculating the accommodative lag from the Power Ref II output for all subjects without an absolute offset calibration. Our decision to do so was also supported by findings that the PowerRefractor (Multichannel Systems version – predecessor to the PowerRef II – 25Hz) compares well to both retinoscopy (mean difference = -0.28D [range -0.43 to 0.05D])⁴¹ and the Grand Seiko autorefractor (mean difference at a 2.5D demand = $0.08 \pm 0.32\text{D}$; mean difference at a 5D demand = $-0.32 \pm 0.48\text{D}$),⁴² and thus we feel that any errors from lack of offset calibration would be small for the 33cm viewing distance.

Summary

In summary, the results of this study suggest that, as a group, children do not have adult-like blur detection thresholds or subjective depth-of-field by age 10. Increased accommodative microfluctuations and younger age are independently associated with greater blur detection thresholds in children aged 3 to <10 years. Additionally, children with larger amounts of uncorrected hyperopic refractive error and smaller pupil size have significantly larger magnitudes of accommodative microfluctuations, which are significantly associated with increased blur detection thresholds.

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Figure 1.

Three representative lines from the blur chart produced by convolution using a Gaussian kernel with standard deviations that represent the minimum level of blur (0.71 arc minutes – bottom line), the median level of blur (2.83 arc minutes – middle line) and maximum level of blur (11.31 arc minutes – top line). (A) Sloan letter optotypes. (B) Shape optotypes.

Figure 2.

Representation of the relationship between refractive error (diopters) and eye position (degrees) obtained from the right eye by the PowerRef II in an adult subject before and after the eye position correction factor was applied to the refractive error data. (A) Refractive error plotted as a function of horizontal eye position prior to applying the correction factor to the data. The gray lines represent the change in slope of the data when eye position is 0° and $>0^\circ$. (B) Refractive error as a function of eye position after the eye position correction has been applied, illustrating the effectiveness of the correction factor.

Figure 3.

Blur detection thresholds in arc minutes as a function of (A) accommodative microfluctuations, (B) age, (C) most plus spherical equivalent refractive error, (D) accommodative lag, and (E) pupil size in children ($n=49$) aged 3 to <10 years.

Figure 4. Accommodative microfluctuations in diopters as a function of (A) most plus spherical equivalent refractive error, (B) age, (C) accommodative lag, and (D) pupil size in children ($n=49$) aged 3 to <10 years.

Figure 5.

Accommodative lag as a function of the most plus spherical equivalent refractive error in children ($n=49$) aged 3 to <10 years.

Table 1

Descriptive and summary statistics for children and adults

		Children	Adults	p-value
		Mean(SD) (95% CI) n=49	Mean(SD) (95% CI) n=10	
Subject Characteristics	Age (years)	6.3(1.6) (5.8, 6.7)	25.3(2.4) (23.5, 27.0)	
	Spherical Equivalent Refractive Error (D)	+1.63(1.18) (+1.29, +1.96)	+0.82(0.40) (+0.53, +1.10)	<0.001
Blur Detection Threshold Experiment	All subjects	n=49	n=10	
	Blur detection thresholds (arc min)	1.44(0.46) (1.31, 1.57)	0.74(0.07) (0.70, 0.79)	<0.001
	Accommodative microfluctuations (D)	0.33(0.11) (0.30, 0.36)	0.24(0.06) (0.20, 0.28)	0.001
	Lag (D)	1.37(0.51) (1.23, 1.52)	1.17(0.29) (0.97, 1.38)	0.10
	Pupil size (mm)	6.2(0.7) (6.0, 6.4)	5.1(0.6) (4.6,5.5)	<0.001
	Similar Range Refractive Error	n=27	n=10	
	Blur detection thresholds (arc min)	1.32(0.47) (1.14, 1.51)	0.74(0.07) (0.70, 0.79)	<0.001
	Accommodative microfluctuations (D)	0.30(0.11) (0.26, 0.35)	0.24(0.06) (0.20, 0.28)	0.04
	Lag (D)	1.28(0.38) (1.13, 1.43)	1.17(0.29) (0.97, 1.38)	0.36
	Pupil size (mm)	6.3(0.7) (6.0, 6.6)	5.1(0.6) (4.6,5.5)	<0.001
Depth-of-Field Experiment	All subjects	n=20	n=10	
	Depth-of-field (D)	1.88(0.55) (1.62, 2.14)	0.93(0.53) (0.55, 1.30)	<0.001
	Accommodative microfluctuations (D)	0.52(0.13) (0.46, 0.57)	0.23(0.04) (0.20, 0.25)	<0.001
	Pupil size (mm)	6.5(0.6) (6.2, 6.8)	5.1(0.6) (5.4,6.2)	0.006
	Accommodative Criterion	n=13	n=9	
	Depth-of-field (D)	1.70(0.49) (1.41, 1.99)	0.91(0.56) (0.48, 1.33)	0.004
	Accommodative microfluctuations (D)	0.54(0.12) (0.47, 0.61)	0.23(0.04) (0.20, 0.25)	0.001

Significant differences ($p<0.05$) between children and adults are in bold.

SD = standard deviation; D = diopters; CI = confidence interval

Table 2

Multiple linear regression for outcome blur threshold, adjusted for independent variables accommodative microfluctuations, age, uncorrected hyperopia, lag and pupil size for children 3 to <10 years.

Parameter	Beta-coefficient	95% Confidence Interval	p-Value
Intercept	1.93	0.75 to 3.13	0.002
Accommodative Microfluctuations	1.82	0.72 to 2.91	0.002
Age	−0.13	−0.20 to −0.07	<0.001
Uncorrected Hyperopia	0.01	−0.09 to 0.12	0.804
Lag	−0.16	−0.36 to 0.05	0.137
Pupil Size	−0.01	−0.17 to 0.14	0.883

Significant ($p < 0.05$) values are in bold.

Table 3

Multiple linear regression for outcome accommodative microfluctuations, adjusted for independent variables age, uncorrected hyperopia, lag and pupil size for children 3 to <10 years.

Parameter	Beta-coefficient	95% Confidence Interval	p-Value
Intercept	0.67	0.41 to 0.93	<0.001
Age	−0.003	−0.01 to 0.02	0.756
Uncorrected Hyperopia	0.05	0.02 to 0.07	<0.001
Lag	−0.05	−0.10 to 0.01	0.109
Pupil Size	−0.06	−0.10 to −0.02	0.003

Significant p-values (<0.05) values are in bold.