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Depth sensitivity investigation on multi-view glasses-free 3D display

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Abstract- *Compared with the 2-view 3D display, the multi-view 3D display provides more views to the observers, which allows a stereoscopic perception relatively closer to real viewing condition. Depth sensitivity (DS) on multi-view 3D display has not been investigated with respect to view number and stimulus contents. A lenticular glasses-free 3D display with alternative view numbers (2 views and 28 views) was used as the test platform. Two types of stimulus were implemented for DS investigation, including random dot stereogram (RDS) and contour stereogram (CS). 20 adults (22.8 ± 2.1 years old) with normal vision participated in the experiment. Experimental results showed that the DS on 2-view display mode was consistent with that measured with the conventional DS test (t-ratio = 0.2560, P=0.8569). Besides, the DS was significantly better for 28-view display mode, compared with 2-view display mode (t-ratio = 4.326, P<0.0001). For the influence of stimulus type, subjects were able to perceive more precise depth information with the RDS (t-ratio=2.023, P=0.0422), compared with the CS. The proposed investigation indicates that depth perception is closely related to view numbers and stimulus content, the proposed investigation provides essential cues for the choice of view numbers and contents to achieve the desired perception effect.*

Keywords: **depth sensitivity, multi-view, random dot stereogram, contour stereogram, glasses-free 3D display**

1. INTRODUCTION

The ability to perceive depth information is an essential function of the human vision. Correctly perceived and processed binocular information allows us to perceive the stereoscopic world [1]. Various attempts have been made by ophthalmologists, optometrists and vision researchers for the assessment of stereo vision. Some of the most widely used tests are Frisby, TNO, Randot and Titmus [2]. However, most of the tests are based on two images with disparity between left eye and right eye to create the depth perception, this is not similar to the viewing condition in our daily life, where the view number is infinite. It is difficult to access stereopsis with real objects, due to the requirement of the precision, facilitation etc. Is the ability of stereopsis for real object perception equal to the results obtained by the clinical test? Will the stereopsis be better if more views are provided? These issues could be addressed with the help of new 3D technologies. Various 3D displays have been developed with advances of electronic and computing technology [3,4]. Currently, two main types of display are stereoscopic 3D display and glasses-free 3D display. Thanks to the flexibility and precision of these digital 3D devices, most specific studies on binocular vision could be carried out. Stereo blindness and stereoacuity were evaluated on a digital 3D display by Gadia et al. [5]. Glasses-free 3D display was used for the stereo vision test [6], and the experimental result is consistent with that of the glasses-type random dots stereogram test and the Frisby-Davis test. Glasses-free 3D display could be a promising platform for binocular vision screenings. On one hand, it removes the effect of glasses, because the traditional stereopsis test usually requires the observer to wear red-green or polarized glasses to depict paired images. However, this causes rivalry or large crosstalk if the interference between views is not reduced to a certain threshold. On the other hand, the use of glasses-free display excludes additional barriers for some observers, because they are not suitable to wear glasses, such as young children or people with some problems with glasses [7,8].

The choice of the stimulus is also important for stereoacuity measurement. The well-known tests include contour stereogram (CS) test and random dot stereogram (RDS) test [7]. The CS test uses two horizontally disparate images to evaluate the stereopsis, such as Titmus Fly test. For the RDS test, the contour of the target is embedded in the random dots, so monocular cues are eliminated. These tests include the Randot stereo test, TNO stereotest, Frisby stereotest and Lang stereotest. In addition to vision impairment diagnoses, stereopsis tests are also important for the vision assessment of normal people, such as the early vision detection of children. However, due to variations of the stimuli and subjects, the standards of stereoacuity are not consistent. Fawcett reported that patients with a history of anomalous binocular vision could acquire better stereoacuity scores with the circle test than the random dot-based Preschool Randot stereoacuity test [9]. The stereoacuity with contour stereo test is 40 arc sec better than that with random dot E stimulus [10]. While another study of Fan showed that subjects with normal binocular vision performed equivalently with Randot test compared with Titmus test [11]. Distinct conclusions mentioned above are related to several factors, such as display type and luminance, and even the density and size of the stereogram might affect the stereo vision perception [12-15]. To better understand the properties of depth perception, it is necessary to carry out an experiment to measure the two main types of stereo test under the restrained condition, with comprehensive consideration of the display, stimulus design and the experiment environment. Here, a depth sensitivity (DS) measurement system based on a lenticular multi-view glasses-free 3D TV is presented. The view number of the 3D display is convertible between 2 views and 28 views. Specific algorisms are used to adapt the image composition according to the required view number and the mechanism of the lenticular sheet. Besides, the effect of stimulus (RDS and CS) on the DS is also compared on the same display platform. Furthermore, the result of the 2-view display mode is compared with conventional stereo test (TNO test), with regard to exploring the consistence of the proposed test and the commonly used stereo test. The better depth perception can be achieved with 28-view display mode on the glasses-free 3D display, since the stereoscopic perception is closer to the real viewing condition when more views are provided.

