Article

The Effects of Spatial Frequency on the Accommodative Responses of Myopic and Emmetropic Chinese Children

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Purpose: The spatial frequency (SF) characteristics of accommodation in children are not well understood. In this study, we measured accommodative responses to grating targets to investigate the SF dependence of accommodation in children.

Methods: The effects of SF and contrast on the accommodative system were evaluated in two groups of children, including 22 with emmetropia and 20 with myopia. The contrast detection thresholds at five SFs were measured using a near-contrast sensitivity function test. The accommodative responses to grating targets with low (1.5 cycles per degree [cpd]), medium (6 cpd), and high (18 cpd) SFs were measured with a Grand Seiko WAM-5500 in dynamic mode for 30 seconds under standard and detection threshold contrast conditions. The accommodative lag and accommodative microfluctuations (AMFs) were compared between the two groups.

Results: Under standard contrast conditions, no significant difference was found in the accommodative lag across SFs ($F = 2.03$, $P = 0.14$) or between the two groups ($F = 3.57$, $P = 0.07$). The AMFs were lowest at 6 cpd in emmetropia group ($F = 6.51$, $P = 0.003$) and in total ($F = 10.82$, $P < 0.001$). Children in emmetropia group showed greater AMFs at high SFs under detection threshold contrast conditions than under standard contrast conditions ($P < 0.05$).

Conclusions: This study demonstrated that the instability of accommodation was SF dependent in children. The AMFs in children were smallest at the medium SF for standard contrast grating targets. Myopic children are less sensitive to the low-contrast-induced blur for high SFs than emmetropic children.

Translational Relevance: This study provides a possibility to stabilize accommodative response of children by transforming SF components of fixation targets.

Introduction

Accommodation is a widely studied physiological parameter of the visual system. The accommodative response can be easily affected by the characteristics of the target, especially spatial frequency (SF)[1–8] and contrast.[8–12]

The controversial results regarding the effects of SF and contrast on accommodation obtained in different studies led us to investigate the effect of SF on the accommodative response in myopic and emmetropic adults under various detection demands created by varying the contrast.[1]

In our 2015 study, accommodative microfluctuations (AMFs), which were defined as the standard deviations of the accommodative responses,[13] were lowest at the SF of six cycles per degree (cpd), which was in agreement with the contrast-control hypothesis.[4,14] The accommodative response is most stable over midrange spatial frequencies, in which the visual sensitivity for detecting contrast is greatest. The accommodative responses and AMFs increased at certain SFs under near-threshold contrast conditions,

indicating that the accommodative stability was impaired under threshold contrast conditions.[12] To obtain reliable data, earlier studies were mostly performed on adults due to their relatively stable refractive statuses and accommodative systems. To our knowledge, no studies have analyzed children's accommodative responses to various SF grating targets or low-contrast targets.

Previous studies[6,15–17] reported that AMFs were greater in myopes than in emmetropes in both adults[6,15] and children,[16,17] indicating that AMFs may be a risk factor for myopia progression. A 2-year data set of early-onset myopic children[17] demonstrated that accommodation instability was a weak predictor of myopia progression. Greater variability in the accommodative response might increase the hyperopic retinal blur[18] and thus lead to myopia. A recent study[6] in young adults also reported an apparent difference in AMFs between emmetropes and myopes at an SF of 16 cpd. However, our study in adults[1] did not find any significant difference in AMFs across SFs between the myopic and emmetropic groups.

In summary, few data are available on the effect of SF and contrast on accommodation behavior in children. Therefore, this study investigated the SF dependence of the accommodative response and AMFs in emmetropic and myopic children. Understanding how the accommodative system in children behaves under threshold contrast conditions was an important goal.

Methods

Subjects

Forty-two children aged 9 to 13 years participated in this study. The children were divided into two groups: 22 children with emmetropia (EMM group) (age: 10.8 ± 1.04 years, spherical equivalent [SE]: 0.20 ± 0.20 D, −0.25 to +0.50 D from noncycloplegic retinoscopy and subjective refraction, uncorrected visual acuity 0.0 logMAR or better) and 20 children with myopia (MYO group) (age: 11.4 ± 0.97 years, SE: −2.04 ± 0.44 D, −1.25 to −2.88 D from noncycloplegic retinoscopy and subjective refraction, corrected visual acuity 0.0 logMAR or better). The myopia progression of the MYO children was at least 0.50 D[19–21] per year according to their medical records. The subjects had an astigmatism less than 0.50 D and a best-corrected visual acuity of at least 0.0 logMAR. Parents or guardians provided informed consent for their children after receiving an explanation of the nature and possible consequences of the study. The study was approved by the ethics committee of the Ophthalmology and Optometry School of Wenzhou Medical University and the WEIRC Scientific Committee and was conducted in accordance with the Declaration of Helsinki.

