

# Study of the Immediate Effects of Autostereoscopic 3D Visual Training on the Accommodative Functions of Myopes

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**Received:** October 24, 2021

**Accepted:** January 10, 2022

**Published:** February 3, 2022

Citation: Huang Y, Li M, Shen Y, et al. Study of the immediate effects of autostereoscopic 3D visual training on the accommodative functions of myopes. *Invest Ophthalmol Vis Sci.* 2022;63(2):9. <https://doi.org/10.1167/iovs.63.2.9>

**PURPOSE.** Stereoscopic viewing has an impact on ocular dynamics, but its effects on accommodative functions are not fully understood, especially for autostereoscopic viewing. This study aimed to investigate the changes in dynamic accommodative response, accommodative amplitude, and accommodative facility of myopes after autostereoscopic visual training.

**METHODS.** We enrolled 46 adults (men = 22 and women = 24; age =  $21.5 \pm 2.5$  [range = 18–25] years, spherical equivalent:  $-4.52 \pm 1.89$  [–8.88 to –1.75] diopters [D]) who visited the Eye & ENT Hospital of Fudan University. The study population was randomly divided into three-dimensional (3D) and two-dimensional (2D) viewing groups to watch an 11-minute training video displayed in 3D or 2D mode. Dynamic accommodative response, accommodative facility, and accommodative amplitude were measured before, during, and immediately after the training. Accommodative lag and the variability of accommodation were also analyzed. Visual fatigue was evaluated subjectively using a questionnaire.

**RESULTS.** Accommodative lag decreased from  $0.54 \pm 0.29$  D to  $0.42 \pm 0.32$  D ( $P = 0.004$ ), whereas accommodative facility increased from  $10.83 \pm 4.55$  cycles per minute (cpm) to  $13.15 \pm 5.25$  cpm ( $P < 0.001$ ) in the 3D group. In the 2D group, there was no significant change in the accommodative lag ( $P = 0.163$ ) or facility ( $P = 0.975$ ), but a decrease in accommodative amplitude was observed (from  $13.88 \pm 3.17$  D to  $12.71 \pm 2.23$  D,  $P = 0.013$ ). In the 3D group, the accommodative response changed with the simulated target distance. Visual fatigue was relatively mild in both groups.

**CONCLUSIONS.** The immediate impact of autostereoscopic training included a decrease in the accommodative lag and an increase in the accommodative facility. However, the long-term effects of autostereoscopic training require further exploration.

Keywords: autostereoscopic 3D, accommodation, myopia, visual training

Display devices and technologies have developed rapidly in the past decades, especially three-dimensional (3D) stereoscopic displays. From early approaches, such as color and polarization-interlaced stereoscopic displays to virtual reality (VR) and autostereoscopic displays, the quality of the presented content is promoted, and these approaches have been widely used for industrial, military, medical, and entertainment purposes.<sup>1-3</sup> The autostereoscopic 3D display is a newly developed technology in which a transparent sheet of lenticular optical elements is mounted in front of a standard liquid-crystal display controlling the exit angle of photons to achieve binocular disparity.<sup>4</sup>

Since the first stereoscopic technology was introduced, the effects of stereoscopic displays on the human visual system have been extensively investigated. One major issue

in these studies is visual fatigue, which is supposedly caused by accommodation-convergence mismatch (i.e. the conflict between the constant accommodative stimulus (AS) and a varying vergence stimulus).<sup>5-7</sup> The aftereffects of viewing stereoscopic 3D displays have also been evaluated in various studies, revealing that stereoscopic viewing can lead to decreased convergence-accommodation to convergence ratio,<sup>8</sup> reduced accommodative magnitude,<sup>9</sup> deteriorated near point of accommodation, near point of convergence, and decreased tear break-up time.<sup>10</sup> These studies mainly examined traditional 3D viewing techniques, whereas little is known about the effects of lenticular sheet-based autostereoscopic viewing. Moreover, the changes in accommodative lag and facility after stereoscopic viewing remain unclear. Because accommodative functions might play a role in the

progression of myopia,<sup>11,12</sup> evaluating the effects of stereoscopic viewing or training on accommodative functions of myopes is necessary.

Therefore, this study aimed to assess the immediate after-effects of autostereoscopic 3D visual training on the accommodative parameters of myopes by comparing them with those of two-dimensional (2D) viewing paradigms, to pave the way for further exploration of whether autostereoscopic viewing can have an impact on myopia progression.

