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Is blur sensitivity altered in children with progressive myopia?

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ABSTRACT

School aged children with progressive myopia show large accommodative lags to blur only cue which is suggestive of a large depth of focus (DOF). While DOF measures are lacking in this age group, their blur detection and discrimination capacities appear to be similar to their non-myopic peers. Accordingly, the current study quantified DOF and blur detection ability in progressive myopic children showing large accommodative lags compared to their non-myopic peers and adults. Blur sensitivity measures were taken from 12 children (8–13 years, 6 myopes and 6 emmetropes) and 6 adults (20–35 years). DOF was quantified using step changes in the lens induced defocus while the subjects viewed a high contrast target through a Badal lens at either 2 or 4D demand. Blur detection thresholds (BDT) were tested using a similar high contrast target in a 2-alternate forced-choice paradigm (2AFC) at both the demands. In addition to the large accommodative lags, micro fluctuations and DOF were significantly larger in myopic children compared to the other groups. However, BDTs were similar across the three groups. When limited to blur cues, the findings of a large DOF coupled with large response lags suggests that myopes are less sensitive to retinal defocus. However, in agreement to a previous study, refractive error had no influence on their BDTs suggesting that the reduced sensitivity to the defocus in a myopic eye appears to be compensated by some form of an adjustment in the higher visual processes to preserve the subjective percept even with a poor retinal image quality.

1. Introduction

Children with a progressing myopia exhibit larger accommodative response lags to a blur only stimulus compared to non-myopic children (Gwiazda, Thorn, & Held, 2005; Gwiazda, Thorn, Bauer, & Held, 1993; Labhishetty & Bobier, 2017; Mutti et al., 2006). When limited to blur only cue, these high accommodative lags are also associated with an abnormal pattern of high response AC/A and high accommodative adaptation (Gwiazda et al., 2005; Gwiazda, Bauer, Thorn, & Held, 1995; Labhishetty & Bobier, 2017; Sreenivasan, Irving, & Bobier, 2012). This abnormal pattern is strongly associated with the progressive nature of myopia both in children and adults/late onset myopes (Abott, Schmid, & Strang, 1998; Gwiazda et al., 1995; Jiang, 1995, 1997). It is not clear whether the high lags reported in these progressive myopic children reflect a large depth of focus (Bernal-Molina, Montes-Mico, Legras, & Lopez-Gil, 2014; Wang & Ciuffreda, 2006). If so, it is unclear if this large depth of focus (DOF) would result from a reduced sensitivity to retinal defocus and if it would be coupled with a reduced ability to perceive blur.

Historically, blur sensitivity has been quantified in terms of DOF, defined as the variation in retinal image distance that can be tolerated without perceiving blur (Campbell, 1957; Wang & Ciuffreda, 2006). DOF is typically examined by changing the object position in physical space (depth of field) and can be measured both subjectively (Atchison, Charman, & Woods, 1997; Rosenfield & Abraham-Cohen, 1999; Yao, Lin, Huang, Chu, & Jiang, 2010) and objectively (Kotulak & Schor, 1986; Marcos, Moreno, & Navarro, 1999; Vasudevan, Ciuffreda, & Wang, 2006a; Yao et al., 2010). Blur sensitivity can also be tested psychophysically using a blur detection/discrimination task wherein the subjects would observe and compare targets with varied levels of rendered blur (Kotulak & Schor, 1986; Maiello, Walker, Bex, & Vera-Diaz, 2017; Roberts, Stevenson, Benoit, Manny, & Anderson, 2018; Schmid, Robert Iskander, Li, Edwards, & Lew, 2002; Watson & Ahumada, 2011). While objective measures of DOF determine the defocus magnitude necessary to induce a consistent change in accommodation, perceptual measures of blur sensitivity would estimate the subjective criterion of either blur detection or discrimination with no or minimal influence of accommodation. Studies on blur sensitivity in progressive myopic children have been limited to blur detection and discrimination measures. Only one study examined blur detection and discrimination thresholds on 40 school aged children (Schmid et al., 2002). They found similar blur thresholds in progressive myopic

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children compared to the non-myopic children. It cannot be assumed that depth of field/focus measures would show the same lack of difference since the psychophysical tasks of blur detection and discrimination do not create or determine blur in the same manner as the DOF measures. Also, given the evidence that adult myopes adapt to a greater extent after a prolonged exposure to blur compared to other refractive groups (Cufflin, Mankowska, & Mallen, 2007; Khan, Dawson, Mankowska, Cufflin, & Mallen, 2013; Wang, Ciuffreda, & Vasudevan, 2006; Webster, Georgeson, & Webster, 2002), a greater disparity would be expected between the ability to perceive blur and depth of focus in myopes.

Traditionally, increased accommodative lags and micro fluctuations found at closer working distances have been attributed to a larger DOF that results from a reduction in the pupil size which in turn acts to reduce the retinal blur circle. Day et al., reported a correlation between DOF and accommodative micro-fluctuations (Day, Seidel, Gray, & Strang, 2009). When DOF was modulated by manipulating luminance level and pupil size, they found a consistent change in the magnitude of micro fluctuations. In a separate study, this group also found that the increased magnitude of micro fluctuations at closer distances was independent of changes in pupil size (Day, Strang, Seidel, Gray, & Mallen, 2006). In agreement, other studies have reported that the change in DOF with stimulus demand was correlated with only accommodative micro fluctuations and not pupil size (Yao et al., 2010). Several studies reported that the accommodative lags and micro fluctuations increased with stimulus demand significantly more in progressive myopes compared to the non-myopes (Day et al., 2006; Langaas et al., 2008; Sreenivasan, Irving, & Bobier, 2011). A recent study compared measures of blur detection, micro fluctuations and a subjective measure of DOF on 49 children (aged 3–10 years), mostly hyperopic, and 10 non-presbyopic adults (Roberts et al., 2018). They found that blur detection and DOF measures were significantly larger in children compared to adults. Increased blur detection thresholds were also associated with larger micro fluctuations, increased hyperopia and smaller pupil size. Given that progressive myopia is associated with greater accommodative lags and micro fluctuations with stimulus demand compared to non-myopic children, differences in retinal blur sensitivity would be expected as a function of stimulus demand between the refractive groups.

Accordingly, the current study sought to compare an objective measure of the DOF with the extent of accommodative lags between progressive myopic children their non-myopic peers and adults with a stable refractive error. Data from myopic children was then compared to non-myopic children and adults. Objective DOF measures were measured using a photorefractor which detected small defocus changes induced by ophthalmic lenses when subjects monocularly viewed a high contrast target at two accommodative demands (2 and 4D) through a Badal optical system. The possible role of accommodative fluctuations on blur sensitivity was also examined. Blur detection was then tested using a computer-generated psychophysical task set at the same accommodative demands (2 and 4D) as those used in the DOF experiment.

