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**Abstract.** We proposed a glasses-free randot stereotest using a multiview display system. We designed a four-view parallax barrier system and proposed the use of a random-dot multigram as a set of view images for the glasses-free randot stereotest. The glasses-free randot stereotest can be used to verify the effect of glasses in a stereopsis experience. Furthermore, the proposed system is convertible between two-view and four-view structures so that the motion parallax effect could be verified within the system. We discussed the design principles and the method used to generate images in detail and implemented a glasses-free randot stereotest system with a liquid crystal display panel and a customized parallax barrier. We also developed graphical user interfaces and a method for their calibration for practical usage. We performed experiments with five adult subjects with normal vision. The experimental results show that the proposed system provides a stereopsis experience to the subjects and is consistent with the glasses-type randot stereotest and the Frisby–Davis test. The implemented system is free from monocular cues and provides binocular disparity only. The crosstalk of the system is about 6.42% for four-view and 4.17% for two-view, the time required for one measurement is less than 20 s, and the minimum angular disparity that the system can provide is about 23 arc sec. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JBO.20.6.065004](https://doi.org/10.1117/1.JBO.20.6.065004)]

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## 1 Introduction

Stereoacuity is defined as the smallest horizontal disparity required to provoke a perception of depth or stereopsis.<sup>1–8</sup> Figure 1 shows the geometry of the angular disparity in an object space.<sup>1</sup> When object A and object B are located at different distances, the convergence angles between the two eyes induced by the binocular disparity also become different. The difference between the two convergence angles  $\alpha$  and  $\beta$  is defined as angular disparity  $\eta$ . From the geometric relation, angular disparity  $\eta$  is derived as follows:

$$\eta = \alpha - \beta \approx \frac{I_{PD} \cdot \Delta D}{D^2 + D \cdot \Delta D}, \quad (1)$$

where  $D$  is the distance between the frontal object and the observer,  $\Delta D$  is the distance between the objects,  $I_{PD}$  is the interocular distance, and  $\alpha \ll 1$  rad,  $\beta \ll 1$  rad are assumed. In many cases, stereoacuity is expressed as the smallest angular disparity  $\eta$  that a patient can discriminate.

Ocular diseases including strabismus, anisometropia, amblyopia, or aniseikonia cause the degradation of stereopsis and lead to poor stereoacuity.<sup>2,3</sup> Therefore, an exact measurement of stereoacuity of a patient is important in evaluating a disease associated with the disruption of normal binocular fusion. However, it is

difficult to separate stereopsis from other monocular depth cues including psychological and physiological cues. A subject may feel depth based on monocular depth cues such as the accommodation, shading, texture gradient, or motion parallax, all of which can affect the stereoacuity value. To address this problem, various attempts have been made to develop a stereotest that minimizes such monocular depth cues.

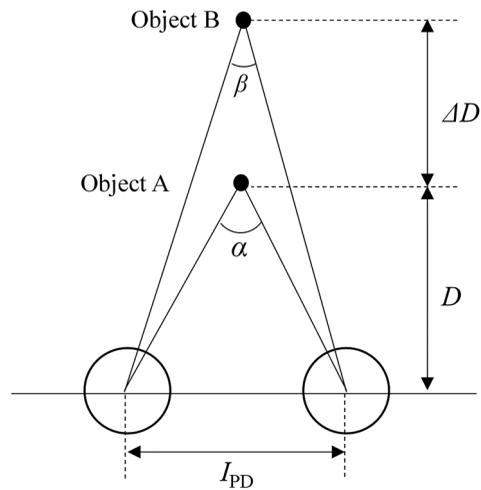
### 1.1 Random-Dot Stereogram

The random-dot stereogram is the most widely used method in the field of stereotesting. Introduced by Julesz,<sup>7</sup> it is composed of randomly arranged dot patterns containing horizontal disparity information inside.<sup>6,7</sup> Therefore, one can perceive depth from the random-dot stereogram only with stereopsis. The randot stereotest is a stereoacuity test which utilizes a random-dot stereogram. It is usually implemented with polarization glasses and several random dot targets with different angular disparities. However, since this method usually involves printed random-dot patterns with the pre-defined disparity levels, it has some disadvantages including a limited range of measurement, a small number of disparity levels, a fixed observing distance, and learning effects.

### 1.2 Randot Stereotest Using the Glasses-Type Three-Dimensional Display System

With the intent to minimize the usual disadvantages caused by the printed random-dot stereogram, we proposed a randot

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**Fig. 1** The geometry of the angular disparity in object space.