## METHODS

### Participants and Ethical Approval

This prospective observational study was approved by the Ethics Committee of Fudan University EENT Hospital (No. 2019092) and followed the tenets of the Declaration of Helsinki. Written consent was obtained from all participants after thorough communication of the aims and risks of the study. Participants were consecutively recruited from patients who visited Fudan University Eye and ENT Hospital (Shanghai, China) between June 2021 and August 2021 with the following inclusion criteria: (1) age: 18–25 years; (2) refractive errors: spherical: −9.00 to −0.50 diopters (D), cylindrical: −1.00 to −0 D, and binocular difference less than 1.0 D; (3) monocular best-corrected visual acuity  $\geq 20/20$ ; and (4) normal stereoacuity. Exclusion criteria included the following: (1) history of exotropia, esotropia, or other ophthalmic diseases; (2) history of taking any medication known to affect the accommodative system within the last 1 month; and (3) history of systemic or psychiatric diseases.

Forty-six healthy adults consisting of 22 men and 24 women (mean age  $\pm$  standard deviation =  $21.5 \pm 2.5$  years, range = 18–25 years, mean spherical equivalent  $\pm$  standard deviation =  $-4.52 \pm 1.89$  D, range =  $-8.88$  to  $-1.75$  D) were recruited. They completed routine ophthalmic examinations, including intraocular pressure (noncontact), axial length (IOL Master), slit-lamp, and manifest refraction examinations conducted by the same experienced optometrist. The participants were randomly divided into 3D and 2D viewing groups, and their baseline characteristics are shown in Table 1.

### Measurement of Accommodative Function

All measurements were obtained while the participants wore spectacles with full optical correction. The luminance of the laboratory room was maintained at approximately 600 lm during the entire experiment.

Dynamic accommodative responses (ARs) were assessed using a Grand Seiko WAM-5500 binocular open-field autore-

fractor (grandseiko.com) in Hi-Speed mode, which allows continuous recordings of ARs every 0.2 seconds with a sensitivity of 0.01 D. Before the response measurement began, the participant was asked to adjust the position to stabilize their head on the chin rest and forehead strap and ensure that they could achieve stereoscopic viewing. To reconcile the effect of the spectacles worn by the participants, formulas described in previous studies<sup>13,14</sup> were used to calculate the actual AS and AR:

$$AS = \frac{1}{\frac{1}{\left[\frac{1}{(0.012-D)}\right]+P} - 0.012} - RE \quad (1)$$

$$AR = \frac{1}{\frac{1}{\left[\frac{1}{R+0.012}\right]+P} - 0.012} - RE \quad (2)$$

In these formulas, 0.012 is the distance from the lens to the eyes in meters, D is the distance from the target to the eye, P is the power of the glasses, RE is the refractive error of the participant, and R is the reading of the autorefractor. For instance, if the mean value of the raw responses was  $-1.18$  D, the spherical equivalent of spectacle lenses was  $-2.25$  D, and the spherical equivalent of the participant's manifest refraction was  $-2.25$  D, the corrected AR should be calculated as follows:

$$AR = \frac{1}{\frac{1}{\left[\frac{1}{(-1.18(D)+0.012(m))}\right]+(-2.25(D))} - 0.012(m)} - (-2.25(D)) = -1.06(D)$$

For accommodative variability and lag, the data points of the participants viewing a high-contrast Maltese cross positioned at 50 cm for 10 seconds were analyzed. The standard deviations represent the variability of the accommodation. The accommodative lag equals the AS minus the average AR.

The accommodative facility test was conducted monocularly (occluding the left eye) using a lens flipper (+2.00 D/−2.00 D lens combination). The participants were asked to focus on a 20/30 letter placed at 40 cm and were instructed as follows: “Try to keep the letter in focus. I will put a lens in front of your eye, which will blur the letter, but the image will become clear again in a short time. You should tap the table as soon as the image is sharp again, and we will repeat this process over a 1-minute period.” The

TABLE 1. Baseline Characteristics of the Participants

	3D Group	2D Group	P Value
Age, years	21 $\pm$ 3 (18~25)	22 $\pm$ 2 (18~25)	0.138
Sex, male/female	14/9	10/13	0.238
Spherical, D	−4.18 $\pm$ 1.93	−4.33 $\pm$ 1.91	0.804
Cylindrical, D	−0.50 $\pm$ 0.45	−0.58 $\pm$ 0.31	0.503
Spherical equivalent, D	−4.43 $\pm$ 1.90	−4.61 $\pm$ 1.92	0.751
Lens power, D	−4.62 $\pm$ 1.92	−4.43 $\pm$ 1.87	0.736
Pupillary distance, mm	63.26 $\pm$ 4.10	63.87 $\pm$ 2.32	0.539
Intraocular pressure, mm Hg	15.47 $\pm$ 3.80	15.03 $\pm$ 2.15	0.629
Axial length, mm	25.67 $\pm$ 0.95	25.61 $\pm$ 1.00	0.812

P value < 0.05 shows statistical significance.



