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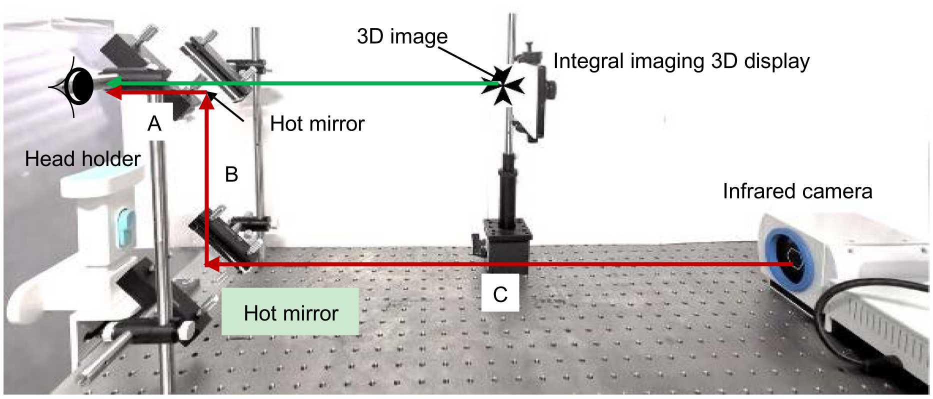

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Effect of Viewpoints on the Accommodation Response in Integral Imaging 3D Display

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Abstract: Integral imaging three-dimensional (3D) display provides quasi-continuous viewpoints within a certain viewing angle. A single human eye can obtain several parallax images corresponding to the viewpoints. In this paper, we studied the effect of viewpoints received by a single human eye on the accommodation response when viewing the 3D image reconstructed by integral imaging 3D display. We analyzed the viewpoints distribution of an integral imaging 3D display and the correspondence relationship between the viewpoints and pixels information in elemental image array. In the experiment, the accommodation responses of human eyes when viewing the 3D image with different viewpoint quantities and dimensions are measured. The statistical results reveal that the more viewpoints received by a single human eye, the closer the accommodation response of the 3D image is to that of the real target. This tendency is obvious when the viewpoint quantity reduces from 10 $\times$ 10 to 6 $\times$ 6. For situations of 2 $\times$ 2 and 1 $\times$ 1 viewpoint, the accommodation response is unstable and different from the real target. When considering the viewpoint dimensions, two-dimensional viewpoints can provide a more natural accommodation response than one-dimensional viewpoints do. For the one-dimensional viewpoint situation, the horizontal arranged viewpoints and vertical arranged viewpoints have no statistical discrepancy.

Index Terms: Integral imaging 3D display, viewpoint quantity, accommodation response.

1. Introduction

When viewing a three-dimensional (3D) scene in the real world, we can obtain four kinds of physiological depth cues, which are binocular parallax, motional parallax, accommodation and convergence. Binocular parallax is a shift in the perspective of viewing due to the existence of separated eyes, and the stereopsis mainly refers to the perception of depth based on binocular parallax [1]. Motion parallax is caused by the relative motion of human eyes and objects [1]. Accommodation response refers that the human eye changes the refractive power to clearly see the object [2]. Convergence response is the eye movement that eyes rotate from the optic axis to the nasal side and intersect on the fixation point [3]. 3D display can bring images that we perceive in our daily life with as few alterations as possible, which is thought to be the trend of the next generation display for it can reconstruct the depth information of the scene. Specifically, the 3D images should provide all the physiological depth cues the same as the real object does. Most of 3D display technologies can offer correct convergence response, binocular parallax, and some of them have correct motional parallax [4]–[6], but the accommodation response is nearly incorrect. Take the stereoscopic 3D display for example, the human eyes focus on the display panel where the pixel rays come from, but the convergence point is on the 3D image point which is in front of or behind the display screen [5]. The difference between the focus point and the convergent point is the so-called vergence-accommodation conflict (VAC) which brings nonnegligible visual fatigue [7]. Thus, correct accommodation response is of vital importance to evaluate the visual fatigue of a 3D display. Usually, researchers compare the accommodation response stimulated by a 3D image with that by a real 3D scene to evaluate the visual fatigue or visual comfort of a 3D display [8]–[11].

Among the variety of naked eye 3D displays, integral imaging 3D display is a kind of true 3D display technique that includes two aspects of both light field recording and reconstruction, and the characteristics of light field reconstruction makes integral imaging 3D display possible to duplicate the conditions of viewing real objects [12], [13]. Therefore, the accommodation responses have been predicted to be consistent with the depth position of the 3D image [14]. However, the light field reconstructed by an integral imaging 3D display is discrete due to the pixelated structure of the recording and displaying devices [13]. So, further study on the accommodation response of integral imaging is needed. Theoretical and measurement researches have been carried out by many research groups. The Nippon Hoso Kyokai (NHK) measured the accommodation responses of 3D images reconstructed by integral imaging 3D display, stereoscopic display and real objects [15], and reported that accommodation responses of integral imaging 3D display were more in accordance with that of real targets. And besides, they also studied on the relationship between depth perception and accommodation responses of integral imaging [16]. The research results suggested that the depth perception and accommodation responses tended to the depth of the reconstructed 3D image. The Sun Yat-Sen University and the National Chiao Tung University studied the accommodation response shifts in integral imaging 3D display which could provide an approach to alleviate the VAC [18]. Additionally, the spatial resolution and angular resolution are important for observer to view the integral imaging display. The spatial resolution directly shows the sharpness of 3D images. Hiura *et al.* analyzed the spatial resolution of integral imaging display at different depth and discussed the effect of 3D images' resolution on accommodation response of human eyes [14]. They suggested that the accommodation responses of 3D images with higher resolution was closer to the real object. The angular resolution density which is determined by the viewpoint quantity. The influence of the angular resolution of 3D images on the accommodation response was studied by Seoul University [17], and the result illustrated that higher angular resolution made the accommodation response closer to the depth of 3D images. In our previous study, the accommodation responses of the 3D image reconstructed by real, focused and virtual modes of the integral imaging 3D displays have been analyzed and compared [19], and the results revealed that focused mode had a better accommodation response. We also had demonstrated that the visual fatigue of integral imaging 3D display was less than that of the lenticular lens type 3D display since the former satisfied the super multi-view (SMV) condition and the latter didn't [20]. The SMV condition is the primary requirement for obtaining a suitable accommodation response [21]. SMV refers that the continuous parallax of the 3D object is sampled with an interval less than half of the pupil diameter, so that two or more parallax images enter a single human eye [22], [23]. The viewpoint is also a significant display performance of integral imaging 3D display except the image resolution and angular resolution. The quantity and arrangement of viewpoints vary in different integral imaging 3D displays, for example, devices with macro-lens array normally has much more viewpoints than those with micro-lens array, and the conventional devices have two-dimensional arranged viewpoints, in comparison with the one-dimensional devices whose viewpoints are one-dimensional arranged [24], [25]. Although, the effect of angular resolution density which is determined by the viewpoint quantity on the accommodation response has been discussed, the influence of viewpoint on accommodation response has not been directly analyzed. Thus, it is necessary to study on the effect of viewpoints on the accommodation response of integral imaging 3D display, especially, the quantity and the dimension of viewpoints.