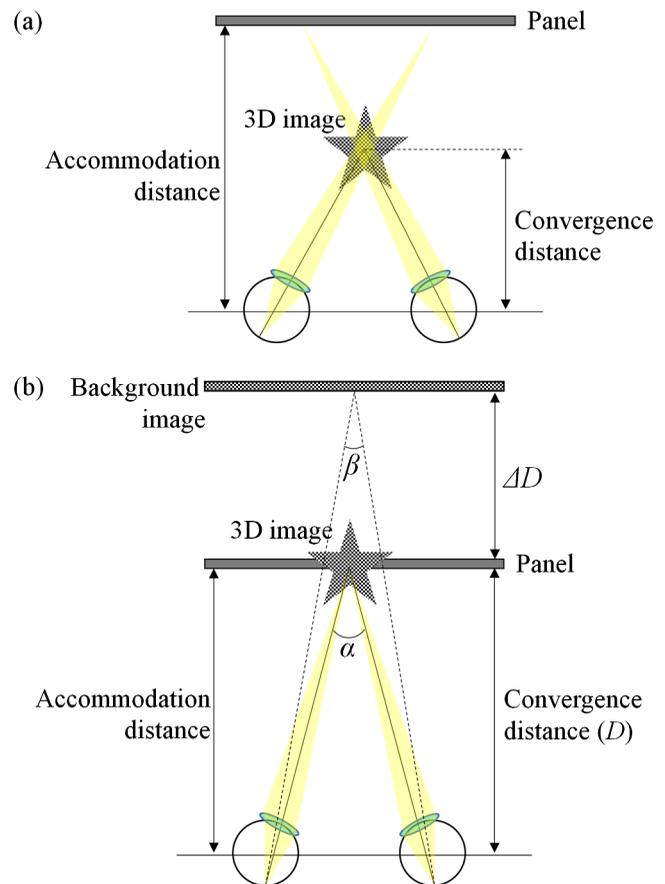
stereotest using a glasses-type three-dimensional (3-D) display system.<sup>4,5</sup> Initially, we had developed a stereotest system using a polarization glasses 3-D television. However, the system had a limited disparity level caused by the large pixel pitch and the line-by-line polarization difference interrupted binocular fusion.<sup>4</sup> Therefore, we devised an improved randot stereotest test system based on a shutter glass 3-D laptop.<sup>5</sup> This system provided diverse disparity levels with a smaller pixel pitch and subpixel rendering<sup>9</sup> and was free from the decrease in stereoacuity caused by spatial multiplexing.

We also applied a depth adjustment technique for accommodation–convergence (AC) conflict reduction in the randot stereotest.<sup>10,11</sup> Figure 2(a) shows the AC conflict caused by stereoscopic images in front of the panel in a glasses-type 3-D display. The light rays are diverged from a pixel at the panel, so the observer unconsciously attempts to focus on the panel. However, the disparity between the left-eye view and the right-eye view induces convergence at the intended 3-D images position, as shown in Fig. 2(a). Since this does not occur in reality, the AC conflict causes stereo fusion to be interrupted, a headache, or stereoblindness.<sup>10</sup> Previous studies showed that the AC conflict leads to poor stereoacuity values both in near and far distance<sup>12,13</sup> and AC conflict affects visual discomfort.<sup>14</sup> In the stereoacuity test based on the glasses-type 3-D display, the AC conflict lessens the correspondence between the real value of the stereoacuity and the value carried out from the test.

To reduce the effect of AC conflict in the stereoacuity test, we displayed the 3-D image in the panel plane. Unlike the usual 3-D scenes, the 3-D scene in the test is exclusively composed of the plane target image and the background. Therefore, it helps to move the background plane behind the panel for reducing AC conflict. Figure 2(b) shows a schematic diagram of the proposed method for reducing AC conflict. The target object and the background image are composed of the random pattern, so the observer cannot recognize the object with the monocular cues. The subjective test shows that the concordance between the conventional randot stereotest and the proposed randot stereotest using a glasses-type 3-D display system increases with the AC conflict reduction method.<sup>5</sup>

### 1.3 Glasses-Free Randot Stereotest

Previous studies have verified the validity of the use of a randot stereotest using a glasses-type 3-D display system. Although the



**Fig. 2** Accommodation–convergence (AC) conflict reduction technique in the randot stereotest using a glasses-type three-dimensional (3-D) display system: (a) AC conflict in 3-D display and (b) AC conflict reduction system.

randot stereotest based on a glasses-type 3-D display system was a breakthrough, questions still arise regarding the issue of wearing glasses. The effect of glasses has remained an unsolved problem in the randot stereotest field. The use of polarization glasses, shutter glasses, or anaglyph glasses may somehow affect binocular stereopsis, and it is different from the actual binocular fusion experiences in the real world. Previous studies showed the difference of stereoacuity value in glasses<sup>15</sup> and glasses-free stereotests or focused on the difference of depth perception in various types of glasses-type 3-D display systems.<sup>16,17</sup> However, the exact effect of the special glasses has been remained as an unsolved problem.

In this paper, we propose a glasses-free randot stereotest using a multiview display system. The multiview display is an autostereoscopic 3-D display method that provides different view images at different viewpoints.<sup>18–23</sup> By locating an optical layer such as a parallax barrier or a lenticular lens sheet in front of the display panel, the observer can view 3-D images without any special glasses. We designed a four-view parallax barrier system for the randot stereotest and generated special view images called random-dot multigrams for use in conjunction with the proposed system. This way, the observer can receive the 3-D information more comfortably than through the glasses-type 3-D display system. The glasses-free randot stereotest has advantages for children or people who have a problem with wearing glasses.

Furthermore, by implementing the glasses-free randot stereotest with multiview display, the effect of optical glasses in stereopsis could be verified. Previous glasses-free stereotests including the Frisby–Davis test dealt with real objects rather than separated views.<sup>24</sup> By contrast, the previous glasses-type stereotests provided stereopsis with the separated views.<sup>4–8</sup> They removed monocular cues with the glasses but the proposed system can play the same role without the glasses. The proposed system takes advantage of knowing the effect of the glasses as well as the convenience of not wearing glasses. The effect of the glasses can be derived by a comparison between the randot stereotest using a glasses-type 3-D display and using a two-view parallax barrier display.