2. Methods

12 school aged children, 6 myopes & 6 emmetropes (Age: 9–14 years), and 6 naïve adults (25–32 years) were recruited from the optometry clinic at the University of Waterloo School of Optometry and Vision Science. Sample size calculations were done based on the pilot data on the DOF obtained from 3 myopes and 3 non-myopes (Appendix A). The mean and standard deviation of the DOF measures obtained from the myopes (0.95 ± 0.18D) and non-myopic children (0.62 ± 0.12D) were used to calculate the effect size. Based on the effect size, a sample size of 6 subjects/group was calculated (with $\alpha = 0.05$; Power $(1 - \beta) = 0.90$). All the myopic subjects had a progressive history of > 0.5D/year change in the refractive error at the time of recruitment with a known progressive record for the past 2 years prior to their recruitment. Four of them were recruited from a previous study which found larger accommodative lags in myopes compared to their non-myopic peers (Labhishetty & Bobier, 2017). Informed consent and assent were obtained after a verbal and a written explanation of the study. The study followed the tenets of Declaration of Helsinki and received ethical approval from the University of Waterloo office of research ethics review board. Children were classified into two refractive groups based on their cycloplegic refraction. The myopic group (MYP) had equivalent spheres between −1.25D to −7.00D. Emmetropic children (EMM) had equivalent spheres between +0.50D to 0D. There were 4 emmetropes and 2 stable myopes in our adult subgroup. Given that their accommodative behavior was found to be similar to that found previously (Abott et al., 1998; Kasthurirangan & Glasser, 2005; Kasthurirangan, Vilupuru, & Glasser, 2003), they were not subdivided based on refractive error. All the myopic subjects were habitual contact lens wearers and wore their lens during the study. Only subjects with astigmatism < 0.50D, no anisometropia, no amblyopia or strabismus and with best corrected visual acuity of 20/20 were included in the study. Critical visual parameters such as the distance and near visual acuity, distance and near phoria using cover test and cycloplegic refraction were measured to confirm the visual status of all the children prior to the measurement visit (Table 1). The measurement sessions followed the screening session by not more than a week. During the measurement sessions, objective DOF and blur detection thresholds were collected over two separate visits.

2.1. Objective depth of focus (DOF)

2.1.1. Experimental design

Accommodative response change to optical lens defocus was measured while the subject viewed a high contrast target through a simple Badal optical system (Fig. 1). The subject was seated 1 m away from the photorefractor with the left eye occluded. An IR passing mirror (Optical cast IR filter, Edmund Optics, USA) allowed an orthogonal presentation of the targets along with a continuous measure of accommodation using the dynamic photorefractor. Two targets (T1, T2) were manually placed at different distances from a +5D Badal lens. Each target was a high contrast (white on black) vertical line that was back illuminated using a white LED. The luminance of the target was 180 cd/m^2. The angular size of the target was 6° and was kept constant across the stimulus demands. A small horizontal offset was present between the distance and the near target (maximum offset was ≈1.5° for the 4D stimulus). While the far target (T1) was always set at optical infinity, the near target (T2) was moved to one of the two distances from the Badal lens to create an accommodative demand of either 2 or 4D. Step changes between the targets T1 and T2 were achieved using a stimulus control tool box with a button that allowed for an instantaneous switch between the targets so that the subject viewed only one high contrast target at a time.

2.1.2. Instrumentation

A custom built dynamic photorefractor (PROSILICA CAM (EC750), Allied Vision Technologies, Canada) was used to continuously monitor changes in the accommodative response and the pupil size (Labhishetty, 2014; Labhishetty, Bobier, & Lakshminarayanan, 2018; Suryakumar, Kwok, Fernandez, & Bobier, 2009). The dynamic photorefractor works at a sampling frequency of 70 Hz, giving an output every 0.014 s.

Table 1
Visual parameters of children, both myopes and non-myopes, and adults.

Parameter	Myopes	Non-myopes	Adults
No. of participants	6	6	6
Age (years)	12.16 ± 1.47	12.08 ± 1.35	28 ± 2.82
Refractive error (D)	−3.31 ± 2.16	0.10 ± 0.09	−0.70 ± 1.28
Near phoria (Δ) ('+' eso; '−' exophoria)	1.00 ± 2.36	−1.5 ± 2.25	−1.33 ± 1.63

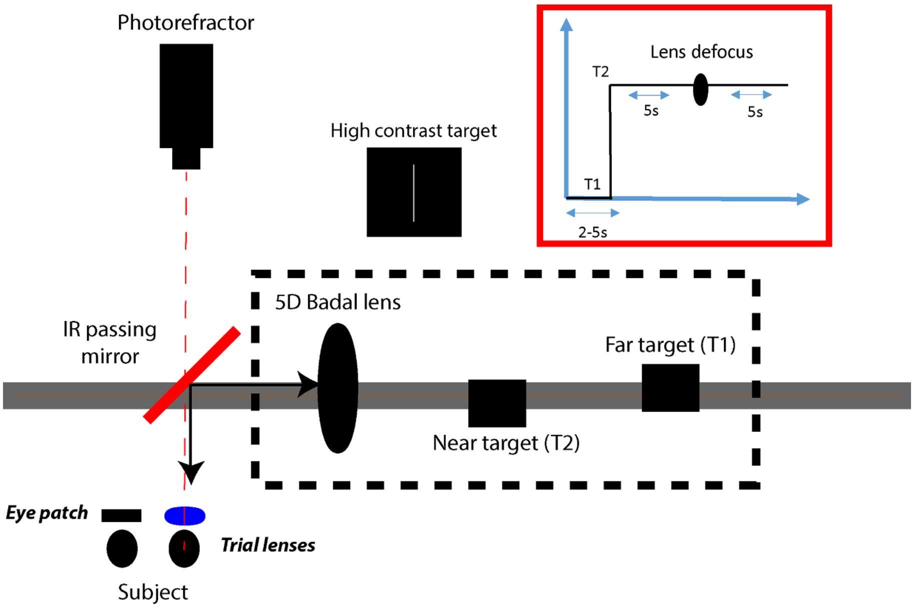

Fig. 1. Experimental design used to stimulate accommodation change to defocus. Badal optical system was used to stimulate step changes in accommodation. Fixation was stepped between the two targets (T1 set at optical infinity and T2 set either to 2D or 4D). Each target was a high contrast vertical line subtending a visual angle of 6 degrees. Accommodative response and pupil size were monitored using a photorefractor. The inset illustrates the sequence where accommodation is initially relaxed viewing the distant target (T1) and then randomly stepped to the near target (T2) at either 2 or 4D. Once accommodation was steady at T2 for 5–10 s, a trial lens was introduced, and accommodation was recorded for an additional 5–10 s.

Photorefraction videos were later analyzed offline using the dynamic photorefraction system (DPRS) for refractive estimations. The individual calibration procedures followed in this study were similar to ones described previously (Schaeffel, Wilhelm, & Zrenner, 1993; Suryakumar, Meyers, Irving, & Bobier, 2007). DPRS was calibrated and validated on children and adults previously (Labhishetty, 2014).

2.1.3. Procedure

One drop of 2.5% phenylephrine hydrochloride was instilled in both eyes of the subject following an initial anterior chamber assessment. 2.5% of phenylephrine was found to have no/minimal impact on objective measures of accommodation (Esteve-Taboada et al., 2016; Richdale et al., 2012). The left eye of the subject was covered with an eye patch during the study. The dynamic photorefractor was aligned with the right eye. Prior to the start of the study, 2–3 practice trials were given to each subject to familiarize them with the experimental procedures involved. Each trial lasted for 15–25 s. During the measurement trial, subjects viewed the high contrast target (white on black) through the Badal lens and were instructed to keep the edges of the target clear or sharp always. Each trial commenced with the subject viewing the distant target (T1) for 2–5 s. The near target set at either 2D or 4D was then viewed for 5–10 s (Fig. 1) at which time an ophthalmic lens was introduced before the right eye for a further 5–10 s. *Eleven lens defocus conditions* were used for a 2D stimulus demand and *fifteen defocus conditions* were used for 4D demand (Table 2). The range of lenses selected was based on the measures of accommodative response lags noted previously at each stimulus demand (Labhishetty & Bobier, 2017; Mutti et al., 2006). Accommodative response, pupil size and micro fluctuations were continuously monitored during the trial. The intent was to determine the lens defocus which induced a significant change in the accommodative response. Three trials were conducted for each lens condition. The order of the stimulus demand and the resulting lens condition were randomized. Frequent breaks were given to the child between the lens conditions.

Three placebo lens conditions were used to determine the influence of proximity and size cues on the accommodative response. First, a *plano* lens was used to quantify the influence of the proximity cue which can occur due to the placement of the lens close to the patient's eyes. Second, a *2.0% size lens* (to magnify the image without any change in the optical power) was placed before the eye in order to determine if perceived magnification from the trial lenses would have any effect on the accommodative response. Third, a *no lens* condition was used to quantify the baseline steady state fluctuation in the accommodative response over time. This baseline measure served as the metric to define when a significant change in accommodation was induced including the defocus conditions and the placebo lens conditions.