In this paper, we researched on the effect of the viewpoints received by a single human eye on the accommodation response in integral imaging 3D display. The viewpoint distribution of

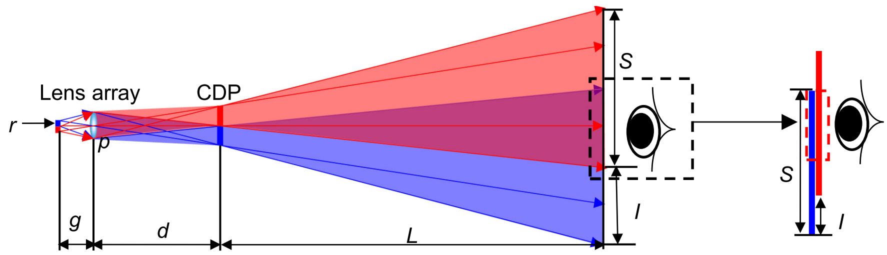


Fig. 1. The distribution of viewpoints.

integral imaging 3D display was firstly analyzed, and the viewpoint quantity received by a single human eye was deduced. The relationship between the viewpoint and pixels in element image array (EIA) was discussed. Then 3D images with various viewpoint quantities and dimensions were designed according to the theoretical analysis. In the experiment, we objectively tested the accommodation responses of human eyes when viewing 3D images with different viewpoint quantities and dimensions. Statistical analysis was performed including linear-regression analysis and multiple comparison tests. The completion of this study would improve the visual comfort evaluation of integral imaging 3D display, and provide the theoretical guidance for developing a comfortable integral imaging 3D display.

2. Analysis of Viewpoints Received by a Single Human Eye

Considering the case of lens and an elemental image, the light rays emitting from a pixel are modulated by the lens and image on the central depth plane (CDP). Then, the light rays continue to propagate in the viewing space with a certain divergence angle, as the red light rays show in Fig. 1. Viewer will see the pixel when his or her one eye locates in the area covered by the divergent light rays. According to the geometric relationship in Fig. 1, the viewpoint size S which is the horizontal or vertical width of the divergent light rays at a certain viewing distance can be deduced as:

$$S = \frac{(L+d)\,p}{gN} + \frac{Lp}{d} \tag{1}$$

where L is the viewing distance from the human eye to the CDP, d is the depth of the CDP, p is the pitch of the lens, r is the pixel size, g is the gap between the lens array and the elemental image, and N is the pixel number of an elemental image in horizontal or vertical direction which also represents the viewpoint quantity of the integral imaging 3D display. Similarly, the light rays emitting from other pixels of the elemental image have the same propagation property, as the blue light rays show. The interval I between two adjacent viewpoints can be deduced as:

$$I = \frac{(L+d)\,p}{gN} \tag{2}$$

Comparing Eqs. (1) and (2), it is obvious that viewpoint size S is much greater than the viewpoints interval I, because the viewing distance L is much larger than the depth of CDP d. Hence, the viewpoints of integral imaging 3D display are overlapped each other in the viewing space, as the magnified part shows in Fig. 1. At one point, the number of the overlapped viewpoints can be expressed as:

$$n = ceil\left(\frac{S}{I}\right) \tag{3}$$

where the function *ceil* means round up to an integer. For an integral imaging 3D display, a viewpoint corresponds to a perspective formed by the pixels in which one pixel from each lens. Therefore, n viewpoints corresponding to the n perspectives can be seen by a human eye.

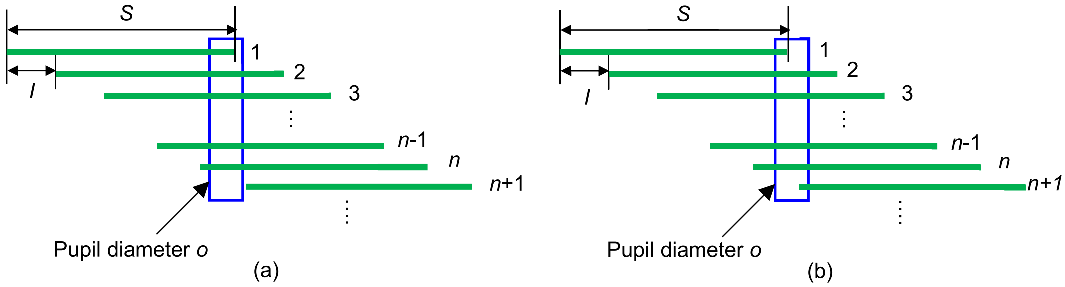


Fig. 2. Viewpoint quantity covered by a single human eye for $o \leq l$. (a) the eye covers the viewpoints from 1 to n, (b) the eye covers the right side of the first viewpoint and the left side of the $(n+1)$-th viewpoint.

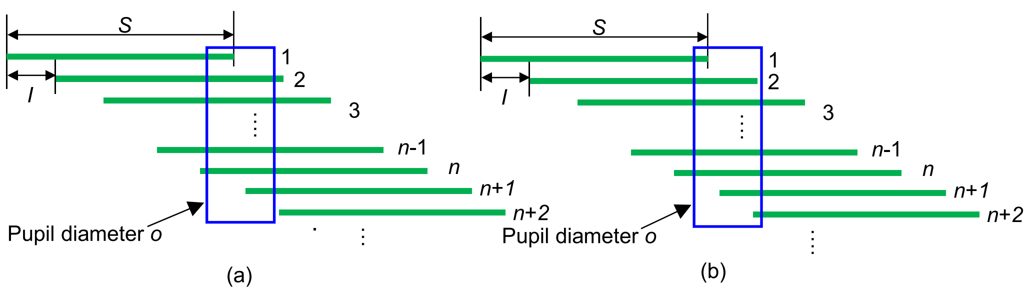


Fig. 3. Viewpoint quantity covered by a single human eye for $l < o \leq 2l$. (a) the eye covers the viewpoints from 1 to $(n+1)$-th, (b) the eye covers the right side of the first viewpoint and the left side of the $(n+2)$-th viewpoint.