Additionally, the effect of motion parallax can be also determined by comparing the results of a glasses-free randot stereotest using a two-view parallax barrier display with results using a four-view parallax barrier display. The proposed system can provide one stereo image pair or two different stereo images without mechanical changes.<sup>18–23</sup> In the test, the subjects are located inside the viewing region and tested with the two-view and four-view glasses-free randot stereotest. By comparing these results, we can discriminate the effect of motion parallax and how it affects the stereopsis.

A preliminary system implementation has been introduced.<sup>25</sup> However, in this study, we discuss the detailed principles and present a feasibility test using actual subjects. In Sec. 2, we discuss the basic principle of the multiview display and introduce a random-dot multigram, which is an expanded concept of the random-dot stereogram for the proposed glasses-free randot stereotest. The system implementation and detailed specifications are presented in Sec. 3. In Sec. 4, we describe a crosstalk measurement experiment as well as a feasibility test for the glasses-free randot stereotest using five subjects.

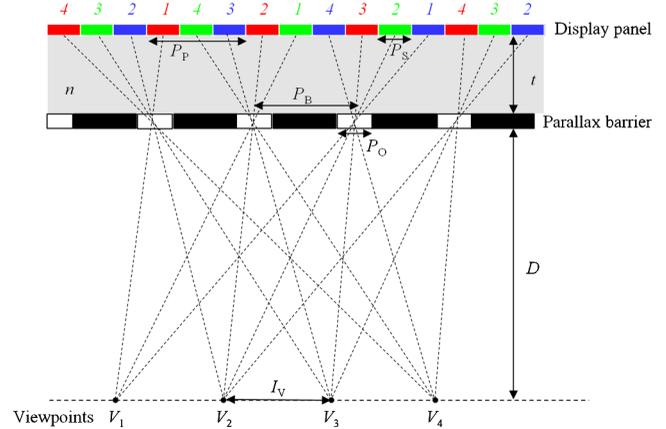
## 2 Principles

### 2.1 Four-View Parallax Barrier Display

A multiview display refers not a specific display system, but rather a type of 3-D display, so it can be confirmed with various optical devices.<sup>20–23</sup> The necessary and sufficient conditions for a multiview display system are to provide different view images to different viewpoints. A parallax barrier is a type of optical device located at the front of the display panel in the multiview display system, which is easy to customize.<sup>25,26</sup> We designed a four-view parallax barrier system for the glasses-free randot stereotest, as shown in Fig. 3.  $P_p$  is a pixel pitch,  $P_s$  is the subpixel pitch,  $P_B$  is the parallax barrier pitch,  $P_O$  is the pitch of the opening,  $t$  is the thickness of the parallax barrier,  $n$  is the refractive index of the parallax barrier,  $V_1, V_2, V_3,$  and  $V_4$  are the viewpoints,  $D$  is the viewing distance, and  $I_V$  is the view interval.

The design rule for the multiview display system requires two steps. Before designing the parallax barrier, we selected an appropriate display panel and fixed the viewing distance  $D$  and the view interval  $I_V$ . The parallax barrier pitch and the thickness can then be derived with the two principles. First, the nearby subpixels should be heading the neighbor viewpoints. Second, the subpixels with the interval of the view numbers  $N_v$  should converge at a point. The first and second design principles are expressed as Eqs. (2) and (3), respectively:

$$t = \frac{P_s}{I_V} nD, \quad (2)$$



**Fig. 3** The design of the four-view parallax barrier system for the glasses-free randot stereotest.

$$P_B = \frac{D}{D + t/n} N_v P_s. \quad (3)$$

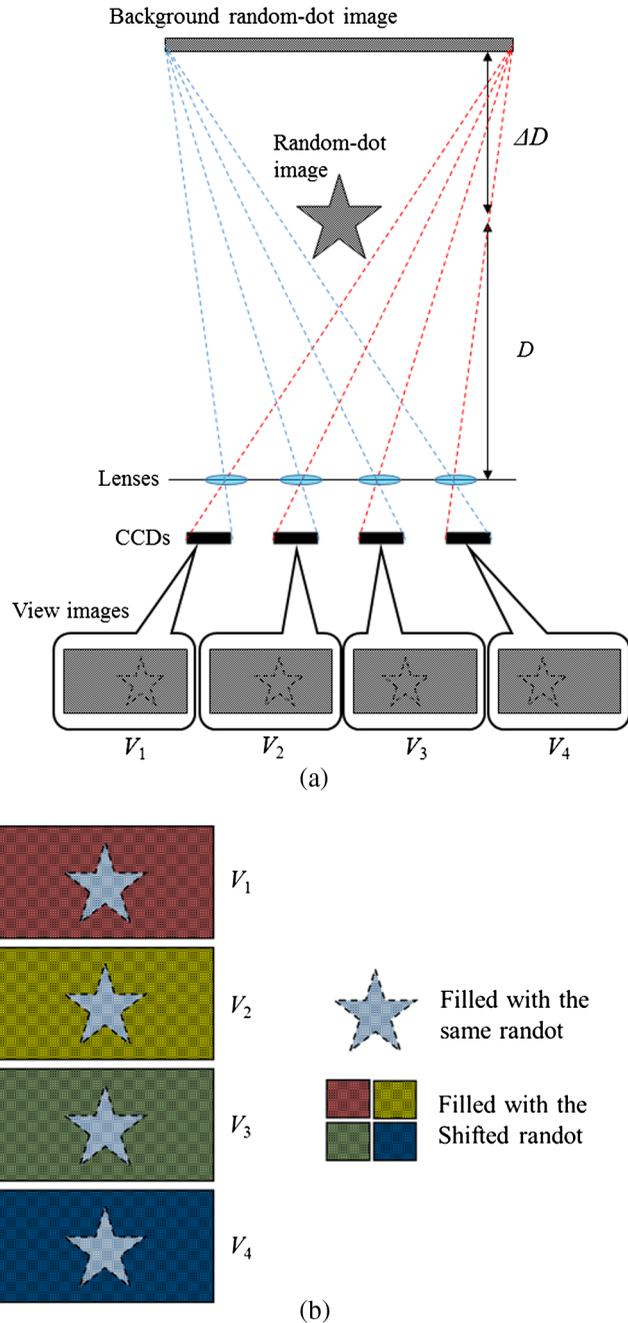
In a normal multiview display, the view interval  $I_V$  is set as the interocular distance or half of it. The average of the interocular distance for adults is about 65 mm,<sup>1–5</sup> however, the randot stereotest is often presented to subjects who are children. Therefore,  $I_V$  should be set in accordance with the subjects' ages. Once  $I_V$  is decided, the parallax barrier is designed with Eqs. (2) and (3): the different  $I_V$  needs parallax barriers with different specifications.  $P_O$  controls the tradeoff between intensity and crosstalk, and it usually takes the value of the subpixel pitch.<sup>21–23</sup>