Table 2
Defocus conditions employed used to measure objective blur thresholds.

Stimulus demand	Placebo condition	Plus lens defocus	Minus lens defocus
2D demand (50 cm)	Plano lens Size lens No lens	+0.25D to +1.00D (0.25D steps)	−0.25D to −1.00D (0.25D steps)
4D demand (25 cm)	Plano lens Size lens No lens	+0.25D to +1.50D (0.25D steps)	−0.25D to −1.50D (0.25D steps)

2.1.4. Analysis

Accommodation data affected by blinks, head or large eye movements were discarded. The remaining data points were used for analysis. Velocity threshold criterion was used to identify the start and end point of the responses (Labhishetty & Bobier, 2017). Accommodative response amplitudes were measured by averaging the response trace for 5 s (350 data points) following the end points measured after step change in the target position and after the lens placement in each condition. The difference between the stimulus demand (at 2 and 4D) and the resulting accommodative response was quantified as the accommodative lag. For the no lens condition, accommodation was measured by averaging the response data from the initial and final 5 s of the trial after the response was made. The difference between the accommodative response before and after the induced lens defocus was defined as the accommodative response change. For each lens condition, three such accommodative measures were obtained which were later averaged. Steady state (accommodative) fluctuations were defined as the standard deviation of the response which was calculated both before and after the placement of a lens. Steady state fluctuations were measured across five lens induced stimulus demands ranging from 1 to 5D (1D steps) and referred to as the effective accommodative demand. Linear regression fits were used to examine the behavior of the steady state fluctuations as a function of the effective accommodative demands and were compared across the groups using a one-way ANOVA. The accommodative response to the plus and minus lenses were analyzed separately. The results were then compared between the three subject groups. Two different parameters were assessed to identify the sensitivity of accommodative system to the lens induced defocus. First, the change in the accommodation response was plotted as a function of the lens induced defocus. Linear regression fits were used to examine the rate of change of accommodation with lens defocus at both 2 and 4D demand. One-way ANOVA was used to identify differences in the linear regression slopes obtained from each group at each stimulus demand. Second, at each demand, the DOF was quantified as the minimum lens defocus that induced a statistically significant change in the accommodative response compared to the baseline no lens condition. Objective DOF was compared using a repeated measures ANOVA with refractive group as a between factor and stimulus demand as a within factor. Finally, a bivariate regression analysis was used to quantify the influence of pupil size and micro fluctuations on the magnitude of the DOF.

2.2. Blur detection thresholds

2.2.1. Experimental design

Simulated retinal blur was created by applying an image processing technique to the high contrast targets used to measure the objective DOF. Psychophysical design and the stimuli were designed using Psykinematix (KyberVision Japan LLC) on a calibrated Macbook Pro (Apple Inc., USA) Retina Display screen (1024X768 pixels) to test the subject's ability to detect blur. The range of luminance levels of the targets was 140–180 cd/m^2 and was measured using Minolta Chroma meter CS-100 (Minolta Camera Co. Ltd., Japan).

2.2.2. Blur detection stimulus

A white on black image was designed with a height (6°) and thickness (0.2°) such that it would mimic the high contrast target used to measure objective DOF (Fig. 2). The image dimensions were kept constant at both the stimulus demands. Simulated blur was created based on the optical and mathematical approximations presented previously (Akutsu, Bedell, & Patel, 2000; Charman & Jennings, 1976). The approximate relationship between the blur circle diameter (degrees) with defocus (D) and pupil diameter was given by,

$$Blur\quad circle(B) = p(D)$$

p is the pupil diameter defined in meters and was kept constant at 0.003 m. D was the defocus in diopters and was kept variable. A cylinder-shaped filter was then created with the radius given by the blur variable (B). The stimulus was then transformed into Fourier space and multiplied with the filter (convolution) to obtain blurred image in Fourier space. Inverse Fourier transformation was then applied to obtain the final blur stimulus (right image in Fig. 2).

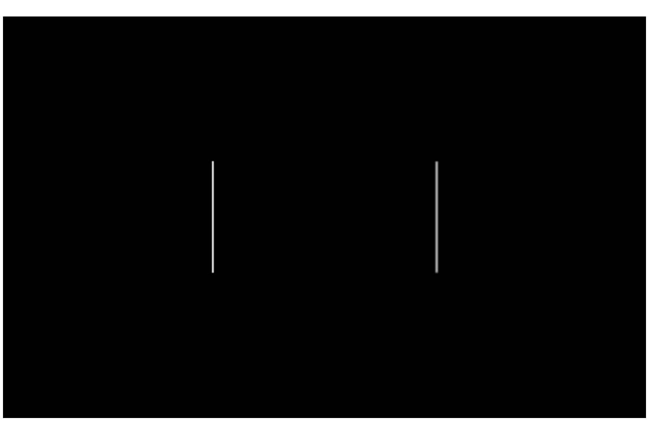

Fig. 2. Blur detection task where two targets (reference and test), which were spatially separated, were presented on a screen. An example of simulated blur level of 1D is shown in this picture.

Accommodative measures taken on 3 adult subjects confirmed that both blurred and clear targets at a particular stimulus demand elicited similar accommodative steady state (Appendix B). Also, the influence of the luminance difference between the clear and blurred targets was tested and had no effect on our blur detection threshold measurements (Appendix C).

2.2.3. Procedure

Blur detection thresholds were determined psychophysically using a 2-alternate forced choice (AFC) paradigm (Fig. 2) similar to the one reported previously (Schmid et al., 2002). Subjects looked at the screen placed at either 50 cm (2D) or 25 cm (4D) with their left eye occluded. Two spatially separated targets (reference and test), were presented on the screen with different levels of blur. First, a practice trial was designed with four blur conditions (reference target at 0D; Test target: 0D, 0.5D, 1D, and 2.0D) to familiarize the subject with the experimental design. The reference target was always maintained at 0 D blur and the rendered blur applied on the test target was randomized between the four blur conditions. The subject's task was to identify the blurred target. During the measurement trials, the reference target was always maintained at 0 D blur and the test target began with 1D of blur. Stimuli were presented for 10 secs for each blur condition with an inter-stimulus interval of 2 s to control for blur adaptation. The spatial position of the targets was randomized to avoid predictability. The magnitude of the blur was subsequently varied in steps of 0.1 D in a 2-down 1-up adaptive staircase. In other words, two correct responses increased the level of difficulty by decreasing the blur magnitude of the test target and one incorrect response increased the magnitude of blur to the test target. The staircase was terminated after 6 reversals and the blur detection threshold was calculated from the average of last 5 reversals. Furthermore, catch trials were included in the staircase (10% of the total trials) whereby a test target of 2D blur was presented along with the reference to enhance the motivation levels of the subjects. Pupil size was recorded for 5 s with the dynamic photorefractor initially while the subject was performing the task at both the working distances.

3. Results

3.1. Sensitivity of accommodation and objective DOF

Pupil measures were also obtained simultaneously along with accommodation at both the working distances from myopes (2D: 5.31 ± 0.60 mm; 4D: 4.9 ± 0.61 mm), non-myopes (2D: 5.35 ± 0.37 mm; 4D: 5.15 ± 0.42 mm) and adults (2D: 5.17 ± 0.28 mm; 4D: 4.72 ± 0.38 mm). DOF and the sensitivity of accommodation were analyzed separately across the stimulus demand (2/4D) and the direction of defocus (plus/minus lens).