Procedure

Contrast Detection

Children in the MYO group were corrected with their SE prescriptions in trial frames. A single ophthalmic lens was used in a trial frame, and the lens was aligned and set up carefully during measurement. Subjects in the EMM group also wore trial frames without any trial lenses. The left eye was occluded during the measurements. Using a method similar to that described for adults,[1] sine wave Gabor targets in five spatial frequencies (1.5, 3, 6, 12, and 18 cpd; with standard contrasts of 25%, 20%, 12.5%, 25%, and 66.7%, respectively) were presented in the center of the screen (Nexus 7 tablet, 2013 model, Google, Inc., Mountain View, CA) and placed 33 cm from the subject. The target maintained an angular subtense of 7°, and the average luminance of the target background was 95.3 cd/m². The horizontal and vertical gratings for all five spatial frequencies were presented in a random order of descending contrast. The contrast-descending strategy[1] for each SF simulated the contrast variation of the grating targets of the CSV-1000 (VectorVision, Greenville, OH). In this sequential forced-choice procedure, the subjects were asked to choose the direction of the gratings by pressing the direction key in a gamepad, and the detection threshold for each SF was determined using the mean value of three measurements.

Accommodation Experiments

The dynamic accommodative responses were measured after the contrast detection threshold measurements. The accommodative responses of the right eyes were recorded for 30 seconds with an open-field autorefractor (Grand Seiko WAM-5500, Hiroshima, Japan) while the subjects viewed a fixation target in the center of the screen 33 cm away. The targets were represented by vertically oriented Gabor patches at three SFs (1.5, 6, and 18 cpd) and were presented in a random order for 30 seconds in two contrasts (i.e., the detection threshold contrast obtained earlier and the standard contrast [described in Xu et al.[1]]), with an interval of at least 1 minute

between measurements. During each measurement, the subjects were instructed to fixate at the center of the target and to keep the target in focus. To record continuous accommodative responses, the autorefractor was in high-speed (5 Hz) mode and connected to a computer. To guarantee the fixation stability, the examiner monitored the eye movements of the subjects using the screen of the Grand Seiko infrared autorefractor and the real-time accommodative response data displayed on the computer screen. The examiner reminded the subject to focus on the grating targets if extra eye movements or abnormal accommodative response data occurred. The accommodative demand and accommodative response were calculated using the following equations.[22]

$$
\text{Accommodative demand} =
$$
$$
((1/\text{DTE}) - \text{Lens} + \text{Rx}
$$
$$
+ ((\text{DLE} * 1/\text{DTE}) * (\text{Lens} - \text{Rx})))/
$$
$$
(1 - (\text{DLE} * (\text{Lens} + \text{Rx})));
$$

$$
\text{Accommodative response} =
$$
$$
(\text{Rx}/(1 - \text{DLE} * \text{Rx} - (\text{Lens}/(1 - \text{DLE} * \text{Lens}))))
$$
$$
- \text{R1},
$$

where R1 is the reading of the autorefractor, Rx is the best subjective correction for infinity, DTE is the distance from the eye to the target, DLE is the distance from the lens to the eyes (12 mm), and Lens is the signed dioptric power of the lens. The accommodative response was subtracted from the accommodative demand at 33 cm to obtain the accommodative lag.

Data Analysis

The differences in the mean values of the detection thresholds among the spatial frequencies and refractive groups were analyzed with repeated-measures analysis of variance (ANOVA).

Any abnormal data due to blinking were removed automatically with customized software for the Grand Seiko WAM-5500 in high-speed mode. The data points of the first 2 seconds were filtered out for more stable and accurate responses. Blinks were identified by refractive changes greater than 6 D/s. Data points from one point before and after the blink were removed. Data rows containing at least 100 effective data points after satisfying the above criteria were accepted for analysis. The AMFs were quantified as the standard deviations of continuously measured accommodative responses for 30 seconds.

AMFs were obtained per SF and contrast. Repeated-measures ANOVAs with a between-subject factor of the group (EMM versus MYO) and within-subject factors of the SFs (1.5, 6, and 18 cpd) and contrasts (detection threshold contrast versus standard contrast) were performed to analyze the data.