2. SUBJECTS AND METHODS

Subjects Twenty healthy subjects (22.8±2.1 years old) participated in the experiments. They are college students and master students in Beijing University of Posts and Telecommunications. The monocular visual acuity of subjects was equal or better than 10/10 without the history of ocular pathology (functional and organic) and strabismus. Approval was obtained according to the tenets of the Declaration of Helsinki. Informed consent was obtained from the subjects orally. All subjects were naive to the experimental procedures and informed of the nature of the study.

Glasses-free 3D Display Description A 50 inch TV (Hisense) with a resolution of 3840*2160 was used as the glasses-free display in the experiment. As shown in Figure 1(a), a slant lenticular was implemented on the LCD panel to achieve light refraction and high dense views. The alignment of the lenticular and the panel was calculated using the unit of sub pixel (0.096 mm). Each lens pitch covered four and two thirds sub pixels (0.3216 mm). Such slight object viewed at the distance of 1.8 m was conspicuous enough to keep the accommodation and the convergence around the lenticular plane. The interval of viewpoints for 28-view display mode was 1 cm, and for 2-view display mode, the interval was 14 cm. The optimal viewing distance was 1.8m. Figure 1(b) shows the distribution of the 28 views on one period according to the lenticular pitch position and subpixels on the LCD screen.

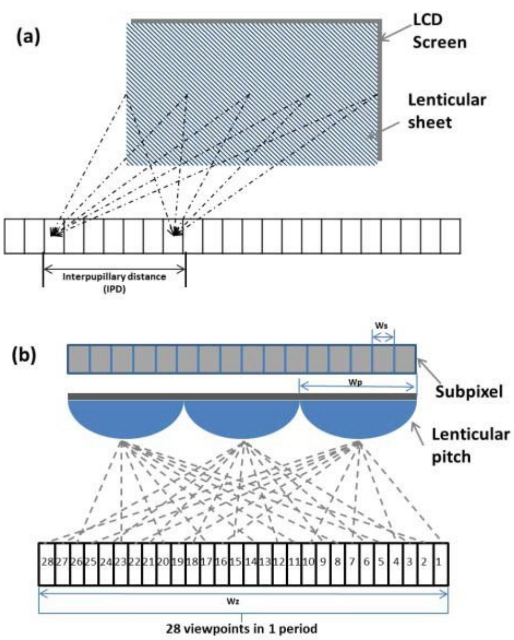

Figure 1. The 28 view glasses-free 3D display, (a) Schematic diagram of the 3D display architecture. (b) The viewpoint distribution according to the attachment of subpixel and lenticular sheet.

Stimuli Creation Two types of stimulus images were used in the study: contour stereogram (CS) and random dot stereogram (RDS). The creation of stereogram for 2-view display mode is demonstrated in Figure. 2. In Figure 2 (a), for the right eye image, four objects were distributed on the image, the left eye image was the same as the right eye image except that one randomly chosen object was shifted rightward. Thus a disparity was created on the object between the paired images. For RDS creation (Figure. 2 (b)), an "E" was embedded in the random dots. The right eye image was composed by random dots, where the dot size was 4*4 pixel and the dot density was 50%. According to a depth map, the "E" pattern in the left eye image was shifted rightward according to the required disparity. The blank area caused by the shift was filled with random dots, in order to synthesize the occluded textures between views [6,16]. The depth information of "E" between the right and the left eye image could only be seen with binocular vision. The direction of the "E" varied from trial to trial (up, down, left, right), as well as its disparity.