When taking the pupil size into account, the analysis contains several conditions. For similarity, we only consider the horizontal distribution of the viewpoints. As shown in Fig. 2, the blue rectangle represents the human eye's pupil with the pupil diameter of o, each green strip with the width S represents a viewpoint, viewpoints distribute in horizontal direction with the viewpoint interval l, and n viewpoints overlapped at one point. For $o \leq l$, there are two situations: 1) when the eye covers the viewpoints from 1 to n, the viewpoint quantity received by a single human eye is n, as shown in Fig. 2(a); 2) when the eye covers the right side of the first viewpoint and the left side of the $(n+1)$-th viewpoint, the viewpoint quantity is $(n+1)$, as shown in Fig. 2(b).

For $l < o \leq 2l$, there are also two situations: 1) when the eye covers the viewpoints from 1 to $(n+1)$-th, the viewpoint quantity received by a single human eye is $(n+1)$, as shown in Fig. 3(a); 2) when the eye covers the right side of the first viewpoint and the left side of the $(n+2)$-th viewpoint, the viewpoint quantity is $(n+2)$, as shown in Fig. 3(b). We can obtain the similar result when the pupil diameter o is larger or the viewpoint interval l is smaller.

Overall speaking, only one viewpoint difference is caused by the eye location at each situation. To ensure the eye can receive the maximum viewpoint quantity, we adopt situation 2) which corresponds to the Fig. 2(b) and Fig. 3(b).The Eq. (4) summaries the viewpoint quantity received by a single human eye for all the situations.

$$n_f = ceil\left(\frac{S}{l}\right) + ceil\left(\frac{o}{l}\right) \tag{4}$$

where the pupil diameter o has an average value of about 4 mm, and function *ceil* means round up to an integer.

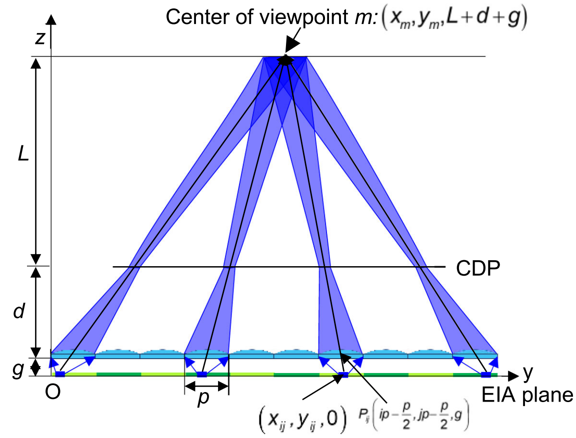


Fig. 4. The correlation between the spatial viewpoint and the pixel position in EIA.

3. The Relationship Between Viewpoints and Pixels in EIA

The method to extract the perspective corresponding to a certain viewpoint has been proposed in the previous study [26]. In this paper, the derivation process of this method is simplified and a Cartesian coordinates system is established in Fig. 4. The EIA plane is on the xo*y* plane, and *z*-axis is perpendicular to the EIA plane. The EIA has $M \times K$ element images which equals to the number of lenses in lens array. The coordinate of the lens in the lens array is known as P_{ij} (ip-p/2, jp-p/2, g), where i denotes the row serial number of the lens and j denotes the column serial number of the lens. And the coordinate of the m-th viewpoint is (x_m, y_m, $L + d + g$). Thus, in each element image, we can find a pixel whose center of light rays is corresponding to the m-th viewpoint. According to the geometric relationship in Fig. 4, we can deduce the coordinate of the pixel (x_{ij}, y_{ij}, 0) corresponding to the m-th viewpoint when only taking the main ray of the pixel into account.

$$x_{ij} = \frac{g\left[\left(ip - \frac{p}{2}\right) - x_m\right]}{L+d} + \left(ip - \frac{p}{2}\right) \tag{5}$$

$$y_{ij} = \frac{g\left[\left(jp - \frac{p}{2}\right) - y_m\right]}{L+d} + \left(jp - \frac{p}{2}\right) \tag{6}$$

By traversing all the elemental images, we can extract the perspective corresponding to a certain viewpoint.

4. The Test of Accommodation Response

The experimental setup contains an optometric device and an integral imaging 3D display as shown in Fig. 5. The optometric device (Powerref3, Plusoptix, Germany) is widely used to measure the accommodation response of human eyes [27]–[29]. In our test, the subject was requested to watch the integral imaging 3D display through a hot mirror, meanwhile an infrared camera was used to detect the accommodation response of subject's eye in real-time. Values of the accommodation response was recorded every 20 ms. The distance between human eyes and the infrared camera is fixed to 100 cm (A + B + C = 100 cm) [30].

The integral imaging 3D display mainly consists of a mobile phone screen and a lens array. The mobile phone screen (Sony Xperia E6883) has the diagonal size of 5.5 inch and contains 3840 × 2160 pixels with the pixel pitch of 0.0315 mm. The lens array contains 120 × 68 lenses in square matrix arrangement. According to the Gaussian imaging formula, the CDP d is 20 mm away in front of the lens array. The detailed specifications of experimental setup are listed in Table 1. The viewing distances are set to 500 mm, 450 mm, 400 mm, 350 mm, and 300 mm, respectively. Thus,