### 2.2 Random-Dot Multigram

To provide a stereopsis experience to the patient, view images without monocular cues must be generated. In a glasses-type 3-D display, a random-dot stereogram was used, as described in Sec. 1.2. However, in a multiview display, the generation method should be expanded from a random-dot stereogram which is produced via the lateral shift of random dot patterns. Since generating the random-dot view images for the multiview display is a new concept, we refer to it as a random-dot multigram in this report. This term was chosen since the term autostereogram already exists to explain the single image stereogram.<sup>27</sup>

The random-dot multigram is generated through the virtual pickup process in a multiview display. Figure 4(a) shows a schematic diagram of the virtual pickup process for the proposed four-view parallax barrier system. The virtual scene is composed of a random-dot image and a random-dot background. The virtual charge coupled devices (CCDs) are located at the viewing distance and capture the random-dot target image and the random dot background image. The interval between the CCDs is identical to the view interval  $I_V$ . The dashed lines indicate the view volume of the multiple CCDs. The distance between the lenses and random-dot target is identical to the observing distance  $D$  because the random-dot target image is located at the display panel plane and the lenses refer to the eyes at the viewpoints. Afterward, the distance  $\Delta D$  between the target image and the background can be derived from Eq. (1) as follows:

$$\Delta D = \frac{\eta D^2}{I_{PD} - \eta D}, \quad (4)$$



**Fig. 4** The random-dot multigram generation method for the four-view glasses-free randot stereotest: (a) virtual charge coupled devices (CCDs) and lenses capture the 3-D scene composed of a random dot image and a background random dot image and (b) a conceptual result for random-dot multigrams generated by the virtual 3-D scene.

where  $I_{PD}$  is the interocular distance and the  $\eta$  is the intended angular disparity. The random-dot multigram with various angular disparities can be generated with Eq. (4).

Since we applied the AC conflict reduction technique described in Sec. 1.2, the random-dot image is located at the center of each view volume. This pickup condition consistently locates the random-dot image at the display panel plane. Figure 4(b) represents conceptual resulting random-dot multigrams that are virtually captured from the CCDs. The random-dot target image filled with the same random-dots is located at

the center, whereas the random background fills the rest of the view image with laterally shifted random-dot patterns.

The generated random-dot multigram is a set of view images and provides a stereopsis experience to the observers with a proper multiview display. The base image of the multiview display is generated from the random-dot multigram. In the case of a multiview display, the base image is generated by interweaving the view images along the lens border or the parallax barrier border.<sup>14</sup> Since our system is a four-view subpixel nonslanted parallax barrier, one-view image is located at every four subpixels of the base image. The size of a random dot should be a multiple of 4. Otherwise, the color of the random dot would not be white, contrary to the original intention.

