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Real Stereopsis Test Using a Three-Dimensional Display with Tridef Software

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Purpose: To investigate horizontal image disparity in three-dimensional (3-D) perception using 3-D animations in normal control patients and patients with intermittent exotropia, anisometropic amblyopia, and partially accommodative esotropia. **Materials and Methods:** A total of 133 subjects were included. Stereopsis was measured using the Titmus Stereo test (Stereo Optical Inc., Chicago, IL, USA) and a 3-D stereopsis test with a 15 inch 3-D display laptop, adjusting 3-D parameters of 0 mm horizontal disparity to 15 mm horizontal disparity. **Results:** When compared with normal controls, the average threshold of the 3-D stereopsis test was significantly reduced for esotropia patients (p<0.001) and for anisometric amblyopia patients (p<0.001), compared to normal controls. No significant difference was observed between normal controls and intermittent exotropia patients (p=0.082). The 3-D stereopsis test was correlated with the Titmus Stereo test (Spearman's rho=0.690, p<0.001). Mean difference in stereoacuity was 1.323 log seconds of arc (95% limits of agreement: 0.486 to 2.112), and 125 (92.5%) patients were within the limits of agreement. **Conclusion:** This study demonstrated that a 3-D stereopsis test with animation is highly correlated with the Titmus Stereo test; nevertheless, 3-D stereopsis with animations generates more image disparities than the conventional Titmus Stereo test. The 3-D stereopsis test is highly predictive for estimating real stereopsis in a 3-D movie theater.

Key Words: Depth perceptions, vision disparity, imaging, three dimensional

INTRODUCTION

Recently, three-dimensional (3-D) devices, such as 3-D laptop computers, 3-D televisions, and 3-D surgical devices (da Vinci robot system), have been developed and are becoming widely used.[1] As a result, demand for 3-D displays has increased, resulting in rapid growth of the 3-D industry. Moreover, with greater numbers of 3-D televisions and computers in the home and with the success of the movie "Avatar," more movies are being released in 3-D.

Stereopsis is defined as a high visual function that requires binocular interaction and normal ocular alignment. Because stereoacuity is dependent on normal ocular alignment and equal visual acuity by both eyes, stereoacuity tests such as

the Titmus, TNO, and Randot Stereo test have been used to evaluate stereoacuity in patients with strabismic disorder and amblyopia:[2,3] numerous reports have shown that patients with amblyopia or strabismus have reduced stereoacuity.[4-6] These tests facilitate assessment of stereopsis and evaluation of sensory outcomes following treatment for strabismus or amblyopia. Additionally, use of stereoacuity testing as a method to evaluate 3-D depth perception has been emphasized. In the tests, static images with vectographic or anaglyphic methods are used to produce stereoscopic images. However, these images are not identical to watching a 3-D movie, because more dynamic images with large disparities are used in movies, and information other than image disparities, such as motion parallax, are also present. In our practice, we have examined patients who could not perceive depth perception in the 3-D movie theater, but had fair stereopsis results on conventional stereopsis tests, such as the TNO or Titmus Stereo test. In contrast, some patients with poor results in conventional stereopsis tests nonetheless enjoyed 3-D movies or games.

Accordingly, we were intrigued as to why some people with fair stereopsis, as assessed by a traditional stereo test, do not perceive 3-D stereopsis in the movie theater. The conventional stereopsis tests ask the viewer to select one stereoscopic image different from the others, although all images in 3-D animations have some degree of image disparity. Moreover, monocular clues exist in the Titmus Stereo test. Even in the Randot or TNO tests, it is possible to correctly respond to a random dot stereogram on the basis of decorrelation of the central dots.[7] All these tests illustrate the potential weaknesses of conventional stereo tests in evaluating real stereopsis. In addition, little is known about the minimum angular image disparity required to perceive stereopsis in 3-D animations in patients with reduced stereoacuity. Therefore, we decided to investigate the minimum horizontal disparities perceived by 3-D image perception of 3-D displays containing animations to investigate associations between the Titmus Stereo test and 3-D stereopsis test results.