**FIGURE 1.** The autostereoscopic 3D display equipment (Shanghai EVIS Technology Co., Ltd.).

number of completed flipping cycles within 1 minute was measured.

Accommodative amplitude was measured monocularly (occluding the left eye) with the distance correction of the participant using the pushup method.<sup>15</sup> The visual target of the participant was the 20/20 row of letters positioned at 40 cm and moved toward the participant until they reported sustained blur within 2 or 3 seconds of viewing. The distance from this point to the spectacle plane was recorded and the inverse of this distance (in meters) was considered the accommodative amplitude (in diopters).

### Autostereoscopic 3D Visual Training

The training video was played on an autostereoscopic 3D display (Shanghai EVIS Technology Co., Ltd.; a refraction-based, lenticular sheet on LCD) with a resolution of  $3840 \times 2160$  pixels and a classical illuminance of  $300 \text{ cd/m}^2$  (Fig. 1).

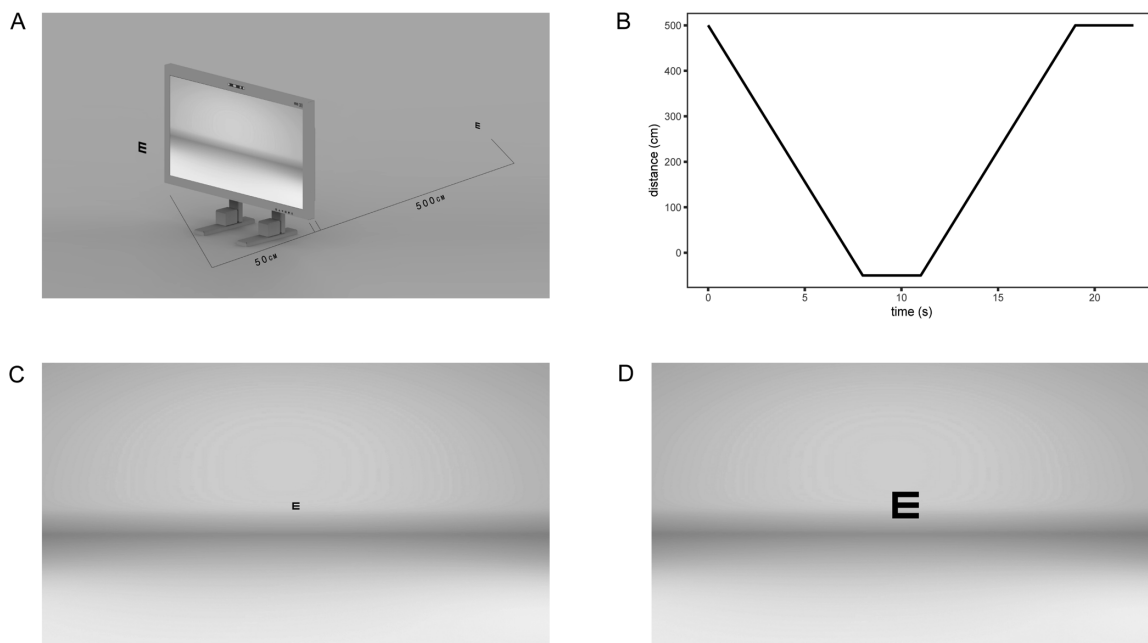
By pressing a single button, this equipment switches viewing modes between 3D and 2D displays in 1 second. The content of the video was a moving standard “E,” designed based on the principles of pencil pushups. Starting from 500 cm inside the screen, it slowly moved to 50 cm outside the screen in 8 seconds. After staying at the position for 3 seconds, it moved back to the original position in 8 seconds, changed the direction, and stayed for another 3 seconds. The total time duration of one cycle was 22 seconds, and the entire video lasted 660 seconds (11 minutes) with 30 cycles (Fig. 2, Supplementary Video). The content of the 2D training video was the same as the 3D training video during the same time period. The only difference was the presence of stereoscopic feeling.

