The difference of distance stereoacuity measured with different separating methods

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Background: The majority of tests to evaluate stereopsis should separate two eyes first. Whether different binocular separating manner may affect the test result of stereopsis is the main purpose of this study. Red-green anaglyphs, polarized light technology, active shutter 3D system, and auto-stereoscopic technique were chosen to evaluate distance stereoacuity.

Methods: Red-green anaglyphs test system was established with an ASUS laptop with the aid of TNO Stereotest glasses. Active shutter 3D system was set up with the same ASUS laptop with the aid of NVidia 3D Vision 2 Wireless Glasses Kit. The polarized 3D system adopted the AOC display. A Samsung naked-eye 3D laptop was used to set up an auto-stereoscopic system. Thirty subjects were recruited. Distance stereoacuity was measured with those computer systems.

Results: The auto-stereoscopic system was failed to measure distance stereopsis. A significant difference was found among red-green anaglyphs, polarized 3D system, and active shutter 3D system (Friedman Test, Chi-square =48.713, P<0.001). No significant difference was found between the polarized 3D system and an active shutter 3D system (Z=−1.134, P=0.257). The stereoacuity of the red-green glasses test was significantly worse than those of the other two test systems (versus shutter 3D test, Z=−4.553, P<0.001; versus polarized 3D test, Z=−4.618, P<0.001).

Conclusions: Different separating methods may affect the test result of distance stereopsis.

Keywords: Stereoacuity; computer; stereotest

Introduction

Stereopsis is a type of binocular function to detect the subtle distance difference. The Howard-Dolman apparatus, which requires the subject to judge the different distances of two rods in 6 m, may explain the concept of the stereopsis most suitable. However, it hardly uses in clinical anymore. Some stereopsis test conduct in the natural situation, such as Frisby near stereotest and Frisby Davis distance (FD2) Stereotest (Stereotest Ltd., Sheffield, UK) (1,2). More tests should separate two eyes first, and then conduct the test.

Separating two eyes means what the left eye could not see the right eye sees, and what the right eye could not see the left eye sees. Similarly, the pattern being observed also be divided into two parts, that is, a part of the pattern can be seen only by the right eye while cannot be seen by the left, and vice versa. The disparities designated between the two parts of the pattern were used to help detect the stereopsis threshold of the subject. Red-green anaglyphs is a kind of method to achieve binocular separating. The disparities are hidden in the picture, having a red and green color. The red

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pattern can only be viewed through the red lens and cannot be viewed through the green lens, while the green pattern can only be viewed through the green lens and cannot be viewed by the red lens. TNO stereotest (Lameris Ootech BV, Ede, Netherlands) belongs to this type of exam method (3,4). Polarized light technology is another widely used method to divide two eyes. The test pattern was having two pictures reflecting polarized light with the direction perpendicular to each other. The polarized direction of the lens before the right eye is also perpendicular to that before the left eye, and parallel to one of the polarized directions of the test picture. Then, the eye can only see the picture through the polarized lens with the same polarized direction and cannot see the picture of the vertical polarized direction—the Fly Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA). Randot Stereotests (Stereo Optical Company, Inc. Illinois, USA), Random Dot Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA) *et al.* are all belonging to this type of technique (5-7). Auto-stereoscopic, or naked eye 3D technique, is a kind of method to achieve a 3D effect without the help of wearing added glasses. Although getting rid of wearing spectacles, dividing binocular is essential. Some methods, such as a lenticular lens, can help to refract the pattern sticking under the lens to the right or left eye, respectively. To achieve the effect that what the right eye sees cannot be seen by the left eye and vice versa. Lang stereotest (Lang-Stereotest AG, Kusnacht, Switzerland) is a type of naked-eye 3D stereopsis screening tool (8-10).