MATERIALS AND METHODS

Patients

Patients older than 4 years were recruited from the outpatient clinic. A total of 133 subjects (mean age±standard deviation, 9.99±3.52 years; age range, 4 to 22 years) were studied, consisting of normal controls and patients with intermittent exotropia, anisometric amblyopia, and partially accommodative esotropia. This research adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of Gangnam Severance Hospital, Seoul, South Korea. Informed consent was obtained from either patients or parents. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during this research. The inclusion criteria were as follows: 1) ability to perform the Titmus Stereo test, 2) no manifest vertical tropia at distance or near fixation with prism cover tests, and 3) no history or presence of anterior segment or retinal disorders. A comprehensive ophthalmic evaluation was performed for all subjects, including best-corrected visual acuity, prism cover test, Worth 4-dot test, the near Titmus Stereo test (Stereo Optical Inc., Chicago, IL, USA), and the near 3-D stereopsis test using a 3-D laptop with Tridef software (DDD Inc., Los Angeles, CA, USA). In addition, any previous experience watching 3-D movies was noted.

Titmus Stereo test

Stereopsis was quantitatively assessed with the Titmus Stereo test with fly, animal, and graded circles. Subjects viewed the stereogram at a distance of 40 cm while wearing polarizing glasses. The examiner used his/her index finger to guide fixation. The subject was asked to grab the wings of the fly and point to the circle that seemed to "jump" out of the book. When a mistake was made, the immediately preceding target was repeated. If a correct response was made on the preceding target, that target's disparity was used as the measurement. If that response was incorrect, steps farther back from the target series were made until the correct response was obtained. The last correct target identified was used as the patient's stereopsis measurement. This test is a Polaroid vectograph-based near stereo test that is sensitive to disturbances or changes of near binocularity. Stereoacuity was recorded as "nil" if the largest disparity could not be passed. A score for nil stereopsis in the Titmus Stereo test was regarded as 6000 seconds of arc (arcsec) for statistical analysis.

3-D stereopsis test

A 15 inch 3-D liquid crystal display (LCD) laptop (LG A530, Seoul, Korea) was utilized. At a distance of 66 cm, each subject watched the 3-D animation "Ice Age 2" with

Tridef software for 2 minutes (Fig. 1). The Tridef software created 3-D images on polarizing film that coated the LCD and the images on the display had the same image disparities. All images on the display had the same retinal disparities. The examiner slowly increased the 3-D parameter from 0 (0 mm image disparity) to 100 (15 mm image disparity). When the subjects perceived stereopsis for the first time, the minimum value of the 3-D parameter was recorded as the 3-D stereopsis score. If patients could not perceive the 3-D image, the 3-D stereopsis score was recorded as nil stereopsis. The 3-D stereopsis score was expressed in arcsec using the following stereopsis formula.[8] Arcsec=pupillary distance×$\Delta d/D^2$×(206265) (Δd=distance between the front object and the back object, D=distance between the observer and the front object).

Statistical analysis

Continuous values were expressed as mean±standard deviation. Stereoacuity values were transformed to log arcsec for the purpose of analysis. If the patient had no measurable stereoacuity, the next log level (0.3 log arcsec progression) above the largest disparity for that test was assigned as "nil." The assignment of the next log level to nil is commonly used in analysis of stereoacuity data.[9,10] The Bland-Altman plot was used to evaluate agreement between the near 3-D stereopsis and the Titmus Stereo tests. The Wilcoxon matched pairs test was used to compare stereoacuity test scores between the Titmus stereo and 3-D stereopsis tests. Due to the noncontinuous scale of Titmus Stereo test scores, Spearman's correlation test was used to test the validity of the 3-D stereopsis test. Statistical analysis was performed using STATA 13.0 (StataCorp, College Station, TX, USA). Results were interpreted as statistically significant when *p*-values were less than 0.05.

RESULTS

A total of 135 subjects were evaluated and separated into four groups, comprising 37 normal controls, 37 intermittent exotropia patients, 31 amblyopia (anisometric amblyopia) patients, and 30 esotropia (partially accommodative esotropia) patients. The mean stereoacuity threshold scores were 409.8±1210.5 arcsec (range, 40 to 6000 arcsec) using the Titmus Stereo test and 2532.6±1977.5 arcsec (range, 481.6 to 12029.2 arcsec) on the 3-D stereopsis tests for all subjects. Stereoacuity threshold scores were better with the Titmus Stereo test, which was statistically significant ($p<0.001$, Wilcoxon matched pairs test). The 3-D movie watching experience was assessed, and 27 (20.0%) subjects had no previous experience, 86 (63.7%) subjects had previously watched 3-D movies in a theater, and 22 subjects said they were not sure or could not remember. Fig. 2 shows the results of comparing the Titmus Stereo test and 3-D stereopsis test in each group. When compared with normal controls, the average threshold of the Titmus Stereo test was significantly reduced for esotropia patients ($p<0.001$) and anisometric amblyopia patients ($p=0.001$), but not for intermittent exotropia patients ($p=0.778$). The average threshold of the Titmus Stereo test for esotropia patients was significantly reduced compared to intermittent exotropia patients ($p<0.001$), and anisometric amblyopia patients ($p<0.001$). Average threshold of the Titmus Stereo test for anisometric amblyopia patients was statistically reduced compared to intermittent exotropia patients ($p<0.001$). When compared with normal controls, the average threshold of the 3-D stereopsis test was significantly re-