### 3 System Implementation

#### 3.1 Glasses-Free Randot Stereotest with Four-View Parallax Barrier System

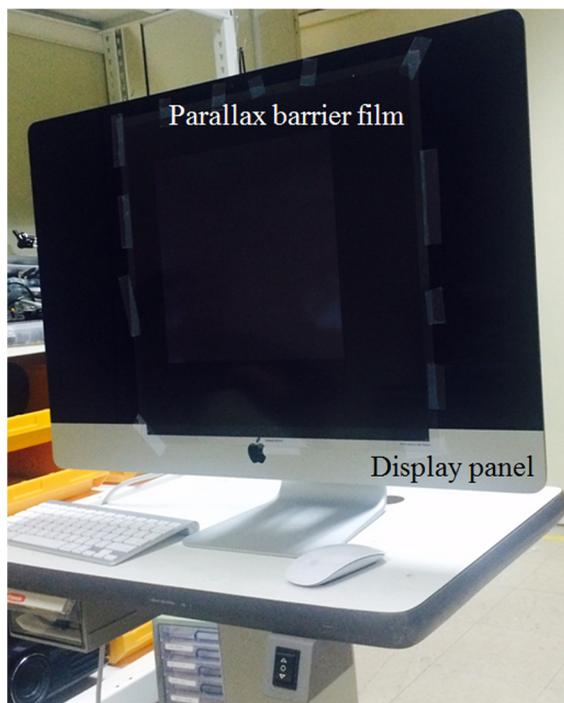
With the principles introduced in Sec. 2, we designed and implemented a glasses-free randot stereotest system with a four-view parallax barrier system. The pixel pitch should be sufficiently small to permit 3-D images to be presented with a small angular disparity. In our previous research, the minimum angular disparity in the near distance (50 cm) was about 30 arc sec with subpixel rendering and 80 arc sec without subpixel rendering.<sup>5,9</sup> In a parallax barrier system, the horizontal resolution is decreased by the number of views  $N_v$ , so the effective subpixel pitch is increased. Therefore, the display panel used in the parallax barrier system should have a smaller pixel pitch to provide a smaller minimum angular disparity level. Therefore, we applied a 27 in. 5K liquid crystal display for this purpose (iMac retina 5K, Apple Inc.) because of its small pixel pitch. Since it has a protective cover glass in front of the display panel, we set the view interval  $I_V$  to half of the interocular distance. The use of a smaller view interval allows a larger thickness  $t$ . In consideration of children as well as adult subjects, the view interval  $I_V$  of the system is set at 31.25 mm. The observers feel the depth with  $V_1$  and  $V_3$  or  $V_2$  and  $V_4$ . The detailed specifications are listed in Table 1. Our system can only provide two different stereo images, and the number of views is not enough to present continuous motion parallax. However, the depth resolution should be sacrificed to increase the number of views. The minimum angular disparity that the implemented system can provide is about 23 arc sec, which is small enough to permit subjects with or without normal vision to be measured. In the future, the glasses-free randot stereotest can provide more views with an improved display panel whose pixel pitch is much smaller than now. However, four-view is the maximum with the state-of-art technologies. Figure 5 shows the implemented glasses-free randot stereotest system. The parallax barrier film is customized and minutely calibrated with the subpixel structure of the display panel, as shown in Fig. 5.

#### 3.2 Random-Dot Multigram for Four-View Parallax Barrier System

The random-dot multigrams with the various disparity levels are generated for the proposed glasses-free randot stereotest. We generated random-dot multigrams with 14 different angular disparity levels (3000, 2000, 1000, 800, 600, 400, 250, 200, 140, 93, 70, 46, 23, and 0 arc sec). The levels with the small angular disparities are quantized because of the quantized subpixels. We

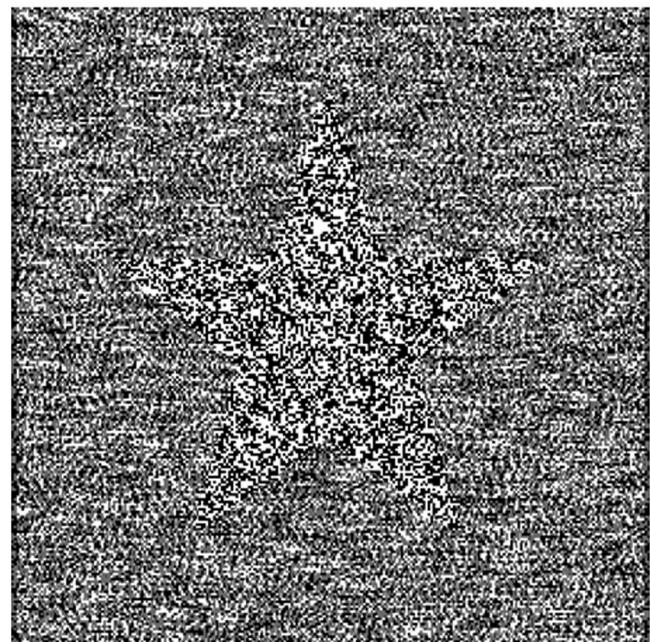
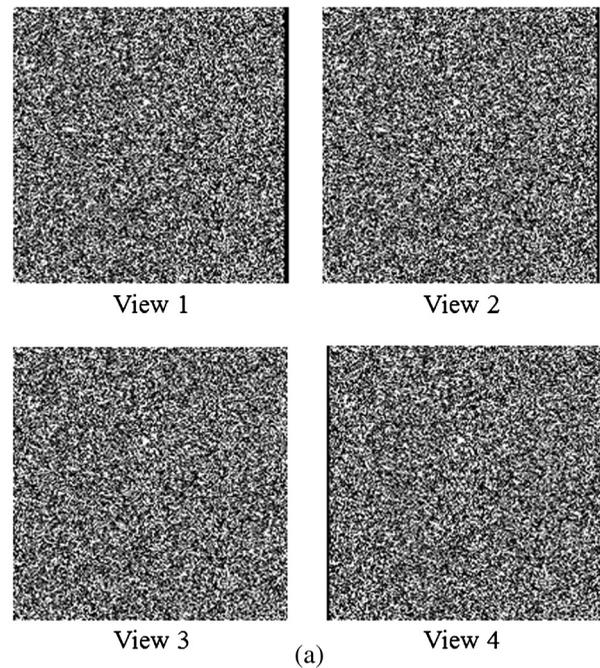
**Table 1** Specifications of the implemented glasses-free randot stereotest using a four-view parallax barrier system.