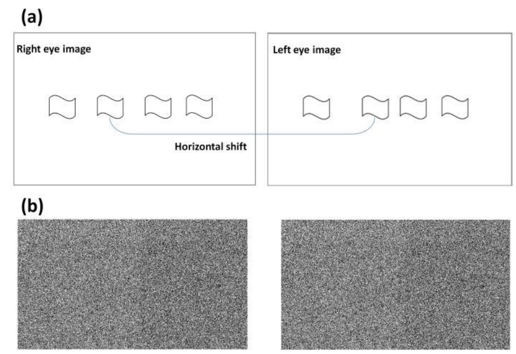

Figure 2. (a) 2 view-display mode stereogram manipulation for CS test, (b) 2 view-display mode stereogram manipulation for RDS test.

For the 28-view display mode stimulus creation, 28 pictures were firstly created with a disparity between each adjacent image, then those images were subsequently compounded by an algorism (Figure 3(a)) [17]. Finally, a single image was created to provide multiple views when it was displayed at the 28-view display mode, as shown in Figure 3(b).

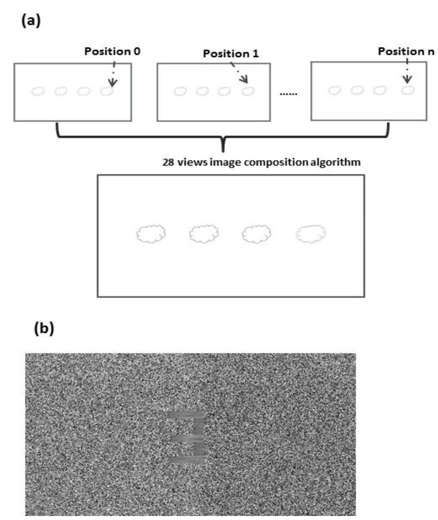

Figure 3. (a) 28 view-display mode stereogram manipulation for CS test, (b) Composed image for 28 view-display mode for RDS test.

Depth sensitivity Measurement There were five sessions in the experiment. Four sessions were carried out on the same autostereoscopic TV, with an algorithm applied to alter the stereograms according to required display mode. DS was measured under the condition of 2-view display mode and 28-view display mode, both for RDS test and CS test (2*2=4 sessions). There was also a session carried out on a printed paper booklet to test the consistence of the standard stereopsis test and the proposed test. Subjects wore red-green glasses to detect the shape of the object which were embedded in the random dots. This type of test is commonly used in general vision screening in China.

The order of the sessions for each subject was randomly selected to balance out impact of fatigue and visual experience. For the sessions carried out with the glasses-free autostereoscopic TV, 8 disparity levels were presented in each session, including 30”, 60”, 100”, 200”, 400”, 800”, 1000” and 1200”. Each level was assigned to a trial. The disparity level was shown from high to low (from 1200” to 30”). The task of the subject was to tell the object with disparity (CS test) or the direction of “E” (RDS test). The last level for which the subject answers correctly is considered as the DS for that session. This method to record DS was adapted from clinical measurements, it has also been used by several related scientific studies[5,18,19]. Besides, all the subjects in the experiment were normal vision adults, the data variability was low and the validity and repeatability of the experiment could be trusted[19]. In order to keep subjects’ heads at the optimal viewing zone, a calibration step was carried out every time at the beginning of the sessions. Subjects were instructed to keep their heads stable, in order to reduce motion parallax effect.

Data Analysis The significance of the data between different conditions was analyzed by Friedman test. Nonparametric statistics was chosen because the distribution of the data did not conform to normal distribution. The analysis was carried out using SPSS in Win 10 system.