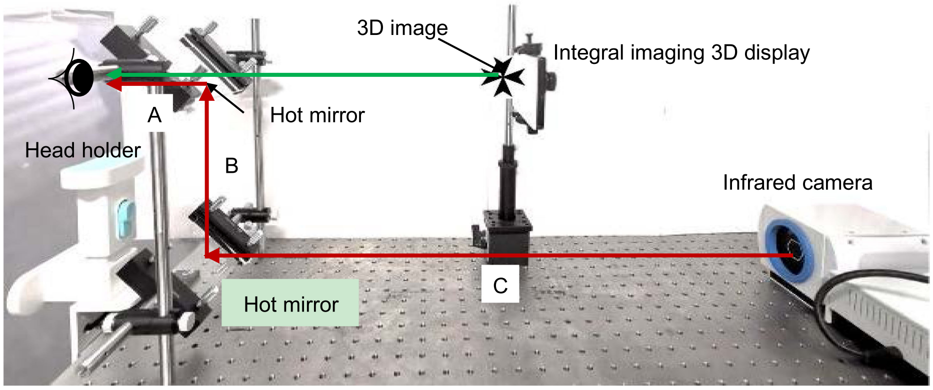
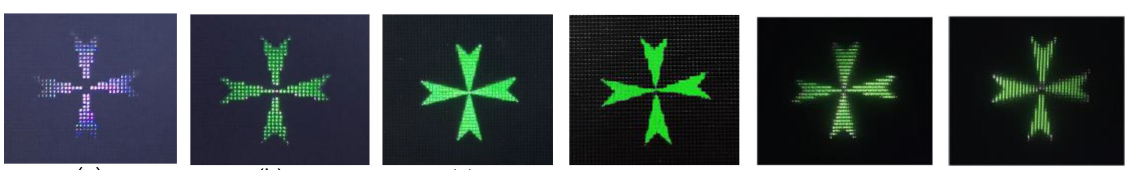


Fig. 5. The photo of the experiment setup.

TABLE 1
Specifications of the Experimental Setup

	Parameter	Value
Mobile phone screen (Sony Xperia E6883)	Number of pixels	3840(H)x2160(V)
	Pixel size (r)	0.0315mm
	Diagonal size	5.5inch
	Pixel structure	RGB stripe
Lens array	Focal length (f)	3.3mm
	Pitch (p)	1.0mm
	Gap between lens array and display panel (g)	3.95mm
	Depth of the CDP (d)	20mm



(a) (b) (c) (d) (e) (f)

Fig. 6. 3D image with different viewpoints. (a) 1 × 1 viewpoint, (b) 2 × 2 viewpoints, (c) 6 × 6 viewpoints, (d) 10 × 10 viewpoints, (e) 10 × 1 viewpoints, and (f) 1 × 10 viewpoints.

the viewpoint size S, the viewpoint interval I, and overlapped viewpoint number n can be calculated according to Eqs. (1), (2) and (3).

Since the average pupil diameter o of an adult is about 4 mm which is greater than I. According to Eq. (4), the viewpoint quantity received by a single human eye is 10 × 10. Through the pixels extracting formula proposed in section 3, we generated EIAs with various viewpoint quantities and dimensions. For the two-dimensional case, we designed 10 × 10 viewpoints, 6 × 6 viewpoints, 2 × 2 viewpoints, and 1 × 1 viewpoint. For the one-dimensional case, we designed 10 × 1 viewpoints (horizontal arranged viewpoint), and 1 × 10 viewpoints (vertical arranged viewpoint). A Maltese cross pattern was used as the model which usually used in the ophthalmic test. Fig. 6(a)–(f) show

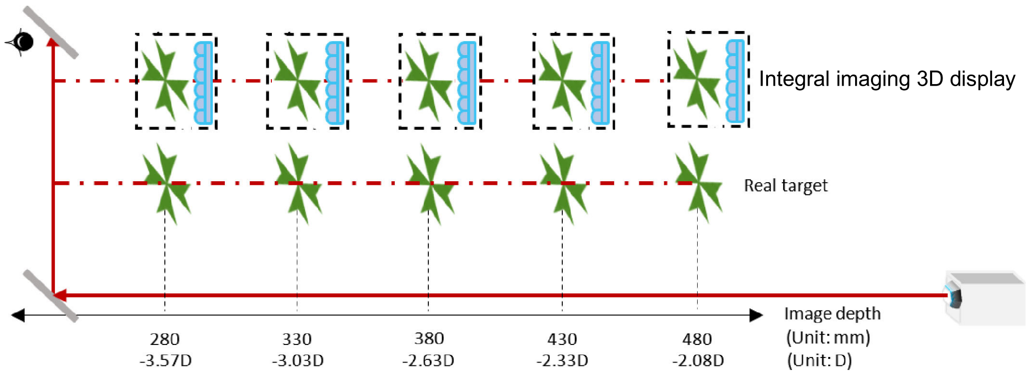


Fig. 7. Target presentation.

the 3D images with different viewpoints. Since the reconstructed 3D image is 20 mm in front of the mobile phone screen, the depths of the 3D images are 480 mm(−2.08D), 430 mm(−2.33D), 380 mm(−2.63D), 330 mm(−3.03D), 280 mm(−3.57D), respectively. Here, the diopter D is the reciprocal of the distance. For the comparison test, a 2D target displayed by the same mobile phone screen located at the same positions was used as a real target.

The test was carried out in a dark room. Ten subjects aged from 22 to 26 participated in the test of two-dimensional viewpoints cases. Seven of them participated in the test of one-dimensional viewpoints cases. Before the test of accommodation response, visual functions of each subject were examined. Two of them have myopia problem. Contact lenses were used to correct their visual acuities.

During the test, each target was presented randomly on a giving depth. The accommodation responses of subjects' eye were tested and recorded for at least 10 s with the time intervals of 20 ms. After each test, there was least five-minute rest to avoid visual discomfort. Repeating the above steps 35 times (7 types of images × 5 depths), all the accommodation responses were obtained, and the accommodation responses of the real target were used as a comparison standard.

5. Experimental Results and Analysis

The experimental results and analysis mainly contain two parts. The first part focused on the viewpoint quantity, and we statistically analyzed the accommodation responses of the 3D images which show different viewpoints quantity (10 × 10 viewpoints, 6 × 6 viewpoints, 2 × 2 viewpoints and 1 × 1viewpoint). The second part focused on the viewpoint dimensions, and we statistically analyzed the accommodation responses of the 3D images which present different viewpoint dimensions (two-dimensional arranged 10 × 10 viewpoints, horizontally arranged 10 × 1 viewpoints, vertically arranged 1 × 10 viewpoints). To remove the influences of individual differences, the accommodation response of the real target was regarded as a reference standard to compare the differences between the accommodation responses of the 3D images [15]. The Linear-regression analysis and multiple comparison tests were carried out in the statistically analysis.