3.1.1. Minus lenses

For a 2D demand, repeated measures ANOVA showed a significant difference in the DOF between the three groups ($F = 31.0$; $p < 0.0001$) and the change in the accommodative response to different lens defocus ($F = 1564.1$; $p < 0.0001$). There was also an interaction found in the accommodative response change to different lens magnitudes across the groups (response change * group: $F = 58.6$, $p < 0.0001$). Post hoc (Tukey) analysis showed that a statistically significant change in the response occurred post −0.25D lens for emmetropes and adults. However, the change occurred post −0.50D in myopes. Accommodative response change was plotted as a function of the lens condition (Fig. 3). Linear regression fits were used to identify the rate at which accommodative system responds to different level of minus lens defocus. The slopes were significantly different between myopes and emmetropes ($F(1, 56) = 30.35$; $p < 0.0001$) and myopes and adults ($F(1, 56) = 36.92$; $p < 0.0001$) but not between adults and emmetropes ($F(1, 56) = 1.79$; $p = 0.18$).

For a 4D demand, repeated measures ANOVA showed a similar

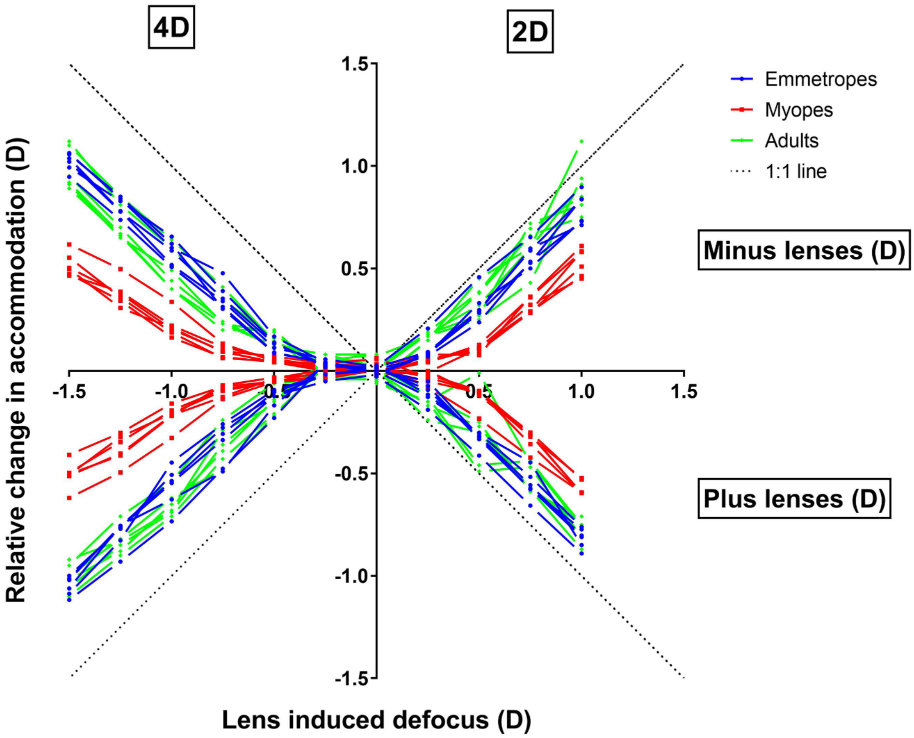

Fig. 3. Sensitivity of accommodation to lenses. Accommodative sensitivity was quantified by plotting accommodative response change as a function of minus and plus powered lens defocus obtained at two different accommodative demands, 4D and 2D. Change in the accommodative response to different lenses was plotted for all individuals across the three groups (blue: Emmetropes; red: Myopes; green: Adults) along with the 1:1 line and connecting lines. Slopes across all the groups at different stimulus demands were significantly different from zero ($p < 0.0001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pattern where significant differences were obtained between the groups ($F = 28.3$; $p < 0.0001$) and the change in the accommodative response to different lenses ($F = 732.9$; $p < 0.0001$). There was also interaction found in the accommodative change resulting from different lens defocus across the groups (change * group: $F = 48.6$, $p < 0.0001$). Post hoc (Tukey) analysis showed that a statistically significant change in the accommodative response occurred post −0.75D in myopes and −0.50D lens in both emmetropes and adults. Accommodative response change was plotted as a function of the lens condition (Fig. 3). The slopes of the linear regression fits defined the sensitivity of accommodative system to different levels of minus lens defocus at 4D demand. The slopes were significantly different between myopes and emmetropes ($F(1, 80) = 115.23$; $p < 0.0001$), myopes and adults ($F(1, 80) = 61.95$; $p < 0.0001$) but not between adults and emmetropes ($F(1, 80) = 1.53$; $p = 0.21$).

3.1.2. Plus lenses

For a 2D demand, repeated measures ANOVA showed a significant difference between the groups ($F = 11.5$; $p < 0.001$) and the change in the accommodative response to different lenses ($F = 1417.0$; $p < 0.0001$). There was also interaction found in the accommodative response change resulting from different lenses across the groups (change * group: $F = 35.7$, $p < 0.0001$). Post hoc (Tukey) analysis showed that a statistically significant change in the response occurred post +0.25D lens for emmetropes and adults. However, the change occurred post +0.50D for myopes. The slopes of the linear regression fits (Fig. 3) were significantly different between myopes and emmetropes ($F(1, 56) = 25.01$; $p < 0.0001$) and myopes and adults ($F(1, 56) = 7.66$; $p < 0.007$) but not between adults and emmetropes ($F(1, 56) = 1.54$; $p = 0.27$).

For a 4D demand, repeated measures ANOVA showed a similar pattern where significant differences were found between the three groups ($F = 14.5$; $p < 0.0001$) and in the response change to different lenses ($F = 226.4$; $p < 0.0001$). There was also interaction found in the accommodative change to different lenses across the groups (change * group: $F = 161.5$, $p < 0.0001$). Post hoc (Tukey) analysis showed that statistically significant change in the accommodative response occurred post +0.50D lens in emmetropes and adults and post +0.75D in myopes. Accommodative sensitivity was tested by plotting the response change as a function of the lens condition (Fig. 3). The slopes of the linear regression fits were significantly different between myopes and emmetropes ($F(1, 80) = 105.55$; $p < 0.0001$), myopes and adults ($F(1, 80) = 128.82$; $p < 0.0001$) but not between adults and emmetropes ($F(1, 80) = 0.16$; $p = 0.68$). Since the sphericity was violated, all the p values were adjusted based on the Greenhouse-Geisser (G-G) test of sphericity.

3.1.3. Placebo lenses

Placebo lenses included plano lens, size lens and a no lens condition and were tested at both stimulus demands in each group separately

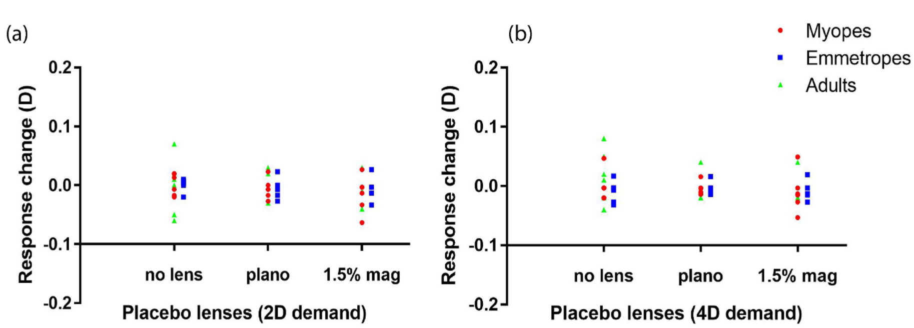

Fig. 4. Placebo lenses and accommodation. The change in the response to different placebo conditions were quantified in all the groups (blue: emmetropes; red: myopes; black: adults). Error bars indicate the standard error in the response change to the lens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 4). Placebo lenses did not induce a statistically significant change in accommodation at both the accommodative demands in myopes ((2D) $F = 2.905$; $p = 0.14$; (4D) $F = 0.05$; $p = 0.83$), emmetropes ((2D) $F = 0.49$; $p = 0.515$; (4D) $F = 1.3$; $p = 0.30$) and adults ((2D) $F = 3$; $p = 0.22$; (4D) $F = 0.51$; $p = 0.54$).