Whether the test results were consistent between different separating methods of an existing controversy. Some researchers found that the TNO stereotest may overestimate the result than other exam tools (11-13). One of the reasons may be the binocular dividing method. However, different step ranges of the different tests may interfere with reasonable interpretation. For example, if a subject got a score 200 seconds of arc (arcsec, ") in Titmus stereotest and another subject got a score 240" in TNO stereotest. Could you conclude that the stereopsis of the first subject was better than that of the second subject? The answer is uncertainty. The disparities set of Titmus were 400", 200", 140", 100", 80", 60", 50", and 40", while the TNO stereotest were 480", 240", 120", 60", 30" and 15" (30" and 15" were deleted in the latest version). The test value 200" in Titmus meant that the actual test value was in a range ≤200" and >140"; while the test value 240" in TNO stereotest meant that the actual test value was in a range ≤240" and >120". That is, the true value of the first

subject may be higher, equal, or lower than the second subject. Overall, the comparison of two stereopsis tests with different measuring intervals should be made very carefully.

Computer-aided 3D technology may help to solve the problem because researchers could design different disparities and different intervals of stereopsis flexibly. Several methods could be adopted to achieve a 3D effect. Red-green anaglyphs are a straightforward way to acquire 3D expression. The picture has a red and green color with certain disparities hidden in it can be shown in the display, then a 3D effect may appear by wearing red-green glasses. Polarized light technology can also be used on a computer display. A specific display that can emit polarized light with the direction perpendicular to each other, accompanied by a set of polarizing glasses, can achieve a 3D effect like printed polarized light 3D test materials (14). Active shutter 3D system equips with liquid crystal shutter glasses, and a monitor with a high refresh rate is another mature 3D technique. A timing controller can synchronize the liquid crystal shutter glasses and the high refresh rate monitor, ensuring certain images send to specific eyes (15). Auto-stereoscopic, or naked eye 3D technique, can also be realized to achieve 3D expression. Parallax barrier technology utilizes vertical apertures to cover the light at certain angles to ensure sending different images to different eyes, while lenticular technology uses the refraction function of microlenses to deviate the light to certain directions to different eyes (5,16).

Whether different binocular separating manner may affect the test result of stereopsis is the main purpose of this study. Distance stereoacuity is the checking index. Separating manners we chose in this study were red-green anaglyphs, polarized light technology, active shutter 3D system and auto-stereoscopic technique. This study continued in two phases. The first phase was to evaluate the practicability for four dividing methods being adopted to evaluate stereopsis in a long distance. The second phase was to compare the test results of those methods selected from the first phrase.

Methods

Computer system

Red-green anaglyphs and active shutter 3D system
A laptop (ASUS G750Y47JX, 17.3" 16:9 full HD 3D (1,920×1,080 120 Hz), ASUSTEK Computer Inc., Taiwan) running Windows 8.1 and NVidia 3D Vision 2 Wireless
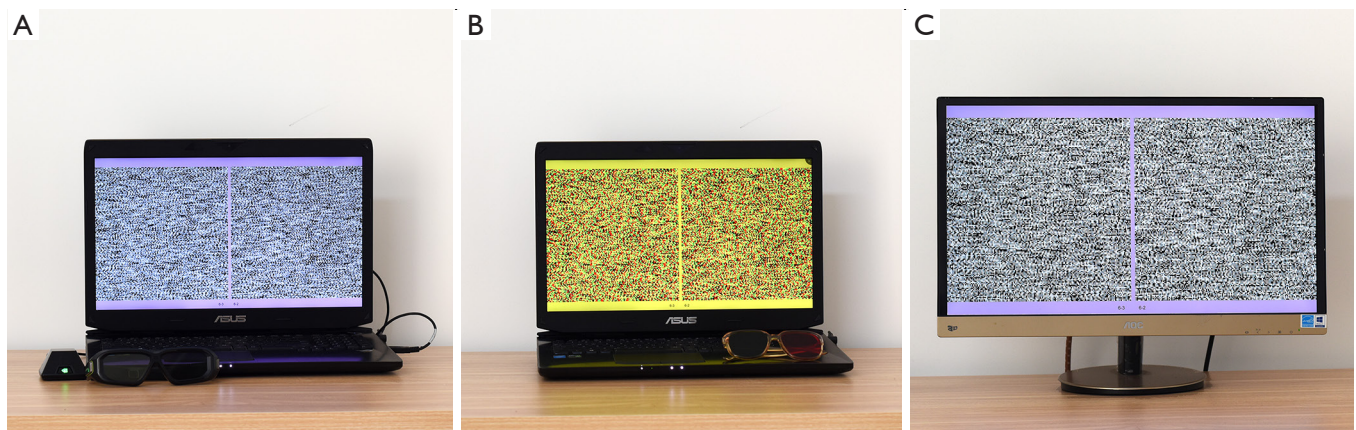
Figure 1 Photograph of the test setups. (A) An ASUS laptop and NVidia 3D Vision 2 Wireless Glasses Kit set up an active shutter 3D system; (B) an ASUS laptop with the glasses of TNO stereotest set up a red-green anaglyphs test system; (C) the polarized 3D display of the polarized light test system.