### Questionnaire

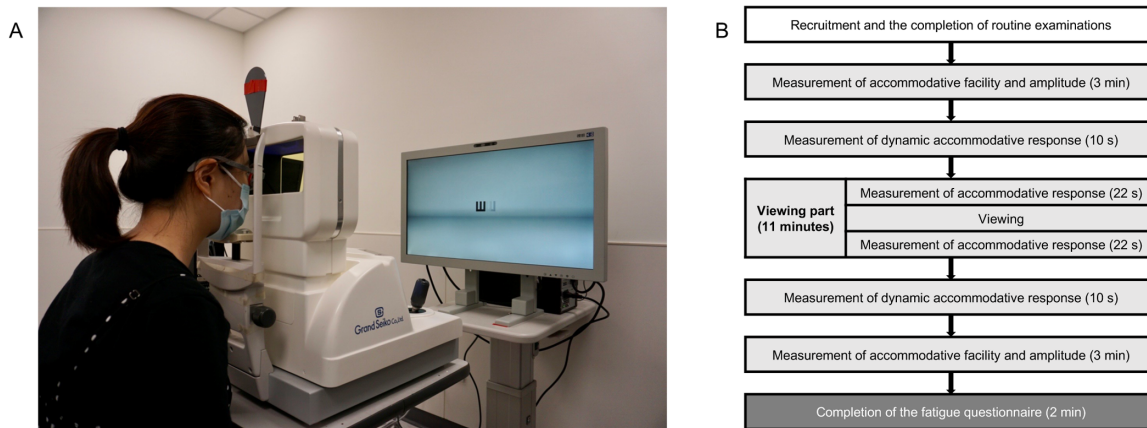
A customized questionnaire designed based on 10 usual symptoms after 3D viewing<sup>9</sup> was administered to each participant to assess the subjective symptoms associated with viewing 3D or 2D videos. The questionnaire was composed of scores for the symptoms, including dry eye, ghosting, tearing, eye strain, dizziness, blur, nausea, headache, vomiting, and inability to concentrate, as well as overall visual fatigue. The scores ranged from 0 to 5 for the 10 symptoms and from 0 to 10 for visual fatigue with higher scores representing severer symptoms. The degree of general visual fatigue was evaluated after the 3D or 2D viewing task (“after viewing”) and for everyday life (“during study or work”). The questionnaire is shown in Supplementary Table S1.

### Procedures

The accommodative facility and accommodative amplitude were measured. The participant was then instructed to sit and watch the target at 50 cm, while the dynamic AR was



**FIGURE 2.** The content of the training video. (A) A side view of the “E” displayed 50 cm in front of the screen and 500 cm behind the screen, moving between the two positions. (B) The target is 500 cm away from the screen at first and then moves to 50 cm in front of the screen, which is shown as  $-50 \text{ cm}$  in this figure. The target stops for 3 seconds at the nearest and furthest points. (C) A front view of the “E” displayed 500 cm behind the screen. (D) A front view of the “E” displayed 50 cm in front of the screen.



**FIGURE 3. The experimental settings.** (A) The participant is instructed to sit 80 cm away from the screen. (B) The flow chart of the steps of the experiment and the approximate duration of each step.

measured for 10 seconds to determine the accommodative lag and variability. Subsequently, the 3D or 2D viewing started. The participant was instructed to sit in the same position, 80 cm in front of the screen (Fig. 3A), and the video was started. Concurrently, the dynamic ARs of the first 22 seconds (the first cycle of training) and the last 22 seconds (the last cycle of training) were recorded. The measurements of the accommodative facility and accommodative amplitude were repeated afterward. Last, the fatigue questionnaire was administered to the participant. The approximate duration of the entire experiment and each procedure is shown in Figure 3B.

**Statistical Analysis**

Data were obtained from measurements of the right eye of each participant and were analyzed using R version 4.1.0 (cran.r-project.org) and SPSS version 26.0. For dynamic measurements of ARs, data points varying more than ±2 standard deviations were excluded to eliminate blinking effects, and the mean value of the ARs during the 10-second viewing was considered the raw response value for further analysis. Differences between pre- and post-viewing data were compared using the paired *t*-test, and differences between 3D and 2D experiments were compared using the two-sample *t*-test and chi-square test. Statistical significance was defined as *P* ≤ 0.05. The curves of the dynamic ARs while watching the video were fitted to the data points using a gam function.

**RESULTS**

All participants (*n* = 46) consisting of 22 men and 24 women (age = 21.5 ± 2.5 [range = 18–25] years) completed the entire experiment. Fusion failures during 3D viewings were not reported (*n* = 23).