3.1.4. Objective depth of focus (DOF)

DOF was quantified as the minimum lens defocus that induced a significant change in the accommodative response compared to the baseline no lens condition. This was done separately for both plus ((Myopes DOF_{2D}: 0.62 ± 0.13D; DOF_{4D}: 0.91 ± 0.20D); (Emmetropes DOF_{2D}: 0.41 ± 0.12D; DOF_{4D}: 0.62 ± 0.13D); (Adults DOF_{2D}: 0.25D; DOF_{4D}: 0.54 ± 0.10D)) and minus lens condition ((Myopes DOF_{2D}: 0.62 ± 0.13D; DOF_{4D}: 0.95 ± 0.18D); (Emmetropes DOF_{2D}: 0.33 ± 0.12D; DOF_{4D}: 0.66 ± 0.12D); (Adults DOF_{2D}: 0.25D; DOF_{4D}: 0.54 ± 0.10D)). Repeated measures ANOVA was used to test objective blur thresholds across the three groups. Stimulus demands and type of lens defocus (plus or minus) were used as within factors. ANOVA showed that there were significant differences across the groups ($F = 35.2$; $p < 0.0001$) and stimulus demands ($F = 107.6$; $p < 0.0001$) but not across the type of defocus ($F = 0.2$; $p = 0.81$). Post hoc (Tukey) analysis showed that objective DOF was significantly larger in myopes compared to both emmetropes and adults ($p < 0.001$). Objective DOF was significantly larger at 4D compared to 2D demand in all the three groups ($p < 0.01$).

3.1.5. Accommodative steady state errors

As shown in Fig. 5, the magnitude of accommodative micro fluctuations was plotted as a function of the accommodative demand. Linear regression fits were used to define the rate of change of micro fluctuations with a change in the accommodative stimulus in each group. The slopes of the regression fits were significantly different between myopes and emmetropes ($F(1, 56) = 59.31$; $p < 0.0001$), myopes and adults ($F(1, 56) = 8.81$; $p < 0.004$) but not between adults and emmetropes ($F(1, 56) = 0.0009$; $p = 0.97$). However, the intercept of the slopes between adults and emmetropes was significantly different ($F(1, 57) = 7.35$; $p < 0.008$). This suggests that emmetropes showed larger variability in their accommodative steady state compared to the adults at all the stimulus demands. A bivariate (Deming) regression was also used to quantify the influence of micro fluctuations on the magnitude of the DOF. As shown in Fig. 6a, accommodative micro fluctuations showed a consistent correlation with

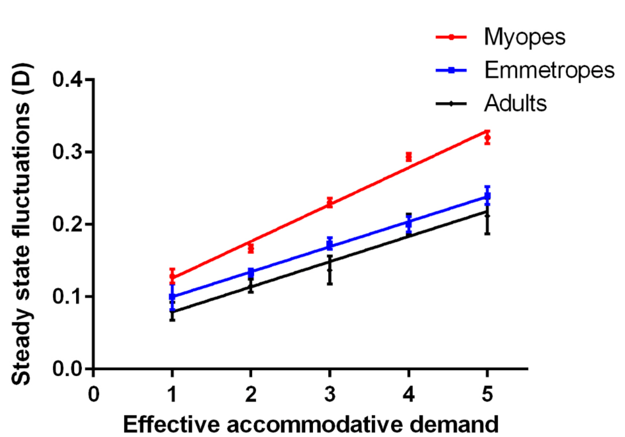

Fig. 5. Steady state fluctuations in the accommodative response were plotted as a function of the effective accommodative stimulus. Linear regression fits were used to identify the rate of change of the micro fluctuations in myopes (red), adults (black) and emmetropes (blue). Micro fluctuations showed a linear correlation with the accommodative demand in both the groups ($p < 0.0001$). Error bars indicate the standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the DOF ($p < 0.0001$).

3.1.6. Pupil size and DOF

Repeated measures ANOVA was used to test whether the difference in pupil size across the stimulus demand and the refractive groups was statistically significant. There was no significant difference in pupil size across the groups ($F = 0.65$; $p = 0.536$) or experimental design i.e. blur detection measures or DOF measures ($F = 0.07$; $p = 0.79$). However, there were significant differences in the pupil sizes across the stimulus demands ($F = 21.57$; $p < 0.001$). Smaller pupils resulted at a 4D compared to 2D demand.

The influence of the difference in the pupil size over the objective DOF estimates across the stimulus demands was tested using repeated measures analysis of covariance (ANCOVA). The three groups (adults, myopes and emmetropes) were considered as between factors. The difference in the objective DOF between the two stimulus demands was considered as the dependent variable and the difference in the pupil size between the two demands was taken as a covariate. No significant influence of the changes in the pupil size on the DOF ($F(1, 14) = 0.87$; $p = 0.36$) was noted across the two stimulus demands. A bivariate regression was also used to quantify the influence of pupil size on the magnitude of the DOF (Fig. 6b). Within the pupil sizes tested in this study, no relationship was found between pupil size and the DOF ($p = 0.79$; Fig. 6b).

3.2. Blur detection thresholds (BDT)

The pupil measures were obtained at both the working distances for the blur detection task from all the three groups, myopes (2D: 5.28 ± 0.68 mm; 4D: 4.96 ± 0.76 mm), adults (2D: 5.10 ± 0.36 mm; 4D: 4.74 ± 0.44 mm) and emmetropes (2D: 5.41 ± 0.67 mm; 4D: 4.98 ± 0.65 mm). There was no significant difference in pupil size across the groups ($F = 0.65$; $p = 0.536$) or experimental design i.e. blur detection measures or DOF measures ($F = 0.07$; $p = 0.79$). However, there were significant differences in the pupil sizes across the stimulus demands ($F = 21.57$; $p < 0.001$). Blur detection thresholds were measured in myopes (BDT_{2D}: 0.37 ± 0.08D; BDT_{4D}: 0.73 ± 0.05D), emmetropes (BDT_{2D}: 0.35 ± 0.02D; BDT_{4D}: 0.72 ± 0.03D) and adults (BDT_{2D}: 0.37 ± 0.02D; BDT_{4D}: 0.67 ± 0.02D). Repeated measures ANOVA was used with groups as the between factor and stimulus demands as the within factor. It showed a significant difference in the blur detection thresholds between 2 and 4D demands ($F = 642.3$; $p < 0.0001$) but not across the groups ($F = 1.80$; $p = 0.19$). Post hoc (Tukey) showed that the blur thresholds at 4D demand were significantly larger than the thresholds obtained at 2D demand ($p < 0.001$).