Glasses Kit (Expressway Santa Clara, CA, USA) was used as an active shutter 3D system (*Figure 1A*). The red-green anaglyphs test system has also used this laptop (*Figure 1B*). The glasses of TNO stereotypes were adopted in our test. At a checking distance of 4.1 m, 1 pixel of disparity was equal to 10". The laptop was warmed up for 1 hour before measurement, and a color calibration instrument (Spyder 5 EXPRESS, Datacolor, Lawrenceville, NJ, USA) was used to calibrate the monitor.

Polarized 3D system

A computer equips with a Polarized 3D display (AOC D2369V/BG, 23" 16:9 full HD 3D (1,920×1,080), Admiral Overseas Co., Taiwan) to establish Polarized 3D system. At a checking distance of 5.5 m, 1 pixel of disparity was equal to 10" (*Figure 1C*).

Auto-stereoscopic test system

Naked-eye 3D laptop (NP550R5M-X02CN, 15.6" 16:9 full HD 3D (1,920×1,080), Samsung Electronics Co., Ltd. South Korea) to establish an auto-stereoscopic test system. At a checking distance of 3.7 m, 1 pixel of disparity was equal to 10". For a naked-eye 3D display based on lenticular technology, 2 pixels is the smallest test unit.

Test symbol

A program was written using C# to generate all random-dot stereograms. The crossed disparity was used in all test graphs. The stereo symbol was a "Pacman" like the symbol

of TNO stereotest. The missing section of the disc may appear in the left, right, up, or down. A test page was having two adjoining sections, which has two Pacmen (*Figure 2*).

It is hard for the inmate the exact color expression on the screen with that of the printed color of TNO. Plate Ⅳ was used at a select color picture (*Figure 3*). According to the color of the Plate IV and the display we used, the RGB code of red was set as (220, 0, 0), while the RGB code of green was set as (85, 220, 85). Three optometry students with normal visual acuity and color vision were asked to do the exam to evaluate the express effect. Close the left eye first. The red disc on the left side could not be seen by the right eye when wearing a green lens—similarly, close right eye. The green disc on the right side could not be seen by the left eye when wearing the red lens—using these codes to create red-green pattern. All of the subject should do the exam first to ensure the separating effect of red-green glasses.