**Accommodative Functions**

The baseline accommodative parameters are summarized in Supplementary Figure S1, which shows no significant difference between the 2D and 3D groups. The changes in the accommodative functions of the two groups are presented in Table 2 and Supplementary Figure S2. For 3D viewing, the accommodative lag decreased from 0.54 ± 0.29 D to 0.42 ± 0.32 D (*P* = 0.004), whereas accommodative facility increased from 10.83 ± 4.55 cycles per minute (cpm) to 13.15 ± 5.25 cpm (*P* < 0.001). No significant differences in the accommodative variability or amplitude were observed. For 2D viewing, significant differences were obtained for a decreased accommodative amplitude (from 13.88 ± 3.17 to 12.71 ± 2.23, *P* = 0.028). The analysis revealed no significant changes in other accommodative functions. The comparison of changes in accommodative functions between 3D and 2D viewings yielded significant differences in accommodative lag (*P* = 0.002), accommodative facility (*P* = 0.011), and accommodative magnitude (*P* = 0.028). We further investigated the correlation between the baseline characteristics, including the group (2D or 3D), age, sex, pupil distance,

**TABLE 2. Accommodative Parameters Pre- and Post-Viewing Task**

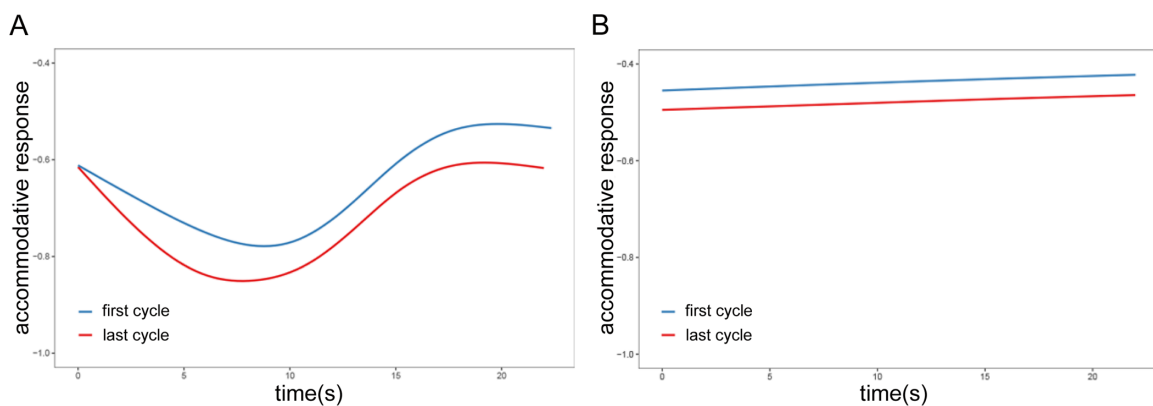
	Pre	Post	<i>P</i> Value
<i>3D group (n = 23)</i>			
Accommodative lag, D	0.54 ± 0.29	0.42 ± 0.32	0.004
Accommodative variability	0.079 ± 0.022	0.086 ± 0.031	0.406
Accommodative facility, cpm	10.83 ± 4.55	13.15 ± 5.25	0.000
Accommodative amplitude, D	12.98 ± 2.68	13.22 ± 2.95	0.592
<i>2D group (n = 23)</i>			
Accommodative lag, D	0.65 ± 0.22	0.70 ± 0.23	0.163
Accommodative variability	0.098 ± 0.046	0.103 ± 0.049	0.684
Accommodative facility, cpm	11.39 ± 4.10	11.41 ± 4.42	0.975
Accommodative amplitude, D	13.88 ± 3.17	12.71 ± 2.23	0.013

*P* value < 0.05 shows statistical significance.