3. RESULT

The DS was measured using RDS test and CS test with the display mode of 2-view and 28-view. Table 1 shows the mean DS and standard deviation of each session. The best stereopsis was obtained when RDS were used with 28-view display mode, by contrast, the lowest DS appeared when CS were used with 2-view display mode. The standard deviation decreased when 28-view display mode were applied, indicating the subjects’ unconscious movement of the head during the experiment. According to our previous study on the visual performance near the best viewing point, slight displacement of viewing position would not significantly affect the results [15]. Figure 4(a) shows the condition when the screen works on 28-view display mode at the viewing distance of 1.8m, Figure 4(b) demonstrates the conceptual experiment of contour test with 28-view display mode.

Table 1 Average DS across all subjects for each session. In the first row, Ref stands for the conventional stereoacuity test on a booklet. In the last row, average AS stands for averaged DS of all the subjects, SD stands for standard deviation.

Display mode	2 views		28 views		Ref
Stimulus	CS	RDS	CS	RDS	RDS
AS + SD (s arc)	270±139	77±69	68±44	35±11	75±61

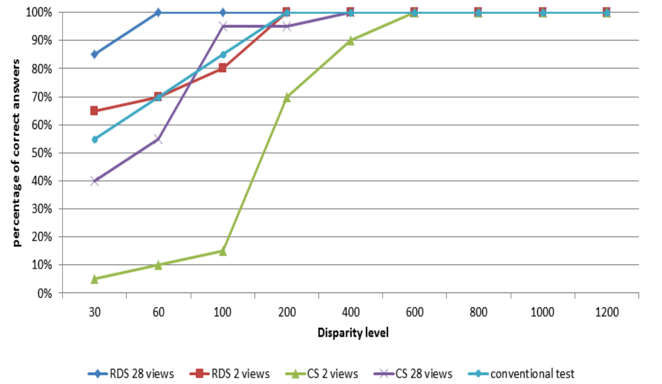

Figure 5. Percentage of correctly perceived depth information as a function of disparity levels. RDS stands for randomdot stereogram, CS stands for contour stereogram.

The percentage of correctly detected disparity as a function of disparity level is shown in Figure 5. Comparing the RDS tests (2-view display mode) with the conventional test at the disparity level of 30”, it was observed that more subjects could perceive depth information correctly with conventional test. However, the difference was not obvious when disparity increased. Comparing the tests of 2-view display mode and 28-view display mode, stereopsis was evidently better with 28-view display mode, both for the stimulus of CS and RDS. Comparing the visual performances when different stimulus was applied (RDS and CS), more subjects could achieve correct depth perception with RDS. The trend was the same both for the 2-view display mode and 28-view display mode. However, the difference between RDS and CS with 28-view display mode was smaller than that of the 2-view display mode.

Table 2 Statistics results for the comparison of different conditions. In the first row, Ref stands for the conventional stereoacuity test on a booklet. The probability level is 0.05, the sample size is 20, and the statistical power is one tailed hypothesis.

Tests	2 views CS	28 views RDS	Ref
2 views RDS	Chi-square=17; P<0.001 Statistical power 0.983	Chi-square = 7; P=0.008 Statistical power 0.573	Chi-square = 0.667; P<0.414
28 views CS	Chi-square=17; P<0.001 Statistical power 0.995	Chi-square=10; P=0.002 Statistical power 0.709	--

The statistics results of Friedman test for the significance between conditions is shown in Table 2. It reveals that there was no significant difference between 2-view display mode and conventional stereopsis test. The DS was significantly better with 28-view display mode compared with 2-view display mode, both for the CS test and the RDS test. The DS was significantly better with RDS test than that of the CS test, both on 2-view display mode and 28-view display mode. The individual data for each test is presented in Figure 6, this allows the readers to explore the visual performances across different test conditions.

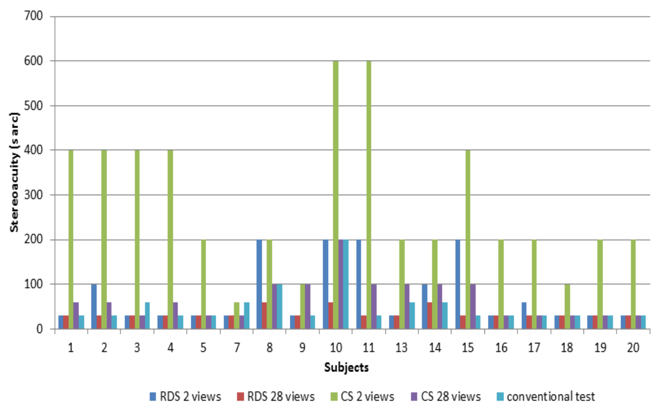

Figure 6. Individual stereoacuity in the five sessions.