Test for the possibility for different separating methods

Disparities of the test symbols were set as TNO stereotest, which is 480", 240", 120" and 60". Three optometry students, whose unilateral visual acuity was no less than 0logMAR, and stereoacuity of them were at least 40" measured by the Fly Stereo Acuity Test did the experiment. The test distance of ASUS laptop and AOC display was 4.1 and 5.5 m, respectively. All of the students pass the test for 60" in red-green anaglyphs, active shutter 3D system and polarized 3D system. In a checking distance of 3.7 m, none of the students can find out the test page for 480" in
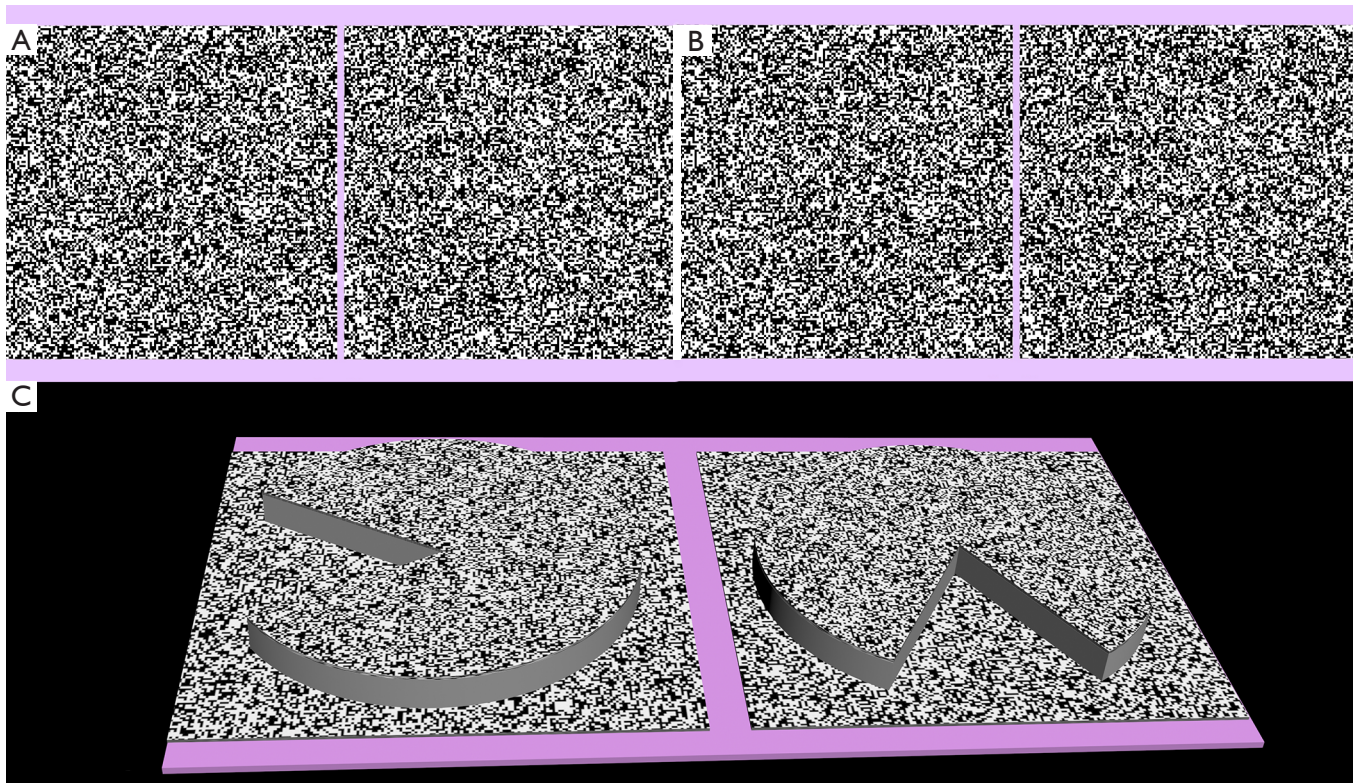
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Figure 2 Simulation diagram of test symbols. (A) Page viewed by the left eye; (B) page viewed by the right eye; (C) when (A) and (B) were fused correctly with two eyes, and the target symbol would appear out of the plane. The missing part of the left disc was on the left side, while that of the right disk was in the down direction.

the naked-eye 3D system. Move to the position of 2.5 m, in which the test disparities increase to 720", and they could not find out the symbol correctly either.

In order to test the failure reason for auto-stereoscopic laptop, we set up a test with a camera (Nikon D810, Nikon Corp., Japan) equipping with a 50 mm lens (Carl Zeiss Makro-Planar T×50 mm F2, Cosina Co., Ltd., Japan) to imitate a single eye of a human being. The 50 mm length of a lens, which be called a standard lens, is more similar to an eye of a human being in perspective relationship in full-frame FX digital camera. A 1 m slide rail was used to carry the camera. The camera can be slid in the rail in a direction parallel to the surface of the laptop screen. The experiment was performed at 40 cm and 2.5 m, respectively. Forty cm is a distance at which adopted as a routine near checking distance of stereopsis test. Two point five m is a distance that 48-pixel disparities of the screen are equivalent to 720". The high-resolution camera fixed on the top edge of the screen was covered by cardboard to avoid evoking the pupil tracking and recognition system.