5.1 Results and Statistical Analysis of Accommodation Responses of 3D Images With Different Viewpoint Quantities

Fig. 8 shows representative results of two subjects when viewing 3D images with two-dimensional viewpoints. Five curves describe subjects' accommodation responses of the real target (green curve), and 3D images which have 10 × 10 viewpoints (red curve), 6 × 6 viewpoints (blue curve), 2 × 2 viewpoints (purple curve), 1 × 1 viewpoint (black curve), respectively. Overall, the

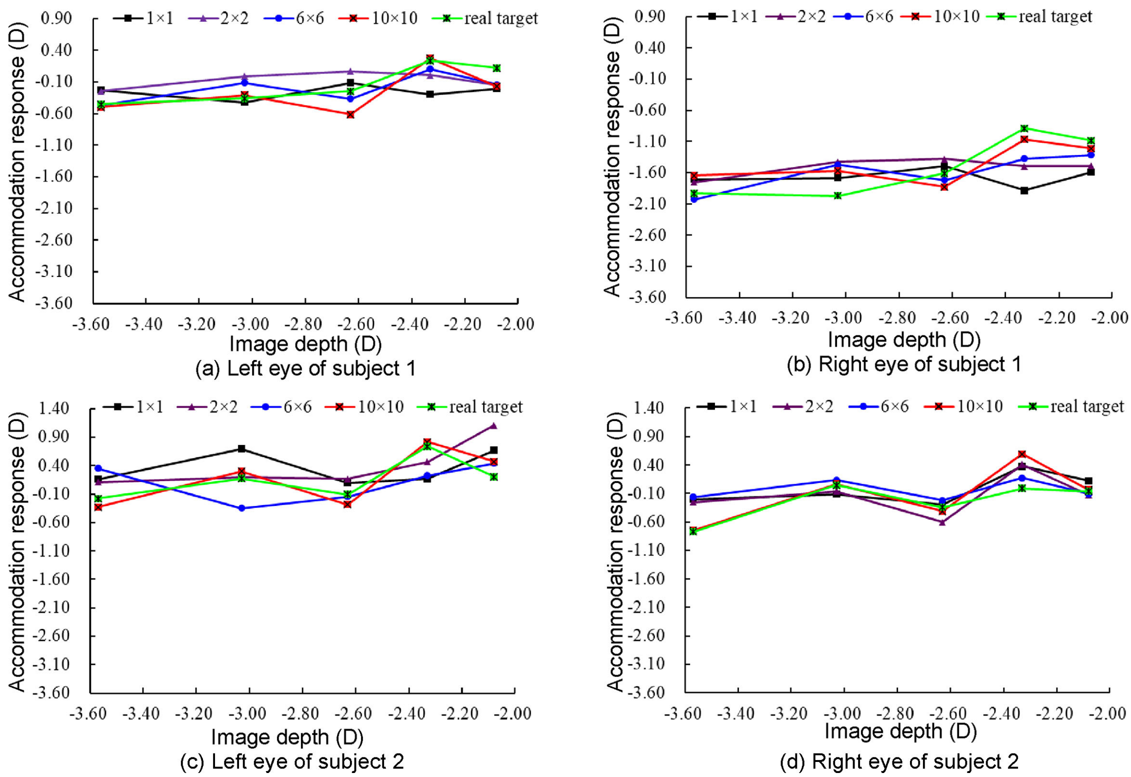


Fig. 8. Accommodation response of 3D image with two-dimensional viewpoints.

accommodation responses of all the 3D images show almost the same tendencies as that of the real target. There are some differences among the 3D images with different viewpoints quantity. To further reveal the differences, the experimental results were analyzed by linear-regression analysis and multiple comparison tests.

The linear-regression analysis and multiple comparison tests were completed in a statistical analysis software called Statistical Package for Social Science (SPSS). The process of linear-regression analysis is to calculate the slope and intercept based on the sample data. Fig. 9 shows the fitted regression lines of the curves in Fig. 8 through linear-regression analysis in which the abscissa axis represents accommodation responses of the real target, and the ordinate axis represents the accommodation responses of 3D images. The slopes and intercepts of the fitted regression line can reveal the differences of the accommodation responses between the 3D images and the real target. When the slope of the fitted regression line is close to 1 and the intercept is close to 0, accommodation responses of the 3D image and the real target is consistent. For the real target (green line), its slope is 1 and intercept is 0. The result shows that the accommodation response of the 3D image with 10×10 viewpoints (red line) is closer to the real target. Besides, the slopes and intercept of the fitted regression lines of each subject are listed in Table 2. For both left and right eyes, the 10×10 viewpoints has the most subjects whose slope of the fitted regression line is close to 1 and intercept is close to 0, followed by 6×6 viewpoints, and 1×1viewpoints has the least subjects. The statistical results reveal that the more viewpoints received by subject's single eye, the closer the accommodation response is to the real target.

Fig. 10 shows the result of the multiple comparison test of 3D images with different viewpoint quantities, and it shows significant differences between the 3D images and real targets. The abscissa axis indicates the depths of 3D images or the real target, and the ordinate axis indicates the number of subjects who show no significant difference of accommodation responses between the 3D images and the real target. The number of subjects who have no significant difference