Fig. 1. (A) Subject watches the 3-dimensional (3-D) movie displayed by a 15 inch 3-D laptop computer. (B) The video clip was converted into a 3-D movie by a TriDef 3-D media player.

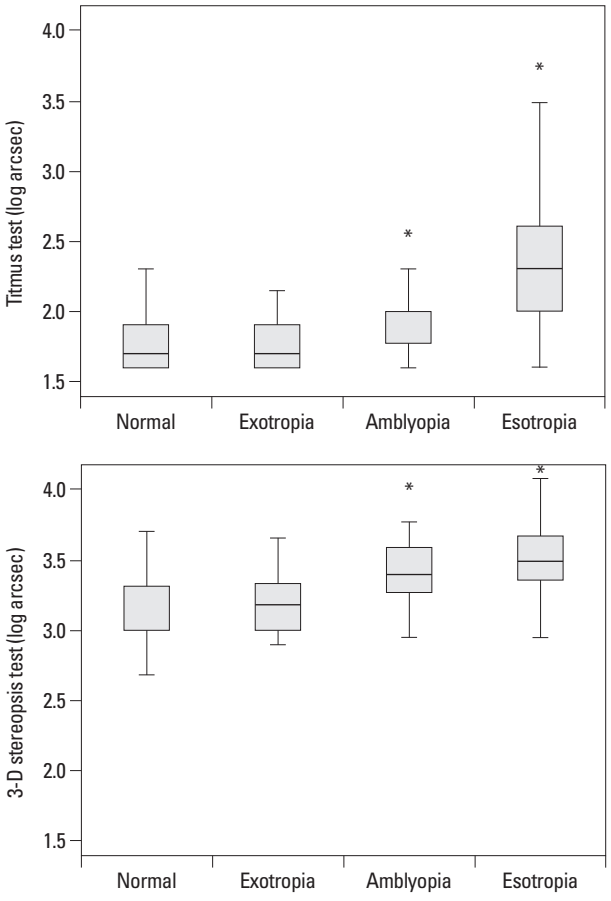

Fig. 2. Box plot illustrating the results of the Titmus Stereo and three-dimensional (3-D) stereopsis tests for each group of patients. *Statistical significance compared to normal controls. arcsec, seconds of arc.

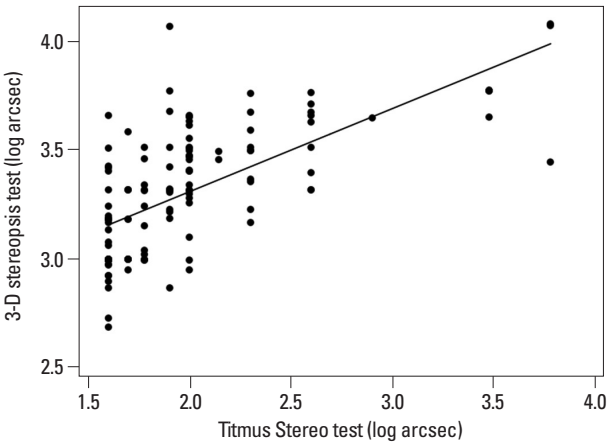

Fig. 3. Scatter plot showing the association between the Titmus Stereo and three-dimensional (3-D) stereopsis tests (Spearman's rho=0.690, p<0.001). arcsec, seconds of arc.