Two pictures were set up a stereo picture follow the ordinary procedure. On the top of one picture marked a letter "R", while on the top of the other picture marked a letter "L". Theoretically, one eye could see only "R" but could not see "L"; similarly, the other eye could see only "L" but could not see "R". Then the stereo effect would appear by fusing two pictures, including setting disparities under this type of separation.

The measurements were conducted at 40 cm and 2.5 m, respectively, from the screen. The Nikon D810 was shot every 5 mm on the slide from the right side to the left side. The mid of the rail was aligned to the mid of the screen. In general, three types of pictures existed alternately, that is expressing only "R" (without or express a little shade of letter "L"), expressing both "R" and "L", and expressing only "L" (without or express a little shade of letter "R"). Photographs including one circulation of the middle part of the rail were chosen (a region with only "R", a region with "R" + "L", and a region with only "L"). By counting the shot number, the length of the domain, including only "R",
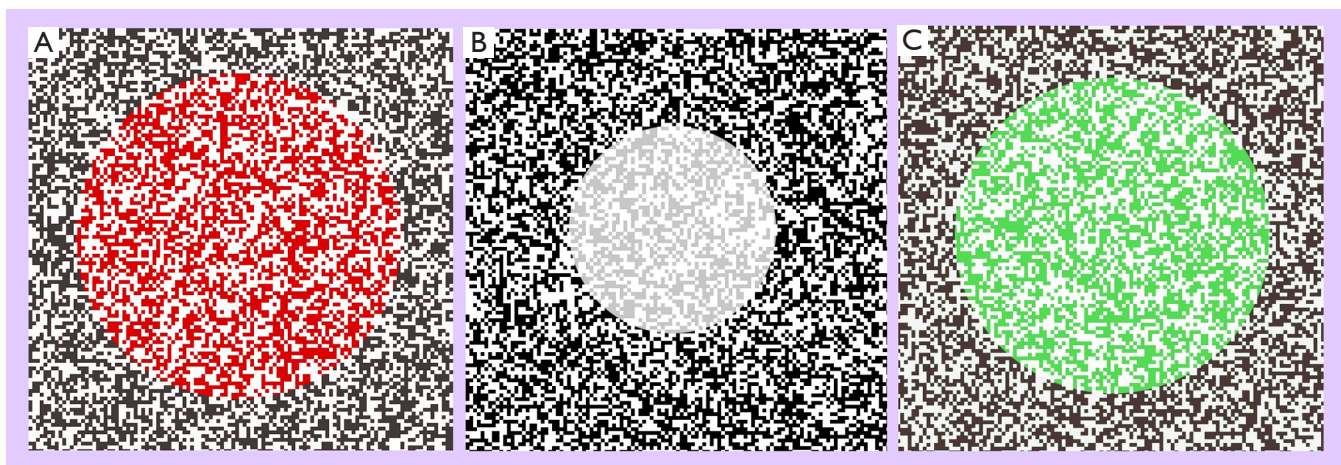
Figure 3 Simulation diagram of Plate IV of TNO stereotest. (A) The color of the circle was red (RGB code: 220, 0, 0); (B) the circle was grey; (C) the color of the circle was green (RGB code: 85, 220, 85).

"R" + "L", and only "L" could be determined (*Figure 4*). They are using this data to judge whether this technique could be conducted at an assigned distance.

Test for comparison for different separating methods

Subjects

A total of 30 subjects (11 males and 19 females), aged 20 to 28 years, were recruited. None of the study participants had amblyopia, strabismus, anisometropia, or severe ametropia. The best-corrected visual acuity was no less than 0 logMAR for each eye. The stereoacuity was at least 40" measured by the Fly Stereo Acuity Test. All participants gave their informed written consent before taking part. The research protocol observed the tenets of the Declaration of Helsinki and was approved by the ethics committee of the Second Hospital of Jilin University (No. 2017-89).