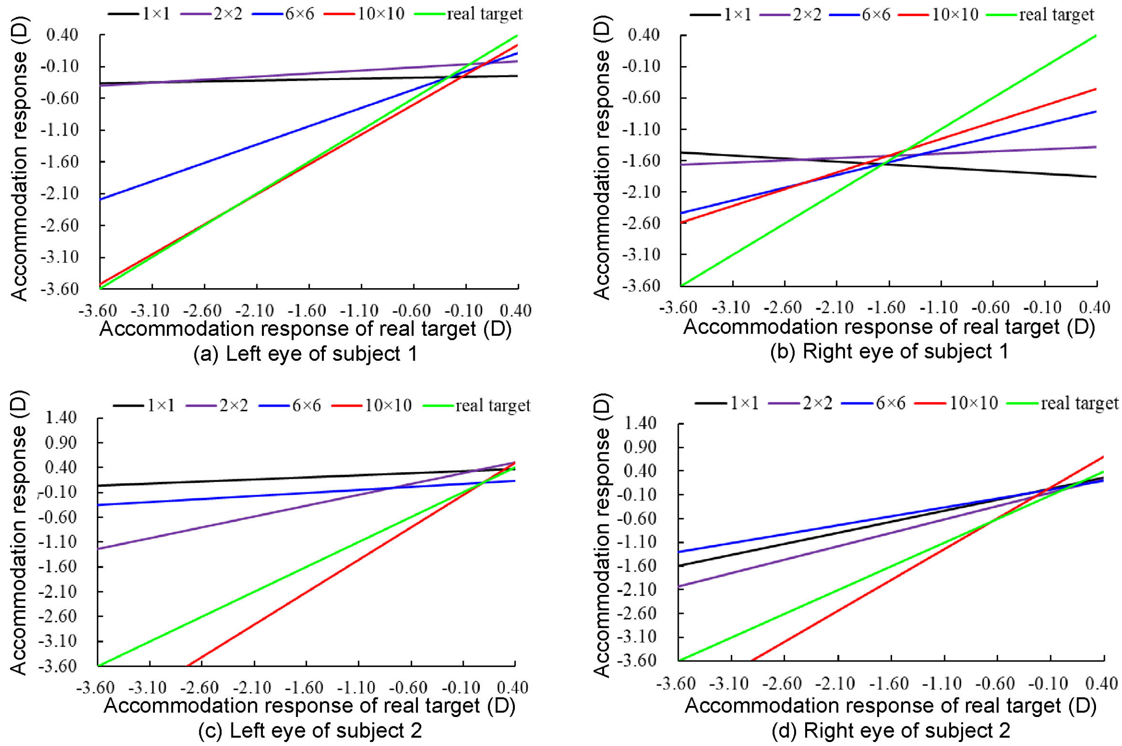


Fig. 9. Linear regression analysis of the accommodation responses of 3D images with different viewpoint quantities.

suggests the degree of similarity between the accommodation response of the 3D image and that of the real target, the more the higher. Although the tendency exists some disparities between each type of 3D image on different depths, the 3D images with more viewpoints (10 $\times$ 10 viewpoints-red bar, 6 $\times$ 6 viewpoints-blue bar) as a whole have more subjects who shows no significant difference than the 3D images with fewer viewpoints (2 $\times$ 2 viewpoints-purple bar, 1 $\times$ 1 viewpoints-black bar). This tendency is more remarkable in the results of right eyes. Fig. 11 shows the results of the multiple comparison test when we exclude the influence of depth and only consider the viewpoint quantity. The result of the multiple comparison test for a 3D image on a depth was regarded as a sample, and 50 samples (10 subjects $\times$ 5 depth) for each 3D image were obtained in total. The abscissa axis indicates the 3D image, and the ordinate axis represents the number of samples who shows no significant difference of accommodation responses between the 3D images and the real target. The results clearly illustrate that the number of samples who have no significant difference increases with the increase of viewpoints number. That is to say, the accommodation responses of 3D images with more viewpoints are closer to the real target which is coincide with the result of linear-regression analysis. The results demonstrate that dense viewpoints can promote human eyes to focus on the 3D images.

5.2 Results and Statistical Analysis for Accommodation Responses of 3D Images With Different Viewpoint Dimensions

Fig. 12 shows representative results of two subjects when viewing 3D images with different viewpoint dimensions. The four curves represent the accommodation response of the real target (green curve) and three 3D images which have 10 $\times$ 10 viewpoints (red curve), 10 $\times$ 1 viewpoints (orange curve), and 1 $\times$ 10 viewpoints (light blue curve), respectively. Similar as Fig. 8, the accommodation responses of these 3D images show almost the same tendencies as that of the real target. To

TABLE 2
Slopes and Intercept of Fitted Regression Lines of Each Subject

Observers		1×1viewpoints		2×2 viewpoints		6×6 viewpoints		10×10 viewpoints	
		slope	intercept	slope	intercept	slope	intercept	slope	intercept
Left eye	1	0.03	-0.25	0.10	-0.05	0.58	-0.12	0.94	-0.13
	2	0.09	0.34	0.44	0.34	0.12	0.08	1.30	-0.02
	3	0.48	0.22	0.53	0.29	0.79	0.08	0.10	-0.10
	4	-0.19	-0.19	0.02	0.09	-0.73	-0.07	-0.21	0.13
	5	-0.70	-1.64	0.16	-0.99	0.31	-0.78	-0.40	-1.40
	6	0.43	-0.44	0.61	-0.24	0.83	-0.08	0.67	-0.15
	7	0.20	-1.61	0.02	-2.02	0.07	-2.07	-0.49	-3.20
	8	0.48	-1.68	0.45	-1.75	0.58	-1.20	0.89	-0.04
	9	0.75	-0.24	0.93	0.40	0.93	0.17	0.94	0.10
	10	-0.60	-0.66	1.56	-0.15	1.95	0.27	0.21	-0.21
Right eye	1	-0.10	-1.82	0.07	-1.40	0.40	-0.98	0.53	-0.66
	2	0.47	0.08	0.56	0.00	0.38	0.05	1.30	0.19
	3	0.34	-0.25	0.60	-0.13	0.38	-0.32	0.22	-0.55
	4	0.65	-0.87	-1.36	-3.10	-1.86	-3.93	-0.74	-2.31
	5	-0.27	-1.02	0.36	-0.71	-0.13	-0.86	-0.37	-1.00
	6	0.42	-0.23	0.03	-0.35	0.71	-0.14	0.21	-0.34
	7	0.54	0.23	0.12	0.07	0.15	-0.02	0.18	0.07
	8	0.60	-1.44	0.27	-2.47	1.16	0.77	0.73	-0.35
	9	0.93	0.28	0.98	0.55	0.96	0.23	0.99	0.22
	10	1.26	0.31	1.90	2.00	1.96	2.08	1.49	1.10

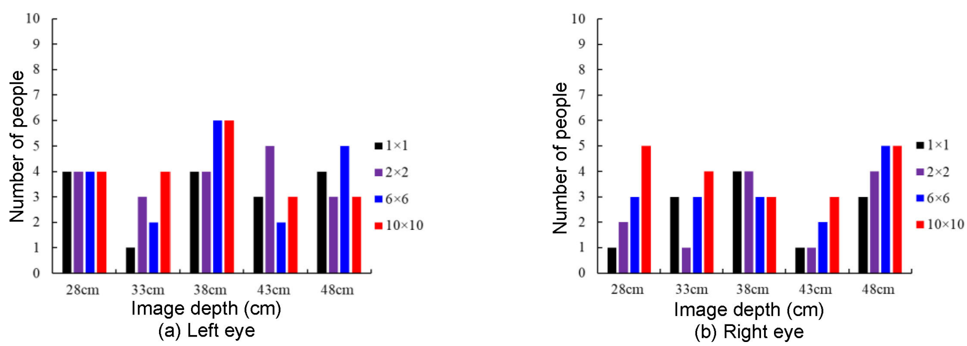


Fig. 10. Multiple comparison test results of 3D images with two-dimensional viewpoints on each depth.

further reveal the differences, the experimental results were also analyzed by linear-regression analysis and multiple comparison tests.