Results

Contrast Detection Threshold

Figure 1 illustrates the l g contrast sensitivity for the EMM and MYO groups. The value increased from 1.5 to 3 cpd and decreased for the higher SFs across both groups ($F = 265.27$, $P < 0.001$). No significant differences were observed between the groups at the tested SFs ($F = 2.51$, $P = 0.12$).

Standard Contrast Condition

Accommodative Lag

The accommodative lag showed no significant difference across SFs ($F = 2.03$, $P = 0.14$) (Fig. 2). The accommodative demand in the MYO group was 2.86 ± 0.03 D, which was statistically smaller than the demand of 3 D in the EMM group ($t = 22.05$, $P < 0.001$). However, no significant difference in the accommodative lag was found between the EMM and MYO groups ($F = 3.57$, $P = 0.07$).

Accommodative Microfluctuations (AMFs)

For all of the subjects, a significant difference in the AMFs among the SFs ($F = 10.82$, $P < 0.001$) was observed for the standard contrast grating targets. As illustrated in Figure 3, the AMFs were lowest at 6 cpd (SF 1.5, 6: $P = 0.001$; SF 6, 18: $P = 0.014$). There was no significant difference between the EMM and MYO groups ($F = 0.356$, $P = 0.554$). For EMM group, the AMFs were lowest at 6 cpd ($F = 6.51$, $P = 0.003$; SF 1.5, 6: $P = 0.012$; SF 6, 18: $P = 0.025$). For MYO group, the AMFs tended to be the lowest at 6 cpd. ($F = 4.81$, $P = 0.014$; SF 1.5, 6: $P = 0.012$; SF 6, 18: $P = 0.359$).

Detection Threshold Contrast Condition

Under the detection threshold contrast conditions, no significant differences in the accommodative lags were found between the EMM and MYO groups ($F = 1.26$, $P = 0.30$) or among the SFs ($F = 0.42$, $P = 0.66$). Figure 4 showed that the AMFs were similar across the different SFs ($F = 0.90$, $P = 0.39$). Additionally, no significant difference was observed between the two groups ($F = 0.87$, $P = 0.36$).
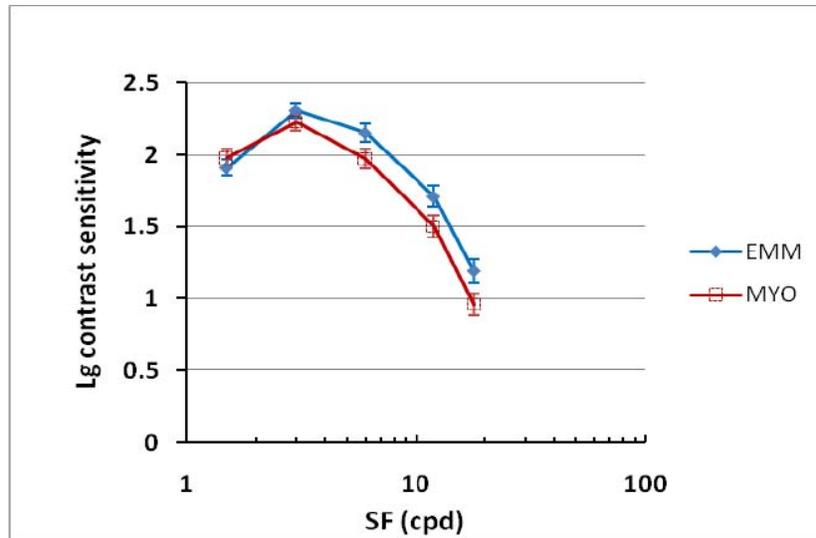
Figure 1. Mean contrast detection thresholds of the EMM and MYO at 33 cm. The *error bars* represent standard errors.

Standard Contrast Versus Threshold Contrast

No significant difference was observed in the accommodative lag between the standard contrast and threshold contrast grating stimuli in the EMM group ($F = 0.44$, $P = 0.52$) or the MYO group ($F = 1.28$, $P = 0.27$).