**TABLE 3.** Changes of Accommodative Functions in Different Refractive Groups

Parameters	Low to Moderate Myopia	High Myopia	P Value
<i>3D group</i>			
Accommodative lag, D			
Pre	0.55 ± 0.31	0.51 ± 0.19	0.790
Post	0.44 ± 0.34	0.38 ± 0.27	0.734
Accommodative variability			
Pre	0.078 ± 0.023	0.083 ± 0.017	0.654
Post	0.087 ± 0.033	0.082 ± 0.022	0.768
Accommodative facility, cpm			
Pre	10.75 ± 4.46	11.10 ± 5.42	0.883
Post	13.39 ± 5.22	12.30 ± 5.89	0.692
Accommodative amplitude, D			
Pre	13.42 ± 2.76	11.38 ± 1.75	0.135
Post	13.64 ± 3.01	11.71 ± 2.38	0.202
<i>2D group</i>			
Accommodative lag, D			
Pre	0.67 ± 0.24	0.57 ± 0.16	0.432
Post	0.73 ± 0.22	0.58 ± 0.24	0.344
Accommodative variability			
Pre	0.100 ± 0.051	0.089 ± 0.017	0.628
Post	0.095 ± 0.039	0.130 ± 0.074	0.157
Accommodative facility, cpm			
Pre	11.58 ± 4.41	10.70 ± 3.01	0.680
Post	11.25 ± 4.62	12.00 ± 4.00	0.746
Accommodative amplitude, D			
Pre	13.27 ± 2.60	16.09 ± 4.34	0.078
Post	12.30 ± 1.78	14.19 ± 3.23	0.296

P value < 0.05 shows statistical significance.

**FIGURE 4.** Changes in dynamic accommodative responses between the first cycle and the last cycle. (A) The 3D group. (B) The 2D group.

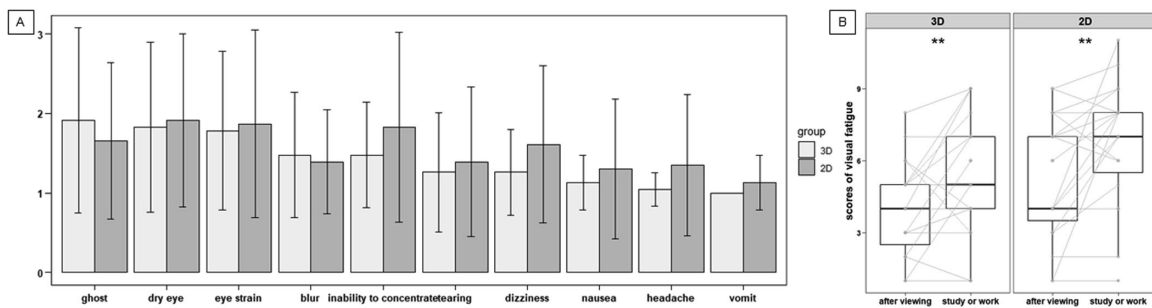
spherical equivalent, axial length, baseline accommodative parameters, and the changes in the accommodative parameters. Variables, including group and corresponding baseline parameters, were then included for general linear regression of the change in the accommodative parameters (Supplementary Table S2). There was no difference based on sex in the outcomes (Supplementary Table S3).

The participants were divided into “low to moderate myopia” and “high myopia” groups for further analysis. The baseline characteristics are summarized in Supplementary Table S4, which shows significant differences in the refractive status and axial length only. In addition, there were no significant differences in these accommodative parameters between the low-to-moderate myopia and high myopia groups (Table 3).

The analysis of the dynamic ARs of the first and last cycle of the training on the 3D display is shown in Figure 4A. The AR fluctuated with varying simulated viewing distances of the target “E.” For 2D viewing, the AR did not follow the change in the size of the target “E” (Fig. 4B). Moreover, the AR increased in both groups, but the increase in the 2D group (approximately 0.04 D) was smaller than that in the 3D group (approximately 0.1 D).

### Subjective Symptoms

After viewing, the participants in the 3D group mainly reported ghost images with an average score of 1.91 and dry eyes with an average score of 1.83. For the 2D group, dry eye was the most severe symptom, with an average score of



**FIGURE 5. The subjective evaluation of visual fatigue. (A)** Scores of each symptom. **(B)** General visual fatigue after the viewing task (“after viewing”) and in everyday life (“during study or work”).

1.91, followed by eye strain with an average score of 1.87. No significant differences were found between the two groups with respect to each symptom (Fig. 5A). However, the overall visual fatigue scores between the two conditions “after viewing” and “during study or work” were significantly different in both 3D and 2D groups (Fig. 5B).

## DISCUSSION

Presently, as stereoscopic 3D displays are becoming increasingly popular, greater emphasis is being placed on the impact of 3D viewing on visual functions, which may also be influenced differently by the type of 3D technology.<sup>9</sup> As a relatively new trending technology, autostereoscopic 3D displays based on lenticular sheets have rarely been examined regarding their effects on accommodative functions of the human visual system. Thus, this study was designed to assess the immediate impact of autostereoscopic 3D visual training on accommodative dynamics and functions in myopes.