Parameters	Value
Pixel pitch, $P_p$	116.51 $\mu\text{m}$
Subpixel pitch, $P_s$	38.83 $\mu\text{m}$
Number of views, $N_v$	4
View intervals, $I_v$	31.25 mm
Parallax barrier pitch, $P_B$	155.14 $\mu\text{m}$
Opening pitch, $P_O$	38.83 $\mu\text{m}$
Thickness, $t$	2.57 mm
Observing distance, $D$	1.38 m
Refractive index, $n$	1.5

**Fig. 5** The implemented glasses-free randot stereotest with a four-view parallax barrier system.

generated four different target images (star, circle, triangle, and rectangle) for each disparity level. We also generated random-dot multigramms with two different dot sizes (4 and 8 pixels).

Figure 6 shows a generated random-dot multigram and the base image generated from the random-dot multigram with the star image target, a disparity of 2000 arc sec, and a dot size of 8 pixels. Figure 6(a) represents the random-dot multigramms for the proposed glasses-free randot stereotest. As shown in Fig. 6(a), monocular cues are entirely excluded, so the single view image does not contain any information regarding the target star image. However, the base image generated from the random-dot multigram shows the star image at the center, as shown in Fig. 6(b). This implies that the subject can perceive the star image in a different depth plane with the multiple view images. Ideally,

**Fig. 6** The generated random-dot multigram and the base image for the four-view parallax barrier system (target image: star, 2000 arc sec, dot size: 8 pixels): (a) generated random-dot multigram and (b) generated base image from the random-dot multigram.

the subject's eyes should be located at the viewpoints so that he or she could obtain the target image information, not with one, but with both eyes, which indicates that the proposed system is free from monocular cues.

### 3.3 Graphical User Interfaces for Glasses-Free Randot Stereotest

For practical usage for ophthalmologists and patients, it is necessary to ensure easy user interfaces. Children patients get tired

easily during the time required for long and boring measurements. Therefore, we developed graphical user interfaces (GUI) for the proposed test. We used the MATLAB (MathWorks Inc., R2012a) guide and an example of the GUI is shown in Fig. 7.<sup>28</sup> The presenter can proceed with the measurement by clicking the buttons on the GUI.

Figure 7(a) shows the captured image of the entire GUI when the test is in progress. Figures 7(b) and 7(c) are the captured images of the bottom part of GUI when the test is in standby and is finished, respectively. The minimum angular disparity is shown directly on the GUI, and the entire test information is saved in the form of a text file, as shown in Fig. 7(d).

## 4 Experiments

### 4.1 Crosstalk Measurement

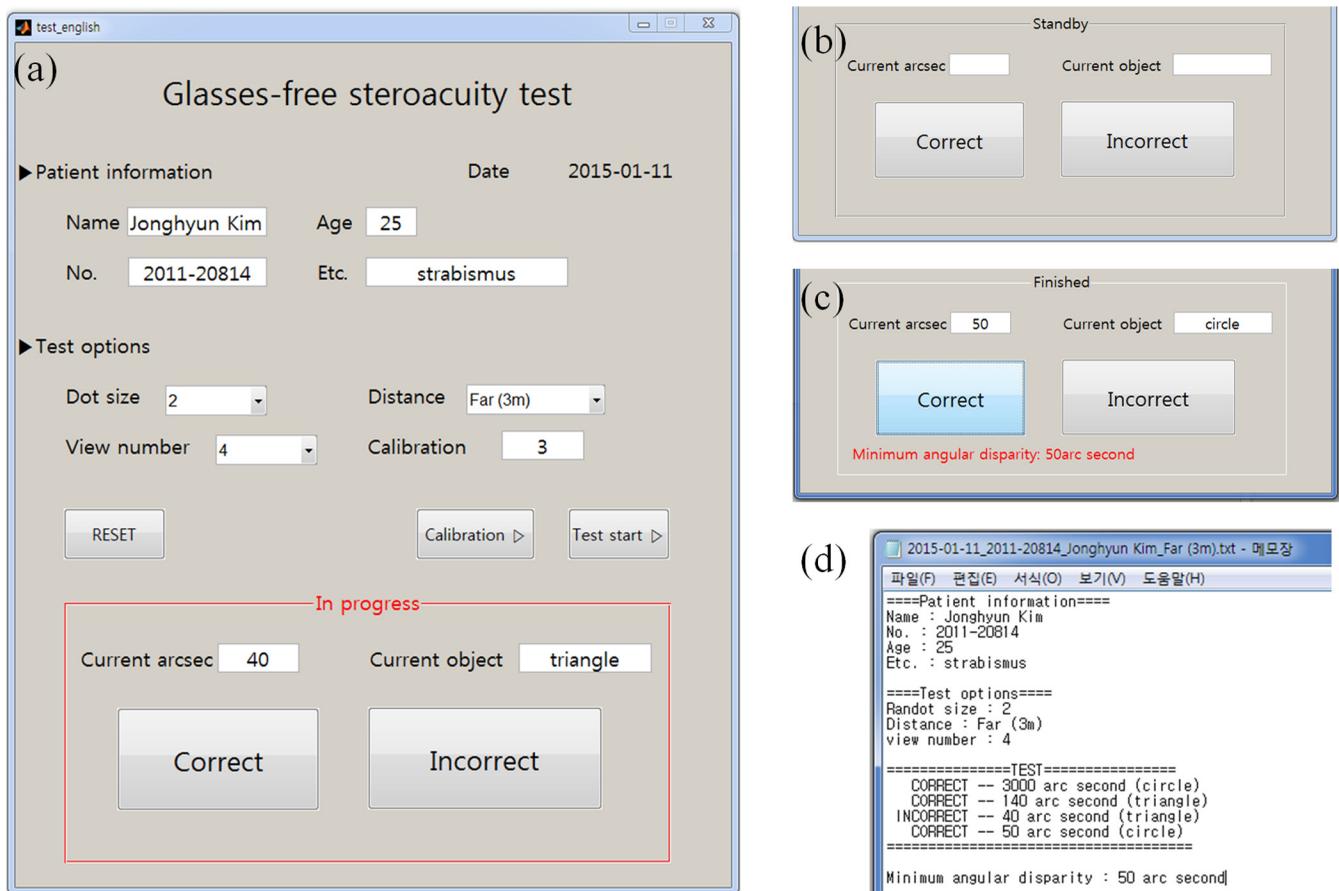
We carried out a crosstalk measurement experiment to verify the 3-D image quality of the implemented parallax barrier system. We measured the lateral intensity distribution at the viewing distance (1.38 m) and a measuring interval of 10 mm using the display color analyzer (KONICA MINOLTA, CA-210). Figure 8 shows the measured intensity distribution showing the crosstalk between four view images. The measured view interval is about 3.125 cm, which is identical to the designed value, as shown in Table 1. Therefore, the patient can feel 3-D images