3.3. Blur sensitivity and accommodation

Accommodative lags ((Myopes DOF_{2D}: 0.64 ± 0.17D; DOF_{4D}: 1.09 ± 0.15D); (Emmetropes DOF_{2D}: 0.35 ± 0.10D; DOF_{4D}: 0.66 ± 0.13D); (Adults DOF_{2D}: 0.33 ± 0.07D; DOF_{4D}: 0.55 ± 0.10D)) were compared with objective DOF and blur detection thresholds across all the three groups (Fig. 7). Repeated measures ANOVA was used to test the difference with group as the between factor and the three parameters including accommodative lags, objective and subjective thresholds as the within factors. At 2D demand, repeated measures ANOVA showed a significant difference between the groups ($F = 80.99$; $p < 0.0001$) and across the three parameters ($F = 6.52$; $p < 0.004$). Post hoc (Tukey) analysis showed that objective DOF were similar to accommodative lags in all the three groups ($p > 0.80$). Furthermore, blur detection thresholds were similar to DOF and accommodative lags in emmetropes ($p > 0.90$) and adults ($p > 0.55$). However, the detection thresholds were significantly smaller compared to objective DOF ($p = 0.01$) and accommodative lags ($p = 0.001$) in myopes ($p < 0.001$). Similarly, at 4D demand, ANOVA showed a

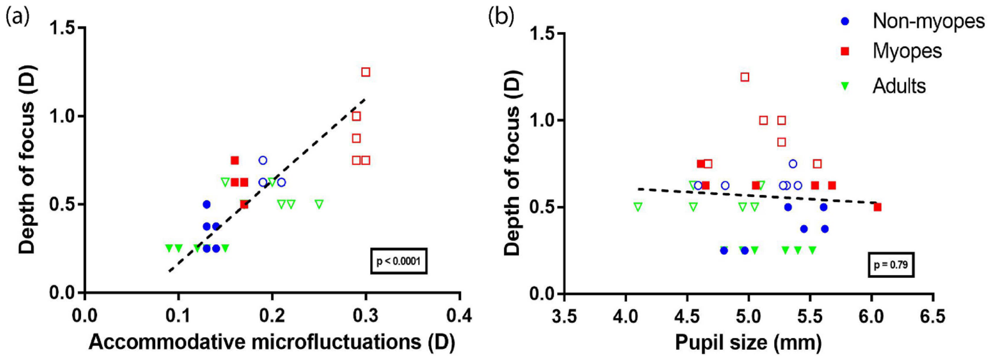

Fig. 6. Depth of focus was plotted as a function of the magnitude of the micro fluctuations (a) and pupil size (b). A bivariate regression (Deming) analysis was used to examine the correlation between the parameters given the variation in both × and y axis. (a) The slope of the regression fit for DOF (y = 4.66x - 0.30) as a function of micro fluctuations was statistically significant from zero ($p < 0.0001$). (b) However, the slope of the regression fit for DOF (y = −0.04x + 0.75) as a function of pupil size was not statistically significant from zero ($p = 0.79$). Closed symbols indicate 2D demand and open symbols indicate 4D demand.

significant difference across the groups ($F = 77.7$; $p < 0.0001$) and between the three parameters ($F = 12.63$; $p < 0.001$). Post hoc (Tukey) analysis showed that DOF measures were similar to accommodative lags in both the groups ($p > 0.95$). However, blur detection thresholds were similar to DOF and accommodative lags only in emmetropes ($p > 0.90$) and adults ($p > 0.45$) but not in myopes ($p < 0.0001$). Objective DOF and accommodative lags were significantly larger in myopic children compared to emmetropes at both the working distances ($p < 0.0001$).

4. Discussion

Blur sensitivity was tested using two parameters, objective DOF and blur detection thresholds. Given that the two measures test different blur pathways (Yao et al., 2010), differences were expected between the two parameters. This difference between the parameters could vary as a function of refractive error or age. For example, DOF measure does not just test subject's sensitivity to blur information. It could also reflect other processes such as subject's ability to accommodate or the sensitivity of the feedback mechanism to blur information, etc. There were three major findings in this study: (1) Progressive myopia had an influence on the magnitude of the DOF and accommodative lags but not on the blur detection ability. (2) Micro fluctuations varied with the magnitude of the DOF (and accommodation). (3) Accommodative response lags, micro fluctuations, DOF and blur detection thresholds were influenced by the accommodative stimulus demand in all the three groups.

4.1. Blur sensitivity

The results of this study pertain specifically to the response of young myopes to a blur cue. It should be noted that under natural viewing conditions (binocular viewing), several other cues such as proximity and vergence are available to drive accommodation effectively (Gwiazda et al., 1993; Rosenfield, Desai, & Portello, 2002; Seidel, Gray, & Heron, 2005; Sreenivasan et al., 2012). Accommodative behavior was reported to be similar between myopic and non-myopic children under binocular viewing conditions (Koomson et al., 2016; Langaas et al., 2008; Weizhong, Zhikuan, Wen, Xiang, & Jian, 2008; Yeo, Atchison, & Schmid, 2013). Furthermore, blur discrimination ability also improves with binocularity (Maiello et al., 2017). Given that the purpose of the current study was to understand if the larger accommodative lags to a blur only cue found in progressive myopes would reflect a large DOF or poor sensitivity to blur, proximity and vergence cues were eliminated and response to blur only cue was examined.

4.2. Objective DOF

Photorefractive measures of accommodation were measured to step (instant) changes in the lens induced defocus to quantify the objective

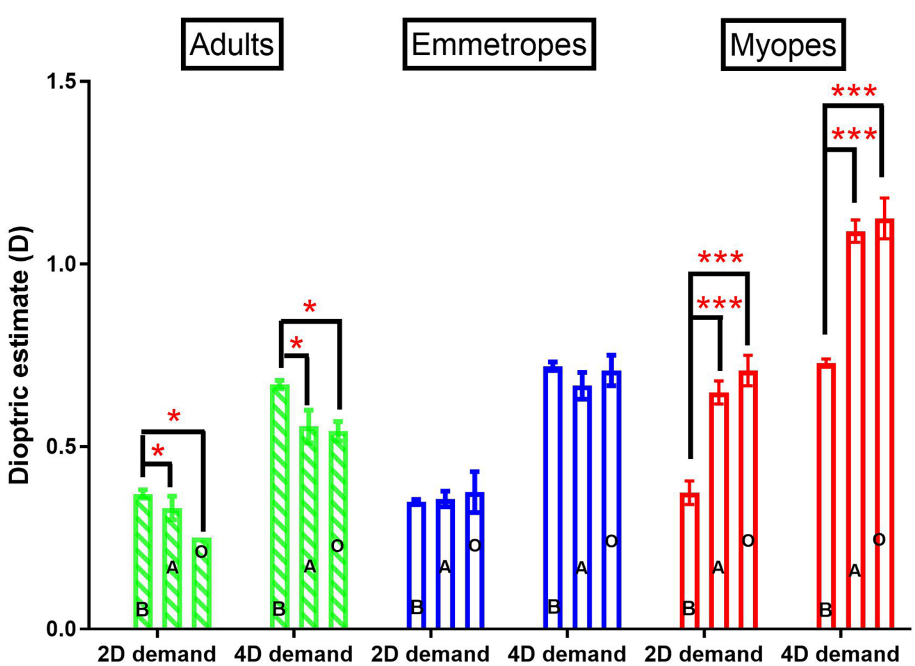

Fig. 7. Blur detection thresholds (B), accommodative lags (A) and objective DOF (O) were compared at each demand in all the three groups: myopes (red, non-myopes (blue) and adults (black). Asterisk symbols indicate statistical significance (* - $p < 0.05$; *** - $p < 0.001$). Error bars indicate the standard error (SE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

DOF at both 2 and 4D demand. In agreement with a previous study on 15 adult subjects (Yao et al., 2010), our study found that the objective DOF increased proportionally with the accommodative demand in adults and children. However, the magnitude of DOF measures in our adult subjects were significantly larger (0.54D ± 0.10D) compared to the previously reported data (0.09D ± 0.02D). It is difficult to explain these discrepancies in the measures given the similarities in the experimental design and pupil sizes tested. The DOF data from adult group, however, were comparable to another study that measured objective DOF on 35 adult subjects with different refractive errors at 4D demand (Vasudevan, Ciuffreda, & Wang, 2006b). A subjective measure of DOF was examined recently on 20 non myopic children between the ages of 6–10 years of age at a 40 cm testing distance (Roberts et al., 2018). The objective DOF measures at similar stimulus demand in the current study were smaller compared to their subjective DOF data (1.88D). The larger variability of subjective measures (Roberts et al., 2018; Yao et al., 2010) might indicate that these measures are less reliable compared to the objective measures of DOF, particularly, in children. In agreement with the previous studies (Charman & Heron, 2015; Day et al., 2006; Sreenivasan et al., 2011), the magnitude of change of steady state micro fluctuations at various stimulus demands was significantly greater in myopes compared to the non-myopic children and adults further supporting its association with accommodative response lags and DOF. In agreement to a recent study (Roberts et al., 2018), our study also found that children showed larger accommodative micro fluctuations compared to the adults across all the stimulus demands.