4. DISCUSSION

Why high depth sensitivity with more views?

The experimental results confirmed our hypothesis that stereopsis is better when more views are provided. This result might be interpreted by four aspects, first is the effect of motion parallax, it is a monocular cue resulting from head motion[20]. In our experiment, although we asked the subjects to keep their heads at the same position, the unconscious movements of the eyeballs were not ignorable. When the eyes were trying to convergence or divergence, to accommodate on the screen, or to fuse the disparity and achieve stereo perception, it was not possible to keep the eye static all the time. The second aspect is the variation of intensity between views, as measured and reported in previous studies, the light intensity distribution of each view could be used to evaluate the uniformity of 3D display. The increase of view numbers reduced the light intensity fluctuations between views, thus the viewing experience was improved [6,17]. The third aspect is the effect of crosstalk, it is well-known that the crosstalk between adjacent views is larger on multi-view glasses-free displays comparing with two views displays. However, on multi-view auto stereoscopic display, the right eye and left eye are not located in adjacent views, for example, the right eye may see view 1 and left eye will see view 6, the interocular crosstalk is not as much as 2-view glasses-free display [21]. The last aspect relates with the maximum displayed clear depth of multi-view displays. Due to the physical structure of the lenticular based glasses-free 3D display, the allowable depth of a scene is determined by the view number and viewing distance. For high dense views glasses-free display, the special bandwidth is broader, so more information of the target could be perceived by the subjects. Besides, it is also reported in previous study that the viewing experience on high dense views glasses-free display was better compared with 2-view display [22].

The difference between CS and RDS

The differences between CS and RDS tests have been investigated in previous studies. For the RDS test, since the subject needs to extract the binocular cues in the stereogram, they need to achieve excellent oculomotor cooperation and sensorial fusion. So it is difficult for the subject with strabismus to detect the depth information. However, the monocular cue is not completely excluded if the subjects cannot keep stable during the test [23]. This often happens for children. It has been pointed out that the stereoacuity score larger than 160” in the RDS test should be interpreted with caution, as there might be artifacts from the monocular cue [24]. For the CS test, the contour of the object stimulates additional mechanisms that will contribute to stereo perception. Some strabismus subjects could perceive the depth in CS test because the contour of the target provides cognitive cues [9]. These conclusions from previous studies give an impression that stereoscopic perception task using RDS might be more difficult for normal vision subjects, in comparison to CS test. In our experiment, all the subjects do not have strabismus, so the effect for impaired sensory fusion is removed. The low depth perception sensitivity with CS test could be explained by the following aspects: The design of the stimuli, there were four objects shown on screen at each trial, and the task was to identify the one that had depth information. However, the four objects were not very close to each other, and there was no background surface to serve as a depth reference (like the RDS test). Thus larger disparity would be required to detect which stimulus was ‘off the plane’ of the display surface. The second aspect could be the different stimulus size of RDS test and CS test. The effect of stimulus size on binocular disparity fusion was investigated in our previous work[12], reporting that the increase of stimulus size could significantly facilitate binocular fusion. In the current study, although DS was measured on the same display and viewing distance in the test of CS and RDS, the random dots that filled within the structure of the “E” enlarged the stimulus size thus made the disparity detection easier. The third aspect is related with crosstalk on glasses-free 3D displays. Due to the white background of the CS, the interference from other views was more obvious than the case of RDS, and this affected binocular perception and reduced stereopsis performance.