In the EMM group, the AMFs were significantly greater for the threshold contrast grating targets than for the standard contrast grating targets at 6 cpd ($F = 4.55$, $P < 0.05$) and 18 cpd ($F = 4.48$, $P < 0.05$). In the MYO group, the accommodative lag ($F = 1.28$, $P = 0.27$) and AMFs ($F = 0.16$, $P = 0.70$) were not significantly different between the threshold contrast grating targets and the threshold contrast gratings (Fig. 5).
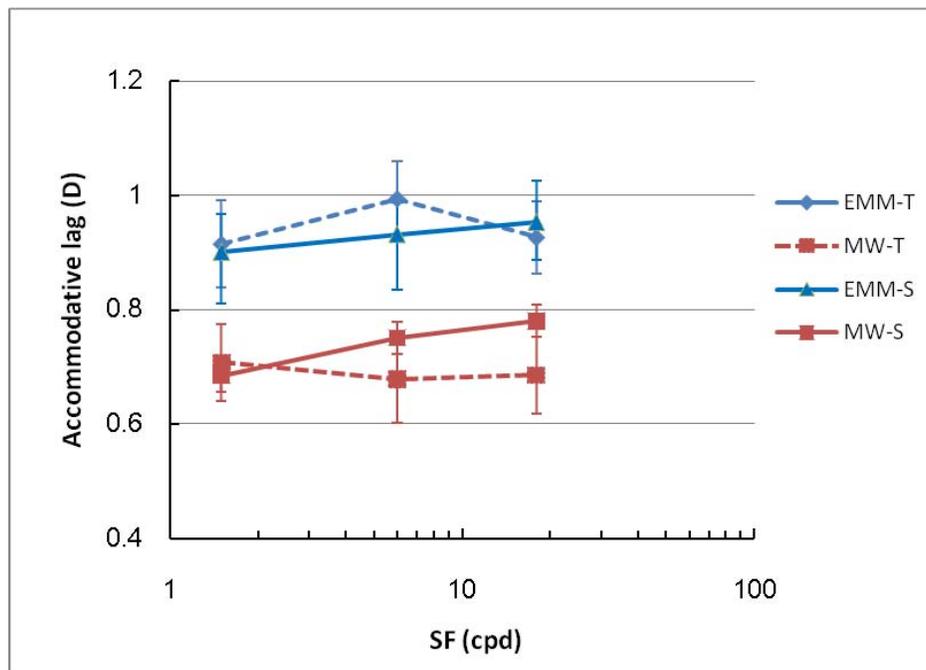

Figure 2. Accommodative lags of the EMM and MYO groups under standard contrast conditions (S) ($F = 3.57$, $P = 0.07$) and threshold contrast conditions (T) ($F = 1.26$, $P = 0.30$). The *error bars* represent standard errors.
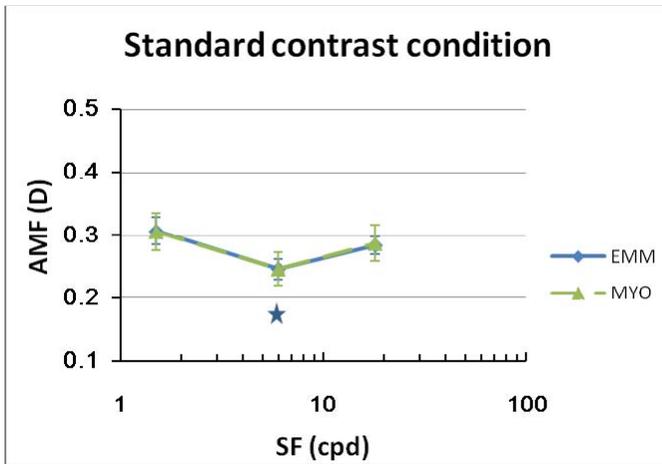
Figure 3. AMFs at low, medium, and high SFs under standard contrast conditions for the EMM and MYO groups. The *error bars* represent standard errors. The *asterisks* indicate significant differences in the AMFs among SFs.
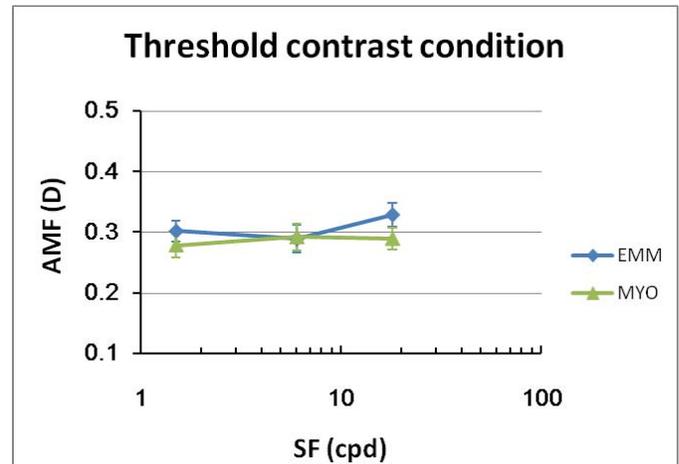

Figure 4. AMFs across various SFs under threshold contrast conditions for the EMM and MYO groups. The *error bars* represent standard errors.