Fig. 13 shows the fitted regression lines of the curves in Fig. 12 through linear-regression analysis in which the abscissa axis represents the accommodation responses of the real target, and the ordinate axis represents the accommodation responses of 3D images. The slopes and intercept of the fitted regression lines of each subject are listed in Table 3. From Fig. 13 and Table 3, the two-dimensional viewpoints has the most subjects whose slope of the fitted regression line is

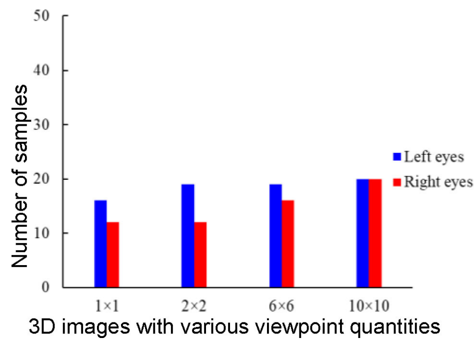


Fig. 11. Multiple comparison test results of 3D images with various viewpoint quantities.

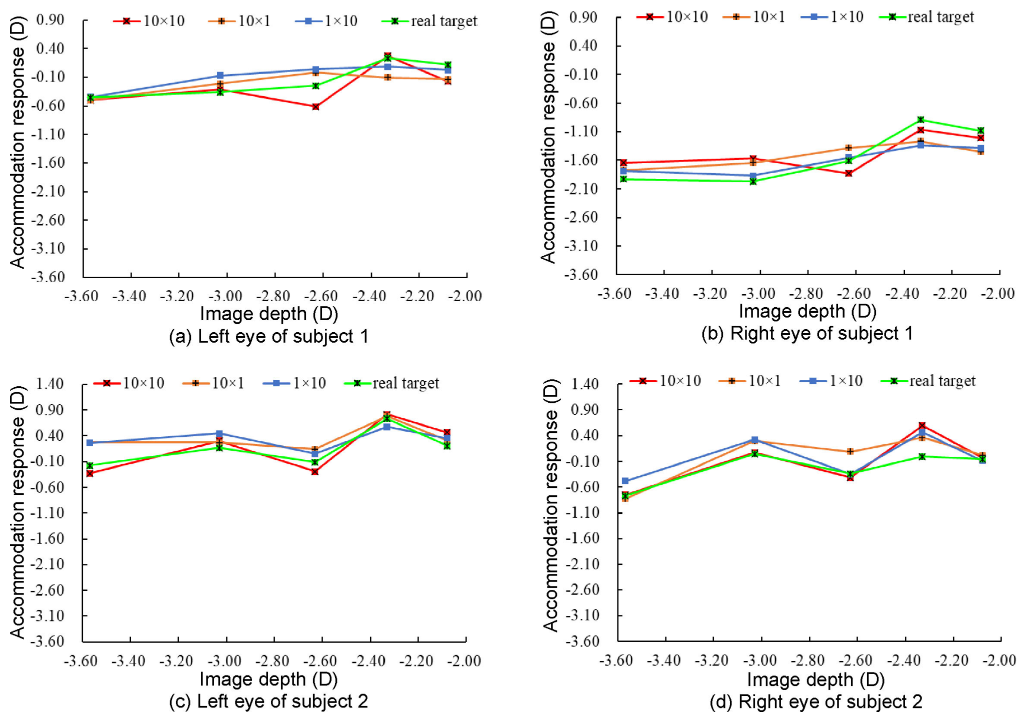


Fig. 12. Accommodation responses of 3D images with different viewpoint dimensions.

close to 1 and intercept is close to 0. For the one-dimensional viewpoints, the horizontal arranged viewpoints and vertical arranged viewpoints have the similar result. Obviously, the statistical results reveal that the accommodation responses of 3D images with two-dimensional viewpoints are closer to the real target than one-dimensional viewpoints. While, the accommodation response of the horizontal and the vertical arranged viewpoints have no statistical discrepancy.

Fig. 14 shows the results of a multiple comparison tests of 3D images with different viewpoint dimensions. The abscissa axis indicates the depths of 3D images or the real target, and the ordinate axis indicates the number of subjects who have no significant difference of accommodation responses between the 3D images and the real target. Although there are some disparities between each type of the 3D image on different depths, the 3D images with two-dimensional viewpoints (10×10 viewpoints-red bar) generally have more subjects who show no significant difference than the 3D images with one-dimensional viewpoints (10×1 viewpoints-orange bar, 1×10 viewpoints-light blue bar). Fig. 15 shows the results of the multiple comparison tests when we exclude the influence of depth and only consider the viewpoint dimensions. The result for a 3D image on each depth