with  $V_1$  and  $V_3$  or  $V_2$  and  $V_4$ , where the distance between those views is about 6.25 cm. The average crosstalk for the system, as calculated from six dominant intensity peaks, is 6.42% for four-view, and 4.17% for two-view, which can be derived from the simple equation.<sup>29,30</sup> These values are acceptable for use in a stereoscopic and multiview 3-D display system.<sup>30-32</sup>

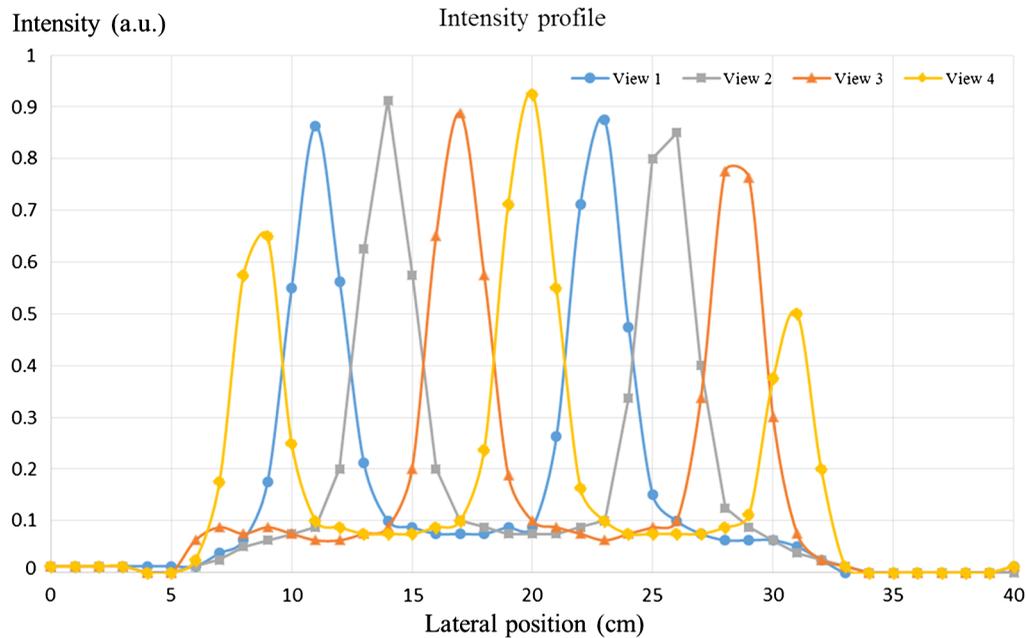
### 4.2 Calibration

Since the implemented multiview display provides a proper view image only at the viewpoints and the view interval is about 3.125 cm, a detailed calibration is required for more accurate testing. We generated an alignment pattern for the experiment, and an example of the calibration process is shown in Fig. 9. In Fig. 9, the “star” image denotes the right-eye view and the “circle” image denotes the left-eye view. The view image changes rapidly as the viewer moves laterally. Therefore, the subject can move his or her position so as to locate the eyes at the proper viewpoints. For a robust test environment, a fixation frame can be utilized to fix the position of the eye and move the alignment pattern laterally on the pixel scale. Our proposed GUI provides this pixel scale calibration algorithm.

To provide a motion parallax experience with a four-view parallax barrier display, we let the subjects locate in the viewing window rather than in the fixed viewpoint. After the calibration process, the subject guesses the target object with a lateral



**Fig. 7** An example of the graphical user interfaces (GUI) for the glasses-free randot stereotest. Patient information, test options, and current test information are shown and the calibration in pixel unit is also provided: (a) captured image of the whole GUI when the test is in progress, (b) captured image of the bottom part of GUI when the test is in standby, (c) captured image of the bottom part of GUI when the test is finished, and (d) the resultant text file containing whole information of the test.



**Fig. 8** The lateral intensity profile of the implemented system at the viewing distance (1.38 m) with a measured interval of 10 mm using the display color analyzer.

movement of head. With the accurate control of eye position, we can achieve a motion parallax condition with the four-view parallax barrier display.

### 4.3 Glasses-Free Randot Stereotest

We presented a feasibility test of the proposed glasses-free randot stereotest system to the subjects. Figure 10 shows the conceptual experiment of the glasses-free randot stereotest with a four-view parallax barrier and the control GUI. The GUI is shown at the additional monitor only for the presenter. The testing process is simpler and faster when the GUI is utilized. Initially, the presenter fills out the test information inside the GUI such as the patient information and test options. The calibration process is then performed using the calibration pattern. The GUI offers lateral alignment in a pixel scale.