Test procedure

Eight test pages were designed to evaluate stereoacuity, ranging from 8-pixel to 1-pixel, which represented 80" to 10" with an assigned test distance. The near stereopsis of all of the subjects was no less than 40". So, the initial distance stereopsis set at 80" is a safe value for all of them, which could distinguish without any difficulty for all of the tests.

At the setting test distance, the test page 80" was started first. The participant was needed to find the missing part of the disc from the left part to the right part. If the subject found them correctly, the test page was reduced to 70", etc., until the subject failed to find out the two images correctly.

Then the earlier disparities were recorded as the stereopsis threshold of the subject. For example, if the participant could find two 3-pixel disparity stereo targets but failed to identify one 2-pixel disparity target, the stereoacuity of the participant was recorded as 30".

Statistical analysis

All data were processed using PASW Statistics 18 software (IBM SPSS Inc.). Shapiro-Wilk test was used to explore the distribution of data. Then chose parametric tests (one-way ANOVA test, paired *t*-test) or non-parametric tests (Friedman Test, Wilcoxon signed-rank test) to analyze the data based on the normality test result. When conducting comparisons between every two groups, three comparisons would be made due to three groups existing. However, $P<0.017$ (0.05/3) was used as the threshold for statistical significance.

Results

Test for the possibility for different separating methods

All of the students pass the test for 60" in red-green anaglyphs, active shutter 3D system, and polarized 3D system. On the contrary, none of the students can find out the test pages for 480" or even 720" in the naked-eye 3D system.

The Full-frame camera with 50 mm standard lenses can approximately imitate the visual angle of a human being. The sliding distance on the slide rail may imitate
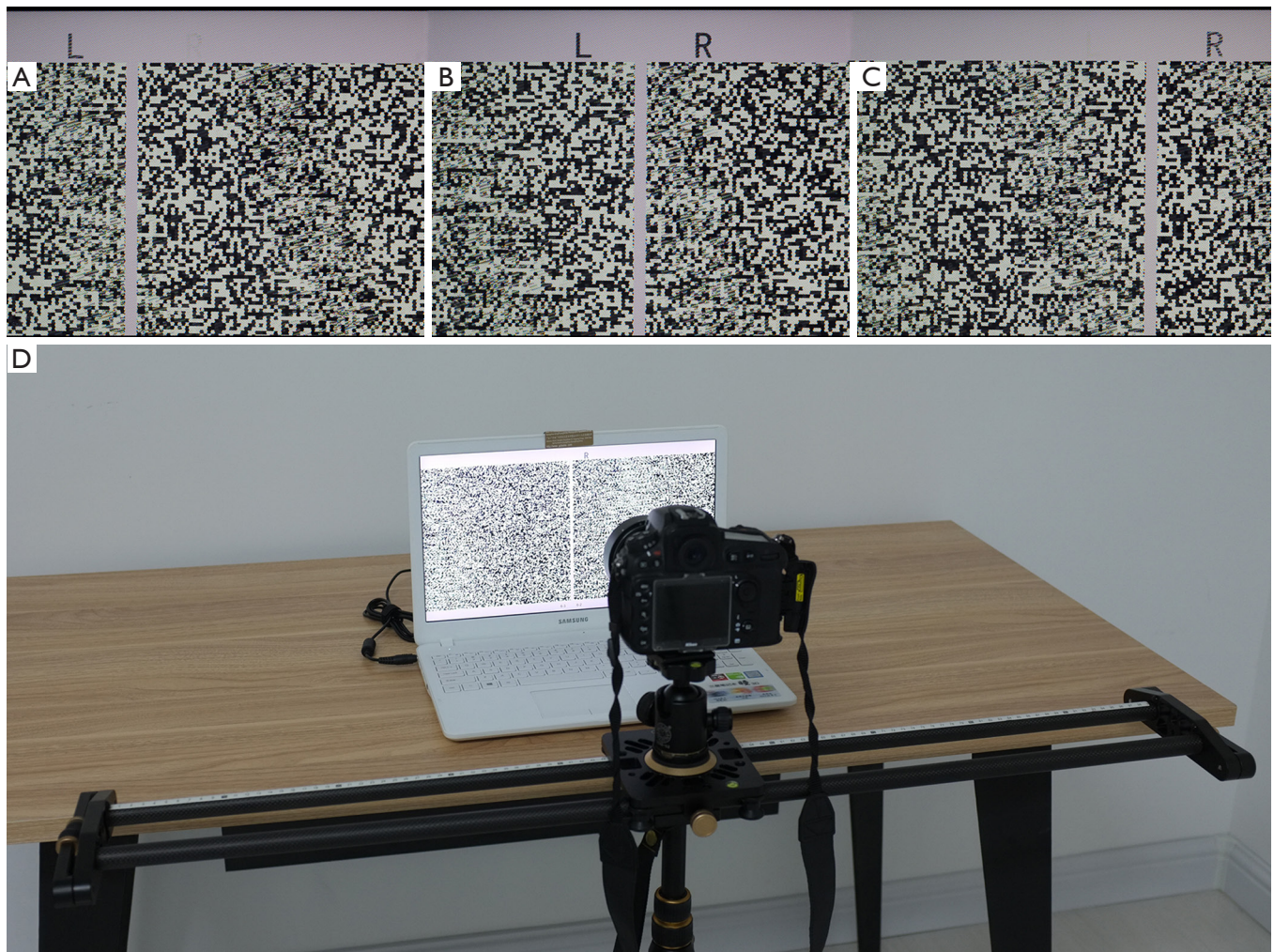
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Figure 4 Photograph showing the test system. (A) Only the letter "L" can be observed; (B) both of the letters "L" and "R" can be observed; (C) only the letter "R" can be observed; (D) photograph showing the test system conducted at 40 cm.