Comparison with previous studies

Stereoaucity has been measured using software-based 3D digital displays with the development of information technology. In the study of Gadia et al, they designed a software to measure stereoacuity using a desktop monitor and 3D glasses [5]. Comparison was made between the software based stereoacuity test and traditional physical test (random dot stereo test). The results indicated that with small disparity, the correct answer percentage for depth detection was higher with physical test compared to software based stereoacuity test. The difference between the two methods became unobvious when the disparity was larger than 32 arc sec. This is consistent with the results in the current study, which indicated that the DS of 2-view display mode with RDS test was similar to conventional stereoacuity test. The stereoacuity on multiple views digital 3D displays was measured by Kim et al, they reported that the stereopsis experience on the 4 views glasses-free 3D display was consistent with the glasses type randot stereotest and Frisby-Davis test [6]. Our results for the depth perception experience on multi-view digital glasses-free 3D display was different from Kim’s conclusion, since an obvious improvement of disparity discrimination was observed on 28 views glasses-free 3D display, comparing with conventional stereoacuity test. This difference could be explained by the limited number of views in the study of Kim, as the platform they have used in their experiment was a 4 views 3D display, and it was reported in the study of Carballeira that the visual comfort increased with the density of views [25].

5. CONCLUSION

By using a multi-view 3D display, we assessed DS under a condition relatively closer to normal viewing conditions (infinite views). The effect of stimulus type on the stereoscopic perception on glasses-free 3D display was investigated. The development of computing technology and electronic technology will bring more digital applications in the field of clinical measurements and treatments. With these digital equipment, clinicians can make more precise measurements, achieve better control on the properties of the stimulus, such as target shape and size, luminance, contrast etc., and they could also implement random orders for the test trials to eliminate the effect of learning. The experimental results of the current study could provide references for the vision science researchers for the choices of stereoscopic stimuli and 3D display platform. However, specific experiments of stereopsis perception on similar 3D displays within the abnormal vision population should be carried out in the future study, for a comprehensive understanding about the advantages and disadvantages of the new technologies in the field of vision research.

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Conflicts of Interest: Zhang D, None; Sang XZ, None; Wang P, None.

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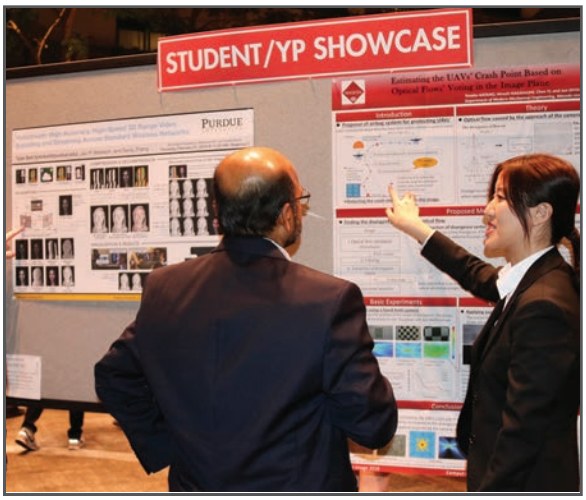

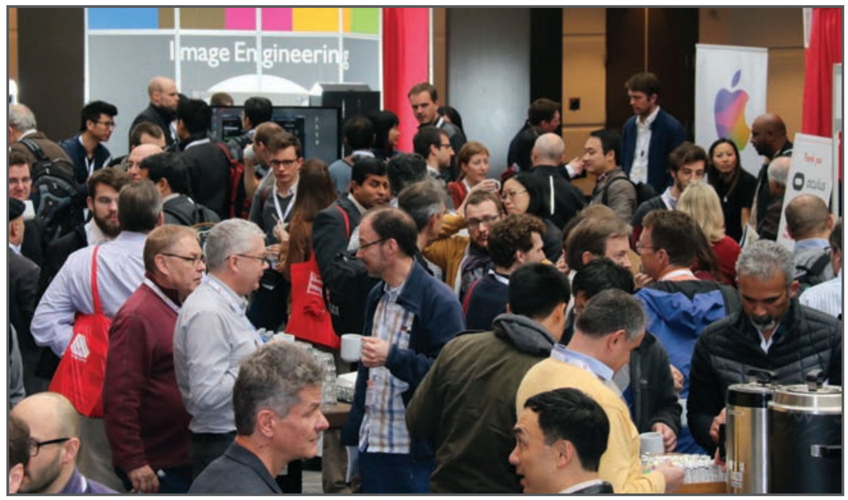

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