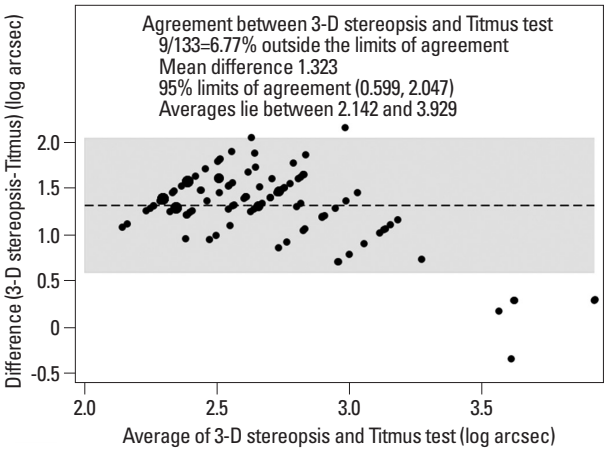

Fig. 4. Bland-Altman plot showing differences between the three-dimensional (3-D) stereopsis and Titmus Stereo tests for 133 subjects. Gray area shows 95% limits of agreement with 95% confidence intervals. Mean difference between the 3-D stereopsis and Titmus tests was 1.323 log arcsec. arcsec, seconds of arc.

duced for esotropia patients (p<0.001) and for anisometric amblyopia patients (p<0.001). No significant difference was observed between normal controls and intermittent exotropia patients (p=0.082). The average threshold of the 3-D stereopsis test for esotropia patients was significantly lower than that for intermittent exotropia patients (p<0.001), but not for anisometric amblyopia patients (p=0.091). The average threshold of the 3-D stereopsis test for anisometric amblyopia patients was lower than that for intermittent exotropia patients (p=0.006).

Correlation between the Titmus Stereo test and the 3-D stereopsis test was evaluated. Using Spearman's correlation test, which included 135 individuals, the Titmus Stereo test score was correlated with the 3-D stereo score (Spearman's rho=0.690, p<0.001). Fig. 3 shows the distribution using a scatter plot.

The 95% limits of agreement using a Bland-Altman plot are shown in Fig. 4. The plot suggests that the difference between the 3-D stereopsis test and the Titmus Stereo test is independent of the level of stereoacuity. Mean difference of stereoacuity was 1.323 log arcsec (95% limits of agreement: 0.599 to 2.047), and 124 (93.2%) of the subjects were within the limits of agreement.

Using a simple linear regression model, age was not associated with the Titmus Stereo and 3-D stereoacuity test results (p=0.122 and p=0.375, respectively). For esotropia patients, the amount of prism diopters (PD) at near was not associated with the Titmus Stereo test (log arcsec) (p=0.211) and 3-D stereoacuity test (log arcsec) (p=0.168). In addition, for intermittent exotropia patients, the amount of PD at near was not associated with the Titmus Stereo test (log arcsec) (p=0.154), but was associated with the 3-D stereoacuity test (log arcsec) (p=0.016). Using simple linear regression, previous experience watching 3-D movies was positively associated with high levels of stereoacuity for the Titmus Stereo and 3-D stereoacuity tests (p=0.011 and

p=0.003, respectively).

DISCUSSION

In the current study, we demonstrated that more image disparity was needed to perceive stereopsis in 3-D animations than the conventional Titmus Stereo test. A 3-D animation is neither a static image nor a test to find one stereoscopic image that is different from others. The average horizontal image disparity in the 3-D stereopsis test is regarded as a value of coarse stereopsis in the conventional stereo test. These differences may be due to dynamic image disparities in the animations. Also, the large disparity used in 3-D media may be a major contributing factor of 3-D asthenopia.

This study confirmed that patients with partially accommodative esotropia need more image disparity to perceive the 3-D perception than normal controls, intermittent exotropia patients, and anisometropic amblyopia patients. As previous studies found consistent results in stereopsis,[11] intermittent exotropia patients had normal stereopsis, but patients with partially accommodative esotropia showed poorer stereopsis.[6,12] Some children with esotropia, who had been diagnosed as "stereoblind" on the basis of conventional stereo tests, perceived stereopsis for 3-D animations that used dynamic images with large disparites.[13] Consistent with this study, larger image disparities were required to perceive stereopsis in 3-D animations than static images in conventional stereo tests. The Titmus Stereo test requests finding one stereoscopic image based on a vectograph image with Polaroid spectacles, which is a different situation from watching dynamic 3-D animations. Therefore, this new 3-D stereopsis test based on 3-D animations provides more reliable information on whether or not a subject can perceive stereopsis for 3-D animations.

Some people can watch 3-D movies without any difficulty, while others suffer from headaches, dizziness, and asthenopia.[14] This phenomenon may be due to discrepancies in convergence and accommodative complex. When we view 3-D movies with goggles, the eyes have to converge to align images on the retina corresponding to a region as if the images were close. This discrepancy between convergence and accommodation complex causes symptoms called 3-D asthenopia. In this study, we used a 15 inch 3-D display laptop computer at 66 cm to reduce the 3-D asthenopia effect on the stereoacuity results. Although we did not assess 3-D asthenopia symptoms, asthenopia that interfered with the test results would be minimal because the viewing time was short and the study was conducted at near distance.