pupil distance. At a shooting distance 40 cm, the length of a domain including only "R" was 2 cm; the length of a domain including "R" + "L" was 4 cm; the length of a domain including only "L" was 2 cm. A subject with normal binocular function could find out the stereo effect only if the pupil distance is larger than 4cm. This value is far smaller than the pupil distance of a normal human being. In other words, every people with normal binocular function could appreciate the 3D effect at 40 cm.

At a shooting distance 2.5 m, the length of a domain including only "R" was 13 cm; the length of a domain including "R" + "L" was 14 cm; the length of a domain including only "L" was 13 cm. If a subject with normal binocular function could find out the stereo effect, pupil distance should not smaller than 14 cm. That is, one could

see a real 3D effect at this distance.

Test for comparison for different separating methods

The test results are shown in *Figure 5*. The data of all of the three groups were not satisfied with a normal distribution according to the Shapiro-Wilk test (shutter 3D test: statistic =0.766, P<0.001; polarized 3D test, statistic =0.760, P<0.001; red-green glasses test, statistic =0.869, P<0.001). Friedman Test was used to test the data. A significant difference was found among the three groups (Chi-square =48.713, P<0.001).

Using the Wilcoxon signed-rank test to detect differences between the paired groups: shutter 3D test versus polarized 3D test, Z=−1.134, P=0.257; shutter 3D test versus red-
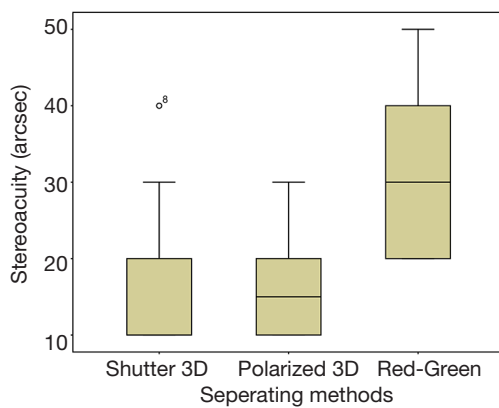
Figure 5 Boxplot of the stereoacuity of three groups. The lower edge of the box represents the first quartile; the line in the box is the median; the upper edge of the box represents the third quartile; the line perpendicular to the whisker above the box represents the maximum value. The circles are outliers. The median and interquartile range [M (QR)] of the shutter 3D test, polarized 3D test, and red-green glasses test were 10 [13], 15 [20], and 30 [20] respectively.

green glasses test, Z=–4.553, P<0.001; polarized 3D test versus red-green glasses test, Z=–4.618, P<0.001. Using the significance level P<0.017 set before the comparisons, the stereoacuity of the red-green glasses test was significantly worse than those of the other two groups, while no significant difference was found between the shutter 3D test and polarized 3D test.