4.3. Blur detection

Similar to the previous studies, blur detection thresholds were tested using simulated blur in a 2AFC design (Schmid et al., 2002; Watson & Ahumada, 2011). In case of the lens induced defocus, blur is detected by the system when the retinal blur circle exceeds a certain threshold (DOF). However, unlike the lens induced defocus, the task with the simulated blur design was to compare the blurriness of the two targets. Blurriness was determined perceptually and not with respect to an induced retinal blur or accommodation (DOF). Also, optical aberrations would act to alter the retinal blur circle obtained in the objective DOF design, while this would not be the case in the blur detection method. Previous studies found that the interaction of optical blur but not simulated blur with aberrations would induce spatial phase shifts (Ravikumar, Bradley, & Thibos, 2010). Accordingly, it is important to note that simulated blur is inherently different compared to the optical lens induced blur which was used in the DOF design and therefore was used to test two different aspects of blur sensitivity. The blur detection task was separate from that of the DOF measures and done without the Badal optometer. However, similar high contrast targets were used at 50 and 25 cm distances (2D and 4D demands) and were scaled in size to subtend a constant visual angle at both the demands. Accommodation to targets with different levels of rendered blur was measured on four subjects and was found to be similar to that when they viewed the reference target (Appendix B). Past studies on adults showed varying results with respect to the magnitude of blur detection thresholds (Kotulak & Schor, 1986; Roberts et al., 2018; Watson & Ahumada, 2011). The differences could be attributed to factors such as the type (simulated blur or actual targets), experimental design (for example spatial forced choice vs temporal forced choice paradigm or the step size of blur employed, etc.), and the range of pupil sizes tested. A recent study tested blur discrimination thresholds across the visual field in adult myopes and non-myopes. Overall, they found that myopes have poorer ability to discriminate blur compared to the non-myopes. Progression status of the subjects was unclear and could be attributed as the one of the major differences that could have to lead to a difference result. Other differences include the age of the subjects, design and the type of simulated blur employed. Also, the current study employed a blur detection task instead of a discrimination task. However, Schmid et al., have found that discrimination thresholds were similar between progressive myopic children and non-myopes. Therefore, it is difficult to comment if the difference in the task employed lead to this discrepancy in the findings of blur sensitivity.

4.4. Target distance and blur sensitivity

It is well known that DOF can be influenced by several factors including pupil size, luminance, retinal image size, contrast, etc. (Wang & Ciuffreda, 2006). Target characteristics such as contrast, luminance, and the range of spatial frequency content were controlled when quantifying blur detection ability and depth of focus. Retinal image size was kept constant at each working distance in both blur detection and DOF paradigms. Although phenylephrine was used to control the pupil size, a difference in the pupil size was noted between the two working distances across all the groups ($p < 0.05$). However, they did not appear to explain the relationship between stimulus demand and the DOF (Fig. 6b). Previous studies reported that phenylephrine affects pupil size ultimately leading to a change in the depth of field (reviewed by Esteve-Taboada et al., 2016). This change has been found to cause differential effects on accommodation depending the type of method (subjective or objective measure) employed. However, given the pupil sizes were similar between myopes and non-myopic children in both DOF and blur detection design, we predict that effect of phenylephrine would be similar in the two refractive groups. Several studies showed that significant changes in the DOF would occur only with smaller pupil sizes (< 2 mm) due to diffraction effects. Given the range of pupil sizes tested in this study, a change of not more than ≈0.1D is expected in the DOF with the variation in the pupil size (Ciuffreda, 2006). Recently, studies found that depth of focus was correlated with accommodative micro fluctuations (Day et al., 2009; Roberts et al., 2018; Yao et al., 2010). In agreement, our study found a positive relationship between accommodative micro fluctuations and DOF (Fig. 6a). Like the objective DOF measures, blur detection thresholds in the current study also showed a proportional increase with an increase in the accommodative demand in all the three groups. Given that this behavior was noted in adults too, the influence of age on such factors as the level of cognitive and attentional ability or can be ruled out. Since the pupil size and micro fluctuations were not monitored continuously during the blur detection task, pupil analysis was not performed on blur detection measures. However, we hypothesize that the larger steady state micro fluctuations found at a closer demand may explain the large blur detection thresholds both in children and adults.

Retinal image quality is not just limited to defocus. The interaction of higher order aberrations (HOA), especially spherical aberrations (SA) and defocus would vary as a function of age, accommodative demand and pupil size (López-Gil et al., 2008; Plainis, Ginis, & Pallikaris, 2005). The interaction would also vary based on the refractive group with myopes exhibiting an overall increase in the magnitude of HOA with a relatively more negative spherical aberration (Charman, 2005; He, Gwiazda, Thorn, Held, & Vera-Diaz, 2005). Although aberrations were not measured in the current study, it should be noted that the individual level of aberrations and their interaction with the lens induced defocus would be different in different groups at 2 and 4D demand (Plainis et al., 2005; Theagarayan et al., 2009; Thibos, Bradley, Liu, & López-Gil, 2013). Previous studies on children and young adults reported poorer image quality in myopes compared to non-myopes (He et al., 2005; Sreenivasan, Aslakson, Kornaus, & Thibos, 2013). He et al., reported a negative correlation between the accommodative lags and Strehl ratio (He et al., 2005). Therefore, in addition to the steady state fluctuations, it is possible that the differences in the accommodative lags (or DOF) obtained at the two demands could be attributed to the differences in the optical aberrations and/or retinal quality, especially in progressive myopic children. Furthermore, although a linear dioptric change is expected based on the way the rendered blur was produced

(Strasburger, Bach, & Heinrich, 2018), it should be noted there is an inherent difference in the way that the optical defocus (objective DOF design) would interact with visual system, especially optical aberrations, compared to the simulated blur (blur detection design). Therefore, the differences obtained between the two sensitivity measurements across the three groups could possibly be attributed to difference in the type of blur employed.

The findings of an increasing micro fluctuations, depth of focus and accommodative lags with increasing stimulus demand cannot be explained by a constant DOF parameter that is used in the current models of accommodation and vergence (Schor & Bharadwaj, 2006; Schor, 1992). A gain parameter such as the accommodative sensory gain (ASG) would predict this behavior of DOF with an increase in the stimulus demand (Jiang, 1997). It is difficult to comment at this point on why the DOF behaves in this manner, but we speculate that this increased optical blur at closer distances might be used to extract depth information from a given natural scene (Zannoli, Love, Naraian, & Banks, 2016). Also, the dioptric gradient would be significantly larger up-close compared to objects placed closer to the far point. For example, imagine two scenarios (1) person looking at a computer screen placed at 40 cm; (2) and a person looking at a tree 6 m away. A change in the fixation in the first case would cause a significantly larger shift in the dioptric defocus compared to the second case with an object at the far point. Therefore, it would be logical to have a larger depth of focus (i.e. greater ability to tolerate defocus) up-close compared to objects farther away.