Our results demonstrated that myopes showed a decrease in accommodative lag and an increase in accommodative facility but no significant change in accommodative variability or amplitude after an 11-minute visual training for this type of 3D display. After viewing the same content on the 2D display, a decrease in accommodative amplitude was observed with no significant changes in other parameters before and after viewing. We also evaluated the dynamic AR during the viewing procedure. The fitted curve of this parameter showed that the response changed with the simulated target distance. In addition, significant differences in the scores of general visual discomforts between “after viewing” and “during study or work” were found in both groups. These findings reinforce the results of previous studies on stereoscopic viewing while opening up a new field of dynamic changes in the ARs of myopes during autostereoscopic 3D training, which may pave the way for further studies of myopia progression under 3D viewing conditions.

The accommodative lag decreased from  $0.54 \pm 0.29$  D before the 3D training to  $0.42 \pm 0.32$  D afterward, indicating that the near accommodative accuracy was enhanced by autostereoscopic viewing. The AR during 10 seconds of watching the Maltese cross at a single distance (50 cm) was recorded immediately after the end of the video, which ensured that the recording was in time and could represent the immediate change in the AR. Ming-Leung Ma et al.<sup>16</sup> reported that vision therapy based on the Convergence Insufficiency Treatment Trial (CITT)<sup>17</sup> led to a change of  $-0.46 \pm 0.22$  D of monocular accommodative lag for a target

at 33 cm. This result is qualitatively consistent with the findings of our study, possibly because the video in our study was also designed based on the principles of pencil pushups. This suggests that the promotion of convergence is one of the reasons for better accommodative responsiveness<sup>18</sup> characterized by a smaller accommodative lag. This is also supported by a previous study indicating that stereoscopic stimuli evoke larger AR compared to two-dimensional stimuli.<sup>19</sup> Moreover, this result allows us to hypothesize that the reduction in accommodative lag could also be related to a relatively low level of visual fatigue,<sup>20</sup> with the general visual discomfort score after the viewing task being significantly lower than that of the daily visual experience. However, the change in accommodative lag was less pronounced in our study than that in the study by Ming-Leung Ma et al. (0.12 D versus 0.46 D). One of the main reasons for this might be that the training duration in our study was much shorter (11 minutes versus 12 weeks, respectively). On the other hand, no significant difference in accommodative lag for 2D viewing was found in our study. Similarly, Hue et al.<sup>21</sup> also found no significant difference in lag between handheld e-reader and printed text at a distance of 50 cm, whereas another study with similar targets on a computer screen found an increase in accommodative lag.<sup>22</sup> Possible explanations for the discrepancies among studies include differences in experimental settings, methods of measuring ARs,<sup>23</sup> target sizes,<sup>24</sup> testing distances,<sup>25–27</sup> and interindividual variations. It has also been suggested that accommodative lag can be affected by the participant’s attentional state exaggerating interindividual variations.<sup>28</sup> The impact of changing the experimental environment or training duration should be clarified in future studies.

In our study, the average near accommodative facility was improved. The baseline data of this study are consistent with those of a previous study in which the subjective accommodative facility of young myopes averaged at 10.5 cpm.<sup>29</sup> The immediate improvement to 13.15 cpm is comparable with the near accommodative facility of emmetropes (13.2 cpm).<sup>29</sup> This finding also agrees with previous research on convergence training.<sup>30–33</sup> However, other studies regarding the impact of stereoscopic viewing on accommodative facility described opposite results.<sup>9,34</sup> The main reason might be the differences in stereoscopic video contents. We designed the video on the principles of convergence and accommodative training, which may be more standardized and uniform than the varying contents of 3D films or games used in other studies. Variations in display equipment may also be one of the reasons for this discrepancy. We did not observe the same changes in the 2D group possibly because the

AR to 2D videos at the same distance was almost constant during the entire procedure and there was no other stimulus of accommodation, which could not improve the facility.<sup>33</sup> This result is in agreement with the findings of other studies conducted on various 2D displays.<sup>35</sup> The visual perception of myopes wearing spectacles may also differ across 3D technologies since traditional 3D viewing requires additional filtering glasses. The impact of this factor on accommodative facility remains unclear and requires further research.

In the current study, there was no significant change in the accommodative variability in the 3D and 2D groups. Maeda et al.<sup>36</sup> also reported no significant changes in the accommodative microfluctuations before and after 3D viewing tasks, but the experimental time of their study was 90 minutes for adults viewing static stereoscopic images, which is quite different from the conditions in our study. Based on the limited literature on this aspect, whether stereoscopic viewing influences the variability of accommodation needs further exploration.