Discussion

Whatever the polarized light technology or the active shutter liquid 3D technology, the brightness of the images would be reduced. However, luminance contrast should not affect the stereopsis for a large range unless it decreases to a very low value (17-19). A large number of traditional stereoacuity test utilize polarized glasses. In the study, the test result showed no difference existing between polarized light technology and the active shutter liquid 3D technology.

Some researchers found the TNO stereotest would overestimate the stereopsis value (11,12). The different test step range of TNO and control tests may affect the comparison results. We adopted an equal step range design to test the consistency and still found that the test result of red-green anaglyphs was significantly worse than polarized light technology and the active shutter liquid 3D technology. TNO red-green glasses existed at least

two differences comparing with the polarized glasses and the active shutter liquid 3D glasses. The first was the unbalancing color input between two eyes, and the second was the difference brilliance between two eyes. The transmittance of the red lens was 92% at the peak of 645 nm, and the green lens was 75% at 530 nm (4). The reddish image viewing through a red lens and the greenish image viewing through a green lens should be fused and then produce depth sense. Some literature involved the chromatic factor and stereopsis (20-22). However, the chromatic factors were all related to stereopsis targets but not the chromatic difference between two eyes. Data of luminance difference between two lenses of TNO glasses were not applied in detail. Simons measured the luminance through the green lens was –0.02 log foot-lambert, and –0.1 log foot-lambert through the red lens under fluorescent lighting. The transmittance of the green lens is higher than that of the red lens. This was different with our test data. In our experiment, a luminance meter (SM208, M&A Instrument Inc. Shenzhen, China) was adopted to measure the brightness. An X-ray reading lightbox was set as a background light source, and the luminance of it was 400 cd/m^2. The luminance value through the red lens of TNO glasses was 29 cd/m^2, while the luminance value through the green lens was 13 cd/m^2. The transmittance of the red lens is higher than the green lens. The manufacturing standard of the glass may change after nearly 40 years. The luminance difference between two eyes may affect the stereopsis test result (17,19), although the exact threshold has not been determined.

Naked-eye 3D technology is used to create a 3D effect without the aid of additional spectacles. Some commercial products, such as Lang stereotest, or Dinosaur Stereoacuity Test (Bernell, a Division of Vision Training Products, Inc., Indiana, USA), were adopted in the clinic to screen stereopsis. We also used the naked eye 3D smartphone to evaluate stereopsis in children and adults (5,16). However, all of the tests were carried out in the near distance. Whether the technique could be conducted at a relatively long distance was still unknown. The auto-stereoscopic, usually using parallax barrier technology or micro-column 3D technology, may transmit different images to two eyes simultaneously. The observe distance and the pupil distance of the observer may affect the realization of a 3D effect. The assumption was verified through our experiment. The 3D effect produced by parallax barrier technology or micro-column 3D technology was affected significantly by viewing distance.

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The limitation of this experiment is that only the distance stereopsis was discussed. The application we used, whatever the polarized light technology or active shutter 3D technology, were all carried out at a long distance. The resolution of the display limited the usage to measure stereopsis precisely in a near distance. The glasses we used in this experiment were designed for TNO stereotest. Whether an isoluminant design of the red-green glasses could improve the test result should be studied further.

Conclusions

The distance stereoacuity measured with polarized light 3D technology and the active shutter 3D technology was the same, while the test result of red-green anaglyphs using TNO stereotest glasses was significantly worse than polarized 3D and active shutter 3D technology. Different separating methods may affect the test result of distance stereopsis.

Acknowledgments

Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at http://dx.doi.org/10.21037/atm.2020.03.73). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was approved by the ethics committee of the Second Hospital of Jilin University (No. 2017-89).

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