In normal controls, minimum fixation disparity in the Titmus Stereo test (68.86±65.88 arcsec) was better than that in the 3-D stereopsis test with animations (1502.5±904.8 arcsec). The lower level of stereoacuity of the 3-D stereopsis test reflected differences between stereoacuity in the forced choice test and stereoacuity in the 3-D animations. Many stereoacuity tests such as the TNO, Lang, and Titmus Stereo tests have been used in clinical settings. However, poor results using conventional stereoacuity tests do not represent the patient's inability to perceive 3-D stereopsis in the movie theater or poor stereopsis in real life. In our study, 5 patients (1 patient with intermittent exotropia, 1 patient with amblyopia, 3 patients with esotropia) with nil stereopsis in the Titmus Stereo test reported that they could perceive stereopsis in the movie theater, and showed fair stereopsis using the 3-D stereopsis test. Therefore, it would be inappropriate to tell patients with poor stereoacuity using conventional stereo tests that they will probably have some difficulty watching a 3-D movie.

The present study found that age was not associated with stereopsis results. Most previous studies on maturation of fine stereopsis revealed that fine stereopsis is still immature at 5 years of age, but reaches an adult level between 6–9 years of age.[15] In this study, the mean age was approximately 10 years, so age in this study population may not have been a significant factor affecting stereopsis results. In subgroup analysis, ocular deviations at near in intermittent exotropia and partially accommodative esotropia patients were not associated with stereopsis in the Titmus Stereo test. Only ocular deviations at near in intermittent exotropia patients were associated with 3-D stereopsis with animations. Angle of deviation was considered as a contributing factor affecting stereopsis. In the present study, many patients had underwent strabismus surgery; therefore, it is expected that the angle of deviation before surgical correction would not be a significant factor affecting stereopsis results.

This study has some limitations. First, we measured 3-D stereoacuity with a 3-D display of a 15 inch laptop computer at a distance of 66 cm. The principle generating 3-D technology in a laptop computer is similar to a 3-D movie theater or 3-D TV, but near stereopsis results in this study may not be the same as distance stereopsis in a 3-D movies theater. Second, we did not evaluate the near conventional stereopsis test with random dots such as the TNO test. The

Titmus Stereo test has monocular clues, so even stereoblind patients could perceive the image differences in the stereoacuity range from 800 arcsec to 200 arcsec in a circle. Third, the 3-D stereopsis test was based on a patient's subjective feelings about stereopsis in 3-D animations. A patient's inattention or general composure might therefore influence the 3-D stereopsis results. Finally, a two minute dynamic animation video clip was used in the study. Therefore, the results may depend on the characters' dynamic range of motions. To reduce this effect, we used the same two minute video clip with a different range of motions in the 3-D animations at each response time.

Our new test has many advantages. Use of a 3-D monitor with animations provides natural viewing conditions, which is conducive to a child's visual attention. This 3-D stereopsis test provides reliable information about how a subject would perceive 3-D movies in a theater. If a subject cannot perceive any stereopsis in the largest disparity in this 3-D stereopsis test, the subject probably would have no perception of stereopsis when he or she watches a 3-D movie. The Titmus Stereo test is capable of indicating an artifactual stereo capability when none actually exists;[16] therefore, our test has advantages in visual attention and a realistic situation. Moreover, unlike a conventional stereo test, which requires a forced choice with a discontinuous level of stereoacuity (i.e., 800, 400, and 200 arcsec), this real stereopsis test provides a continuous level of stereoacuity with animations.

In conclusion, we have evaluated a 3-D stereopsis test with animations for normal controls and for intermittent exotropia, anisometropic amblyopia, and partially accommodative esotropia patients. Our findings suggest that the 3-D stereopsis test with animation was highly correlated with the Titmus Stereo test; however, the 3-D stereopsis with animations needs more image disparity than the conventional Titmus Stereo test. We believe that the 3-D stereopsis test using a 3-D display may be a possible alternative to the conventional stereo test because it is more visually attentive and provides more realistic information about perceiving stereopsis in 3-D animations. In the future, this new objective stereopsis test with a 3-D display will hopefully be a useful tool to detect nil stereopsis in patients with strabismus or amblyopia, and could play an important role in the treatment of strabismus and amblyopia.

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