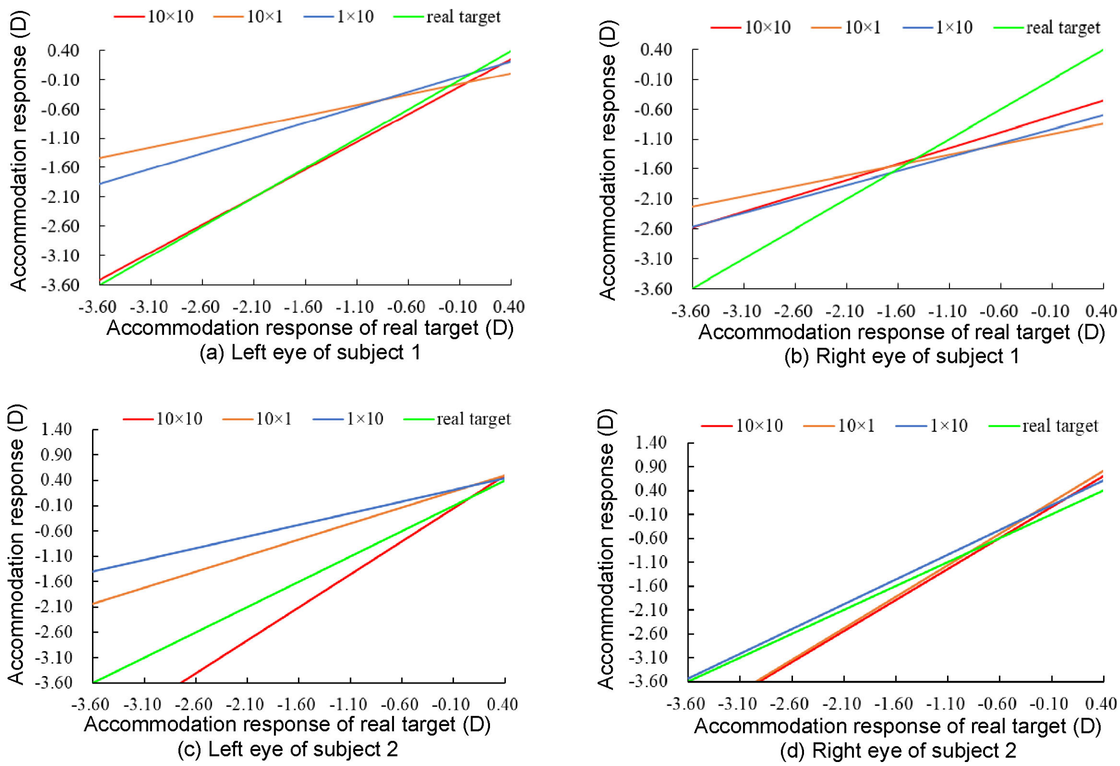


Fig. 13. Linear regression analysis results of the accommodation responses of 3D images with different dimensions.

TABLE 3
Slopes and Intercept of Fitted Regression Lines of Each Subject

Observers		10×10viewpoints		10×1 viewpoints		1×10viewpoints	
		slope	intercept	slope	intercept	slope	intercept
Left eye	1	0.94	-0.13	0.36	-0.14	0.52	0.00
	2	1.30	-0.02	0.63	0.25	0.46	0.26
	3	0.10	-0.10	0.68	0.20	0.75	0.39
	4	-0.21	0.13	0.12	0.24	0.58	0.17
	5	-0.40	-1.40	0.18	-0.98	0.05	-0.96
	6	0.67	-0.15	0.37	-0.46	0.92	0.16
	7	-0.49	-3.20	-0.12	-2.47	-0.38	-2.95
Right eye	1	0.53	-0.66	0.35	-0.98	0.47	-0.88
	2	1.30	0.19	1.32	0.29	1.04	0.21
	3	0.22	-0.55	1.07	0.30	0.84	0.16
	4	-0.74	-2.31	0.42	-1.08	0.47	-0.99
	5	-0.37	-1.00	-0.09	-0.91	-0.41	-1.01
	6	0.21	-0.34	0.68	-0.13	1.62	0.58
	7	0.18	0.07	0.74	0.51	0.51	0.14

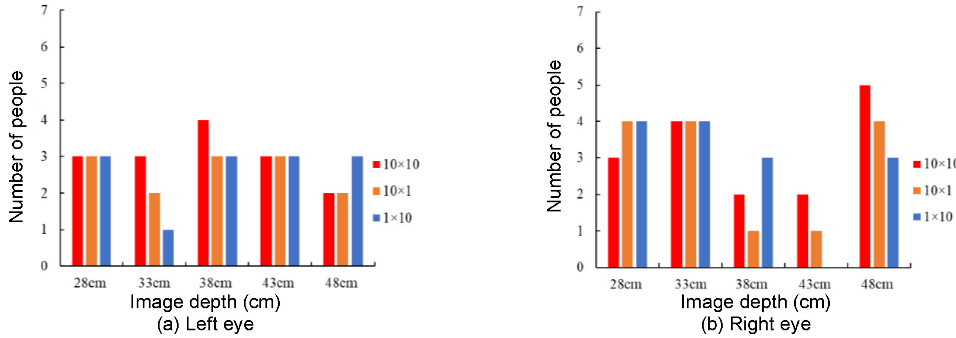


Fig. 14. Multiple comparison test results of 3D images with different viewpoint dimensions on each depth.

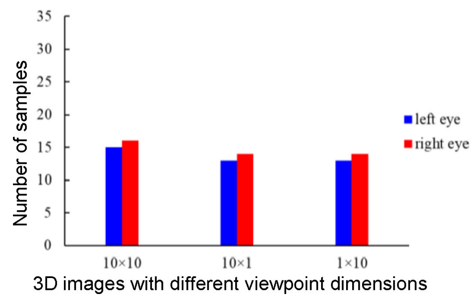


Fig. 15. Multiple comparison test results of 3D images with 10 × 10 viewpoints, 10 × 1 viewpoints, and 1 × 10 viewpoints.

was regarded as a sample, and 35 samples (7 subjects × 5 image depths) for each 3D image were obtained. The horizontal axis indicates the 3D images, and the vertical axis represents the number of samples who show no significant difference of accommodation responses between the 3D images and the real target. The results distinctly demonstrate that the number of samples who shows no significant difference for two-dimensional case is more than the one-dimensional case. Additionally, for one-dimensional cases, the number of samples for horizontally arranged case is almost equal to vertically arranged case. Therefore, the accommodation responses of 3D images with two-dimensional viewpoints is closer to the real target, and there is no obvious difference between horizontal and vertical cases. From the results, we can conclude that two-dimensional viewpoints can promote the human eye to focus on the 3D images, while only horizontal or vertical viewpoint have no difference for the focusing.

6. Conclusion

In this paper, we studied on the effect of the viewpoints received by a single human eye on the accommodation response. The spatial distribution of viewpoints was analyzed, and the viewpoints quantity received by a single human eye was deduced. The accommodation responses of 3D images with various viewpoint quantities and dimensions were tested objectively. The results of linear-regression analysis and multiple comparison tests both show that the accommodation responses of 3D images have the same tendency as that of the real target. And with the increase of the viewpoints, the accommodation responses of 3D images are closer to the real target. This tendency is obvious when the viewpoint quantity reduces from 10 × 10 to 6 × 6. For 2 × 2 and 1 × 1, the accommodation responses are unstable and much different from the real target. Additionally, the accommodation responses of 3D images with two-dimensional viewpoint are closer to the real target than the one-dimensional viewpoint. While, there is no obvious difference between horizontal and vertical cases. This research proves that the viewpoint quantity and dimension received by a single human eye should be considered. More viewpoints and two-dimensional viewpoints are helpful for comfortable 3D perception. The result of this study is useful to researchers for developing an integral imaging 3D display with high visual comfort.

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