There was no significant difference in monocular accommodative amplitude in the 3D group, but a mean reduction of 1.17 D in the accommodation amplitude was observed in the 2D group. The results corroborate the findings of previous studies,<sup>37,38</sup> which reported approximately 1.00 D loss of accommodative amplitude after using electronic devices at a relatively near distance. These results could be explained by accommodation fatigue when watching 2D displays<sup>35</sup> because there was no change in the AS. For 3D viewing, the convergence-accommodation cross-coupling allows a continuous change in the AR with varying convergence demand,<sup>39</sup> which might be the reason why there was no significant change in the accommodative amplitude after 3D viewing.

The pattern of the dynamic AR curve at the beginning and end cycles of the training further proved that varying convergence demand in 3D viewing can evoke a commensurable AR, which is supported by the results of previous studies.<sup>19,40,41</sup> Another finding in our study was that the AR tended to increase after the 3D visual training, which showed the changing process and supported the final decrease in accommodative lag.

In this study, blurry vision and dryness of the eye were most frequently reported by the participants among possible symptoms after the viewing task. This is consistent with findings of studies on visual fatigue after stereoscopic viewing.<sup>42-44</sup> However, the symptom scores were quite low in both groups with an average score of no more than two out of five, and the scores of the “after viewing” condition were significantly lower than those of the “during study or work” condition representing the general daily experience. These results demonstrate that watching the video did not tire the participants and also support the discussion above regarding the improvement in accommodative accuracy and facility.<sup>45</sup> The low grades of these symptoms could be due to the relatively short duration and smaller binocular disparity compared to conditions in other studies.

It has been reported that accommodative functions are possibly relevant to the onset and progression of myopia. Based on the literature, the accommodative lag can cause hyperopic defocus, which further pushes the eyes to become longer to maintain clear vision.<sup>11,46,47</sup> Moreover, a lower accommodative facility, which means delays in attaining focus when changing fixation, can also lead to short-term hyperopic defocus.<sup>46</sup> The observed improvement in accommodative accuracy and facility of myopes (including those

with high myopia) in our study allows us to cautiously hypothesize that accommodative training using autostereoscopic 3D technologies might be beneficial for slowing the onset and progression of myopia. However, the impact was temporary in our study, and we could not conclude whether the autostereoscopic 3D display could influence the refractive status and visual acuity of myopes. Although several studies reported improved visual acuities with longer training durations,<sup>48-50</sup> the long-term impacts of stereoscopic displays should be doubted because the environments and subjects differed substantially across studies and the true association between the accommodative system and myopia has not been clarified.

The limitations of this study include the small sample size and the fact that we used the push-up method instead of the autorefractor to measure the amplitude of accommodation. In addition, we only focused on accommodative functions without measuring convergence as accommodation-convergence crosslinking has been well studied, and the current experimental settings restricted the possibility of simultaneously measuring accommodation and convergence. Convergence changes in myopes viewing 3D displays should be studied with a larger sample size in the future.

In conclusion, the immediate impact of autostereoscopic 3D training included a decrease in accommodative lag and an increase in accommodative facility. Based on our findings, it can be assumed that autostereoscopic technology may be useful for improving the accommodative functions of myopes. However, the long-term effects of autostereoscopic training require further exploration.

### Acknowledgments

Supported by The National Natural Science Foundation of China (Grant No. 81770955); the Joint research project of new frontier technology in municipal hospitals (SHDC12018103); the Project of Shanghai Science and Technology (Grant No. 20410710100); the Clinical Research Plan of SHDC (SHDC2020CR1043B); the Project of Shanghai Xuhui District Science and Technology (2020-015); the Shanghai Rising-Star Program (21QA1401500); and the Shanghai Engineering Research Center of Laser and Autostereoscopic 3D for Vision Care (20DZ2255000).

Disclosure: **Y. Huang**, None; **M. Li**, None; **Y. Shen**, None; **F. Liu**, None; **Y. Fang**, Shanghai EVIS Technology Co. Ltd (F); **H. Xu**, None; **X. Zhou**, None

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### SUPPLEMENTARY MATERIAL

**SUPPLEMENTARY VIDEO. The content of the training video.** Starting from 500 cm inside the screen, a standard “E” slowly moves to 50 cm outside the screen in 8 s. After staying at the position for 3 s, it moves back to the original position in 8 s, changes the direction, and stays for another 3 s. The total time duration of one cycle was 22 s and the entire video lasted 660 s (11 min) with 30 cycles.