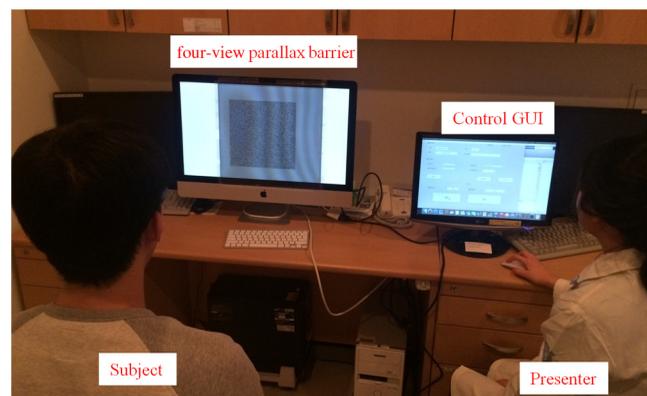
The measurement process is followed by the calibration. The system randomly shows the base image generated from the randot multigram images with various angular disparities. The program shows the base image with the biggest angular disparity

(3000 arc sec) to the subject, and the answer to the presenter. If the answer is correct, half of the remaining levels can be skipped. If the subject is not correct, the subject is tested with a one-level higher disparity consecutively, and so on. The measurement is repeated to determine the stereoacuity value of the subjects. The required time for the entire test, including the calibration process, is <1 min and the required time for the measuring process is <20 s.

We presented the Frisby–Davis test, the randot stereotest using the glasses-type 3-D display, and the proposed glasses-free randot stereotest to five adult subjects with normal vision and the experimental results are summarized in Table 2. This study was conducted in compliance with the Declarations of Helsinki and was approved by the Institutional Review Board of Seoul National University Bundang Hospital. Written informed consent was obtained from all participants. The observing distance is 3 m for the Frisby–Davis test and the randot stereotest using the glasses-type 3-D display, whereas the observing



**Fig. 9** Example of the calibration process used in the glasses-free randot stereotest (Video 1, MOV, 2.41 MB) [DOI: <http://dx.doi.org/10.1117/1.JBO.20.6.065004.1>].



**Fig. 10** Conceptual experiment of the glasses-free randot stereotest with a four-view parallax barrier and the control GUI. The control GUI is shown in the additional monitor.

**Table 2** The experimental results of the feasibility test: glasses-free randot stereotest (four-views/two-views, dot size 4 pixels/8 pixels), the randot stereotest using the glasses-type 3-D display, and the Frisby–Davis test. The average values of two performances for every test are shown in arc sec, except for the eyesight.

Subject	Glasses-free (dot size: 4 pixels)		Glasses-free (dot size: 8 pixels)		Stereoscopic (shutter glass)	Frisby–Davis	Eyesight (L/R)
	Two-view	Four-view	Two-view	Four-view			
A	23	23	23	23	32.5	40	1.0/0.8
B	35	23	46	23	22.5	40	1.2/0.8
C	146	35	23	23	25	50	1.5/1.5
D	23	23	23	23	37.5	50	1.0/1.0
E	23	46	23	23	20	40	1.0/1.0

distance is 1.38 m for the proposed glasses-free randot stereotest. The average values of the two performances for every test are shown in arc sec, except for eyesight.

Although the number of subjects was not sufficient to derive a statistical analysis, we were able to confirm that the proposed glasses-free randot stereotest system worked successfully. The proposed glasses-free randot stereotest system provides a stereopsis experience in both the two-view and four-view modes with different dot sizes (4 and 8 pixels). The results also show concordance between the proposed glasses-free randot stereotest and the existing stereoacuity test.

Since our feasibility test was only conducted using subjects with normal vision, the resulting stereoacuity values were nearly <50 arc sec. However, the experimental results indicate that the system provides stereopsis experiences down to 23 arc sec, as expected, and the variation among the values is negligible. One exception is shown in a two-view glasses-free randot stereotest when the dot size is 4 pixels, but we think it is an outlier because the test was started from two-view/4 pixels and the subject got used to the glasses-free randot stereotest after the first experiment. Experimental results show that our system is a reliable device for measuring stereoacuity. The quantitative concordance can be verified with better precision with subjects having optical malfunctions compared to the stereopsis.

## 5 Conclusions

We proposed here a glasses-free randot stereotest using a multi-view display system. We designed a four-view parallax barrier system and proposed a random-dot multigram, which is a set of view images for use in the proposed glasses-free randot stereotest. We analyzed the design principles and the image generation method in detail and implemented a glasses-free randot stereotest system with a four-view parallax barrier system. We also developed a GUI and a calibration method for practical use. We used the system to evaluate five adult subjects with normal vision. The experimental results show that the proposed system provides a stereopsis experience to the subjects and the glasses-type randot stereotest, the Frisby–Davis test, and the proposed method are all in general agreement. The implemented system was free from monocular cues and only provided the binocular disparity. The crosstalk of the system was about 6.42% for four-view and 4.17% for two-view, the time required for one measurement was <20 s, and the minimum angular disparity that the system could provide was about 23 arc sec. We expect that

the proposed glasses-free randot stereotest can be further applied to the clinical field when verifying the effects of glasses and motion parallax in cases of stereopsis.

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