4.5. Myopia and blur sensitivity

Unlike the case of DOF, with an increased accommodative demand, the change in the accommodative lag and accommodative micro fluctuations found in the young myopes was not coupled with an increase in blur detection thresholds. The similarity in the blur detection thresholds between the myopic and non-myopic children agrees with a previous investigation (Schmid et al., 2002). However, their study did not examine the DOF. A recent study on non-myopic children and adults found that blur detection thresholds varied with accommodative micro fluctuations (Roberts et al., 2018). Given this finding, the increase in blur detection arising from increased accommodative demand (25 cm) may have resulted from increased accommodative steady state fluctuations as measured at the same demand using the Badal optical system (Fig. 5). However, in the case of the myopes, their relative increase in accommodative fluctuations in the Badal measures was not associated with an increase in blur detection threshold. If the accommodative responses were similar between the DOF and blur discrimination studies, the disparity between perceived blur and retinal defocus could reflect some form of a perceptual adaptation to preserve the subjective sense of clarity or visual resolution even with a defocused image on the retina (Wang et al., 2006; Webster et al., 2002). Perceptual or blur adaptation is a well-established phenomenon wherein the subject's visual resolution tends to improve after a brief period of adaptation to a blurred environment. This adaptation has been postulated to result from gain adjustments in the visual channels that process the spatial information. Given the reduced behavior of accommodation in myopes, the persistent defocus on the retina might possibly lead to a similar form of gain adjustment in the visual channels ultimately leading to this unique behavior that we found in these young myopes.

Accommodative behavior has been long studied in progressive myopia (Sivak, 2012). However, the causal link between the two remains unclear. Ophthalmic treatments in the form of near addition lenses (bifocals or PALs) have not provided clear evidence for a motor etiology. The basis of their application aimed initially at reducing the accommodative effort (thus reducing accommodative lags) have been ineffective to arrest the development and progression of myopia (Berntsen, Sinnott, Mutti, & Zadnik, 2012; Gwiazda et al., 2003, 2004). In agreement, our earlier study supports the notion of reduced blur sensitivity as the causative agent which can account for the lags of accommodation and related AC/A patterns during myopic progression (Labhishetty & Bobier, 2017). We predict that the reduced blur sensitivity then may be a consequence arising during excessive ocular growth that leads to this well characterized abnormal pattern of accommodation in myopic children. It would be interesting to see if the changes in the resulting accommodative pattern proves to be a more sensitive measure than refractive or axial length changes as means to determine the efficacy of a given myopia treatment in children.

5. Conclusion

The high lags of accommodation to blur only cue found during myopia progression are associated with a larger DOF. Increased accommodative micro fluctuations appear to underlie the findings of increased DOF. However, young progressive myopes can readily detect/differentiate a blurred object similar to their non-myopic peers and this atypical behavior could possibly arise from some form a compensatory mechanism such as the blur adaptation to preserve the subjective percept even with a poor retinal image quality.

Acknowledgments

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Appendix A

A.1. Sample size calculations

Sample size calculations for this particular study were done based on the pilot data on the Objective DOF obtained from 3 myopes and 3 non-myopes. The mean and standard deviation obtained from the myopes (0.95 ± 0.18D) and non-myopic children (0.62 ± 0.12D) were used to calculate the effect size. Based on the effect size, a sample size of 6 subjects/group was calculated (with $\alpha = 0.05$; Power $(1 - \beta) = 0.90$).

Our results on similar blur detection thresholds is in agreement with a previous study which tested blur detection and discrimination thresholds on 20 progressive myopic children and compared them to 20 age matched non-myopic children (Schmid et al., 2002).

Appendix B

B.1. Control experiment – accommodative behavior to simulated blurred targets

A control experiment was performed on 4 subjects from the adult subgroup (26.5 ± 1.91 years) at 50 and 25 cm. The purpose was to determine whether the blurring the target induced any change in accommodative steady state. A 5 min dark adaptation period was given prior to the start of the experiment. Two targets (no blur and 1D blur) were presented successively at the center of the Macbook screen for 5 s each with an inter-stimulus interval of 5 s. Accommodative response from the right eye was continuously recorded using the dynamic photorefraction system (DPRS). This was

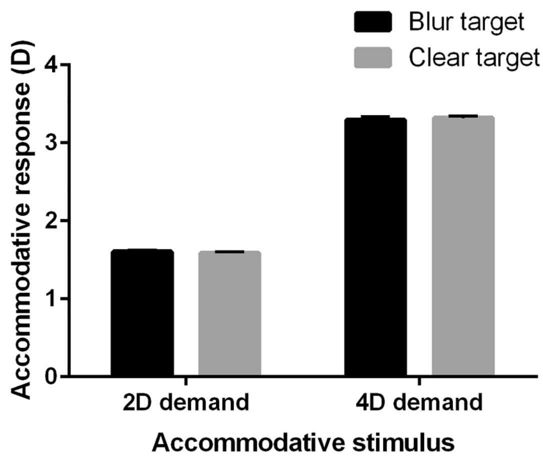

Fig. 8. Accommodative response was measured while the subjects looked at the no blur and 1D blur targets both at 2D and 4D demand. Error bars indicate the standard error (SEM).

repeated at two working distances, 25 cm and 50 cm from the subject (Fig. 8). The extent of the targets was adjusted to subtend a constant angular size at each distance.

These simulated targets did not result in any significant changes in the accommodative steady state at either 50 cm (Blur target: 1.60 ± 0.05D; Clear target: 1.58 ± 0.02D) or 25 cm (Blur target: 3.29 ± 0.10D; Clear target: 3.31 ± 0.04D) working distances in any subject. Therefore, targets were used to quantify the subjective blur thresholds in children using an adaptive psychophysical design.

Appendix C

C.1. Control experiment – luminance

This experiment was done to rule out possible influence of luminance difference between the reference and blur target on the final blur detection measures. First, luminance of the blur target (different levels) was measured along with the reference (no blur) target using Minolta Chroma meter CS-100 (Minolta Camera Co. Ltd., Japan). Table 3 shows the luminance of blur targets ranging from 0D to 1D (0.1D steps). The luminance of the blur target was then plotted as a function of the dioptric approximate of the target.

A linear regression equation, as shown below, was used to quantify the relationship between luminance and the dioptric estimate, where x is the luminance estimate and y is the corresponding dioptric value.

$$y(D) = (-0.0239 * x(\text{cd/m}^2)) + 6.85$$

C.2. Psychophysical experiment

The procedure employed for calculating the luminance thresholds was similar to the blur detection task described previously. Luminance thresholds were determined using a 2-alternate forced choice (AFC) paradigm. Subjects looked at the screen placed at 50 cm with their left eye occluded. Two targets (reference and test), which were spatially separated, were presented on a screen with different levels of luminance. The reference target was always maintained at the maximum luminance (i.e. luminance of a no blur target (L)) and the test target with a variable luminance level). Stimuli were presented for 10 secs for each condition with an inter-stimulus interval of 2 s. The spatial position of the targets was randomized to avoid predictability. The luminance value was subsequently varied within a 2-down 1-up adaptive staircase, whereby the luminance changed by 50% until the first reversal and 25% thereafter. The staircase was terminated after 6 reversals and the luminance threshold was calculated from the average of last 5 reversals. The final luminance value was converted into the dioptric approximate by using the regression equation as shown above.

Table 3
Luminance measures of high contrast targets with varied levels of blur filters.

Dioptric filter (D)	Luminance (cd/m^2)
1	139.1333333
0.9	145.95
0.8	154.6666667
0.7	165.5
0.6	166.15
0.5	166.5333333
0.4	167.5666667
0.3	170.8
0.2	175.65
0.1	178.5
0	180.85

Table 4
Comparison between actual blur detection thresholds and blur thresholds calculated based on the luminance values.

Subject	Blur detection threshold (D)	Blur threshold (D) estimate based on the luminance measures (cd/m^2)
1	0.32	0.8302
2	0.38	1.4994
3	0.46	2.2403
4	0.4	0.7824
5	0.36	0.9019
6	0.32	0.7107

The experiment was performed initially on six naïve adults (28 ± 2.82 years). The measures of blur detection threshold and luminance threshold were obtained on two separate days. The blur estimates obtained based on the luminance threshold values were significantly larger than the actual blur detection thresholds (see Table 4). This suggests that the difference in the luminance cue would not explain the magnitude of blur detection thresholds seen in our subjects.

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