Discussion

This study demonstrated the SF dependence of AMFs in children, which was the same as the dependence reported in adults in our previous study.[1] However, the accommodation to the threshold contrast target differed between children and adults as well as between the refractive groups.

Accommodation Lag

To the best of our knowledge, no study has reported the accommodative behavior of children fixating on SF grating targets. This study demonstrated that children showed different accommodative behavior patterns than the adults. Under standard contrast conditions, the accommodative lag had no significant differences across SFs, which contradicted studies on adults that showed an increase in the accommodative response for higher SFs.[23,24]

In this study, no significant differences in the accommodative lag were found among the refractive groups under the standard or threshold contrast conditions. The difference in the accommodative demand between the EMM and MYO groups did not induce a significant difference in the accommodative lag, indicating this difference in the accommodative lags would be even smaller with the same accommodative demand. The association between accommodative lag and myopia development has been debated in the literature. Earlier studies[20,22,25] reported an increased lag of accommodation in

progressing myopes, which resulted in hyperopic retinal defocus and led to myopia progression. Later studies[26–29] questioned this finding because the development of myopia in young adults or children was not accompanied by an increased lag of accommodation. A large-scale study[30] indicated that the increased lag of accommodation may be a consequence, not a cause, of myopia. As reported in some studies,[31,32] the lag in accommodation could have been greater before the emmetropes became myopic. In addition, some longitudinal studies[27,28] showed that the lag in accommodation was not associated with yearly myopia progression. Based on our findings, the accommodative lag was not a good indicator of the differences between emmetropes and myopes.

Accommodative Microfluctuations

Similar to the findings in adults,[1,4,6,7,33] this study demonstrated the lowest AMFs for children at 6 cpd, supporting the contrast-control hypothesis.[4,14] AMFs represent accommodative errors that may be used to detect the direction and magnitude of the required response. Previous studies[15–17] have indicated that AMFs might be a risk factor for myopia progression, considering the blur signal they may produce. However, we did not find a significant difference in AMFs for the same frequency between the EMM and MYO groups. The differences of AMFs among SFs were more obvious in EMM group because there were smaller standard deviations in EMM group. In the present study, grating of a certain SF was used as the fixation target, whereas previous studies used text, a
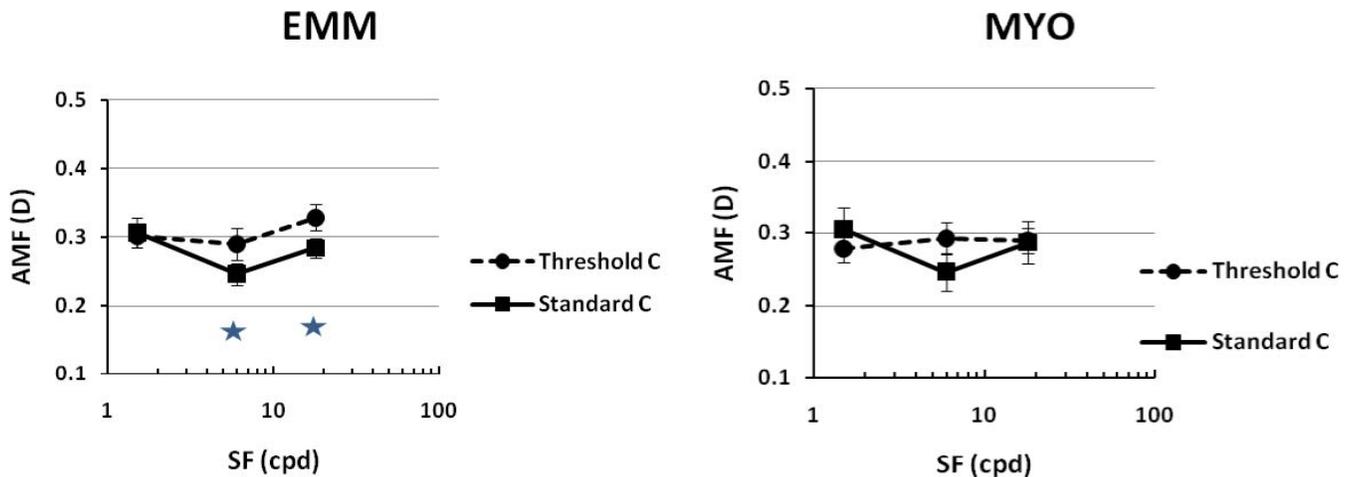
Figure 5. AMFs across low, medium, and high SFs under the threshold contrast conditions (Threshold C) and standard contrast conditions (Standard C) for the EMM and MYO groups. The *asterisks* indicate significant differences in the AMFs between the two contrast conditions. The *error bars* represent standard errors.

Maltese cross and/or an image that contained various SFs. For broadband targets, myopes and emmetropes may choose different SF components to maintain accommodation, causing differences in AMFs. This possibility requires further confirmation.

Standard Contrast Versus Threshold Contrast

The present results showed that neither the accommodative lag nor AMFs under threshold contrast conditions were SF-dependent in the EMM and MYO groups, similar to findings for adults.[1] However, in contrast to the accommodative lag in adults, the accommodative lag in myopic children did not show any improvement under the threshold contrast conditions, and their accommodative responses were relatively stable even under threshold contrast conditions. Some researchers have asserted that the accommodative responses would decrease to a resting state under very low-contrast conditions,[7,10,34] whereas others have indicated that they should increase to a much higher level.[1,11] The nearly empty field caused by the threshold contrast may result in an open-loop condition of accommodation to decrease the accommodative responses; alternatively, the accommodative responses may greatly increase for some SFs because of the subsequent blur-induced and voluntary accommodations. The accommodation measurement was easily influenced by two main factors, the instructions to the subjects and the influence of higher level control. Because the instructions to the subjects were quite consistent, the voluntary components may play a major role. The

accommodative responses in children did not decline to a rest level under low-contrast conditions, which did not accord with the first hypothesis. We speculate that the accommodative response strategy used for low-contrast targets differs between children and adults. The children may not have learned how to use a voluntary accommodative response to increase the contrast of the targets, which may partially explain the results of a study reporting a decrease in the accommodative lag from children to young adults.[35]

This study also found that the variation in AMFs under the two contrast conditions differed among the ametropia groups. The MYO group did not show any significant variation between the threshold contrast conditions and the standard contrast conditions, whereas increased AMFs with medium and high SFs, especially high SF, were observed in the EMM group under threshold contrast conditions. Our previous study in adults (Xu et al.[1]) showed that the accommodative variation increased as the contrast decreased[7] and that the effect of the low-contrast-induced blur was more obvious at higher SFs than at low SFs.[36] The increase in the AMFs at high SFs may result from detection of the blur signal induced by low contrast. The increased AMFs at high SFs under threshold contrast conditions that were observed in the EMM group but not the MYO group indicated that the children with myopia may be less sensitive to the blur than the children with emmetropia, supporting the previous finding[37] in adults that myopes were less sensitive to the presence of blur than emmetropes. However, the low-contrast-induced blur signal only

affected the instability of accommodation but not the amount of accommodative response at high SFs in children. It indicated AMFs were more SF dependent than accommodative responses. In our previous study conducted with adults[1] using a similar method, the AMFs increased at the high SFs for both MYOs and EMMs. We speculate that progressive myopic children are more dull to blur signals compared with EMMs and myopic adults.

The results of this study reveal the characteristics of accommodation for low-, medium-, and high-SF grating targets at two contrasts in emmetropic and myopic children. For the standard contrast gratings of the low, medium, and high SFs, the accommodative lags in the MYO group were 0.68, 0.75, and 0.78 D, respectively. These lags were close to the reported mean values of 0.76 D[28] and 0.74 D[29] in myopic children at similar ages and refractive conditions, respectively, when fixating on a target consisting of a 5×5 array of Chinese characters at a distance of 33 cm. The average AMFs in the MYO and EMM groups were between 0.25 and 0.31 D, which was comparable with a previous study that reported AMFs in emmetropic and myopic young adults of between 0.24 and 0.27 D using a high-contrast Maltese cross as a fixation target at a distance of 33 cm.[38] The current data show that the children's accommodative responses to the SF grating target were comparable with the accommodative responses to broadband visual targets.

In this study, no marked difference in the contrast sensitivity was found between the EMM and MYO groups, in accordance with the results of some previous studies[38,39] in adults.

Conclusions

This study demonstrated that instability of accommodation but not the amount of accommodation is SF dependent in children. The AMFs were the lowest at the medium SF in children for standard contrast grating targets. Based on our results, children with myopia are less sensitive to the low-contrast-induced blur for high SFs than children with emmetropia.

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