Various Factors that Interfere with the Accurate Assessment of the Three-rods Test and Modified Three-rods Test to Resolve Monocular Cues

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Abstract

Binocular stereopsis is a higher-order visual function and is thought to play an important role in spatial cognition in everyday life and many occupational settings. Various stereotests are used clinically to evaluate binocular stereopsis, and the three-rod test is used to assess stereopsis in various occupations in Japan. It is known that there are factors such as monocular cues in various stereotests that make it difficult to accurately evaluate the stereoscopic function, but the existence of such factors in the three-rod test has not been clarified. Here, we show that practice effect and monocular cues exist in the conventional three-rod test and that we devised a modified three-rod test to address the monocular cues. In the conventional three-rod test, performance improved when multiple tests were performed in a short time under binocular condition, and performance was significantly better in the monocular condition compared to the blind condition, indicating the existence of practice effect and monocular cues, respectively. The modified three-rod test with a wider central rod excluded the effect of monocular cues and maintained binocular cues on test performance. Their results suggest that the three-rod test with the simple modification can be a useful method for testing stereoscopic functions.

Introduction

Stereopsis is a binocular cue to perceive the depth information of the surroundings that results from the processing of disparity in the images formed on the retina of each eye. Although stereopsis is not indispensable for depth perception, it plays a critical role in tasks involving distance estimation¹ or oculomotor coordination². Several previous studies have also shown that good stereopsis may be important for daily activities such as athletics³, walking⁴, and car driving⁵⁻⁷. Therefore, accurate assessment of the degree of stereoscopic function is important from both a social and clinical perspective.

Various methods of stereo vision testing have been developed and used, but they are known to have problems such as inconsistent results and difficulty in reproducibility due to a variety of factors that affect the results. It is often unclear to what extent the test results accurately reflect the stereoacuity^{8,9}. Perception of depth is generally considered to be achieved by a combination of monocular and binocular cues. Stereopsis is a binocular cue, which allows us to obtain relative depth information rather than absolute distance. Furthermore, the disparity cue of two objects separated by the same distance depends on the viewing distance. Unless there is a problem such as strabismus, stereopsis develops in early childhood and is relatively free from misperception^{10,11}. On the other hand, the monocular cue is characterized by skills learned based on life experiences, which provide only indirect information about the depth and are known to be susceptible to environmental and intrinsic factors^{12,13}. Thus, an ideal stereoacuity test would be devoid of any monocular cues or other factors that have inappropriate effects, otherwise, these factors may give rise to the invalid results in stereotest^{14,15}.

As a feasible testing method for measuring stereoacuity, the three-rod test is adopted and conducted by several Japanese governmental institutions for occupational qualification. For example, the Japan Self

Defense Forces (JSDF) and the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) enforces aircrews such as pilots to pass a depth perception standard tested by three-rod test for active duty on aircraft. The Road Traffic Act in Japan also demands drivers of large vehicles or commercial cars to pass the three-rod test. The criteria to pass the three-rod test in these institutions is common and set at the mean error distance of 20mm or less, however, there is no standardization as regards the number of measurements. For qualification of driver's licenses and the JSDF aircrews, three measurements are taken, and the mean of error distance is assessed. On the other hand, for civilian pilots, the number of measurements is five.

Previous research has shown that the statistically significant positive correlation of results between three-rod test and stereotests used in daily ophthalmic practice (distance Randot Stereotest and Titmus Stereotest)¹⁶. The authors also reported that the results of the three-rod test done on separate days were positively correlated¹⁷. These studies collectively support the validity of the use of the three-rod test as a means of evaluating binocular stereoacuity. However, the result of stereoacuity measured by the three-rod test can be affected by several factors including test distance, binocularity, masking, and direction of movement¹⁸. Moreover, factors such as practice effects associated with repeated measurements or monocular cues may make results in the three-rod test as if there is good binocular stereopsis.

To test this, we used an actual testing protocol employed in driver's license in Japan and testing for aircrews in JSDF -test distance of 2.5 m with the number of measurements of three- as a set of experiments. To examine a practice effect on the three-rod test, we performed the three-rod test under binocular condition multiple times over a short period of time. To examine whether monocular cues affect the outcome of the three-rod test, the three-rod test was conducted under monocular, blind, and binocular conditions with the normal or wider central moving rod. The results to be presented indicate that the repeated testing affected the outcome of the three-rod test and the monocular cue was present in the three-rod test, and this cue can be partly explained by the relative width of rods.

Methods

Ethics Statement

This study was conducted in accordance with the Declaration of Helsinki at Aeromedical Laboratory, Japan Air Self Defense Force (JASDF). All experimental procedures were approved by the institutional Ethical Committee of Aeromedical Laboratory, JASDF. All subjects were briefed on the scope and procedures of the experiment, and their written informed consent was obtained before participation.

Subjects

A total of 68 subjects (16 female, 52 male, age range 22-56 years, average:37.1) were recruited from within the JASDF and participated in the study. The exclusion criteria were a best-corrected visual acuity

(BCVA) of less than 1.0 in both eyes and a history of neurological and mental illnesses. No subjects were excluded on this basis. Because not all participants were naive to this test (10 of 68 had prior three-rods test experience), we did not make it a condition of participation whether or not the subject had been tested by the three-rods test in the past. However, we did require that at least six months had passed since the last test.

Visual examinations

Subjects underwent a variety of ophthalmologic examinations, including BCVA and three types of clinical stereotests. BCVA was measured with the Landolt Chart. The subject's dominant eye was determined by using Rosenbach test¹⁸. The interpupillary distance (IPD) of each subject was measured by auto refractometer, NIDEK AR-330A (NIDEK Co, Tokyo, Japan).

Near stereoacuity was assessed using Randot stereotest (Stereo Optical Co, Chicago, US), Titmus Stereotest (Stereo Optical Co, Chicago, US), and New Stereo Test (Handaya, Tokyo, Japan) at the standard viewing distance of 40cm with appropriate spectacle correction.

Three-rods test

The three-rods test was conducted using an electric depth perception testing device, Kowa AS-7JS1 (Kowa Co, Tokyo, Japan). This device has a wide rectangular viewing window of 4.4 cm * 10.4 cm at the front surface. Inside the device, three black-colored rods are displayed. Each rod was 3 mm in diameter with a separation of 30 mm laterally. The rods were seen through the viewing window against an evenly illuminated white background (Fig. 1a). The center rod moves back and forth between the two fixed rods at the speed of 50 mm/second. The moving range of the center rod was set at 110 mm and 100 mm for forward and backward directions respectively.

During measurements, subjects sat on a chair at the distance of 2.5m apart from fixed rods and put their head on the headrest with a chin cup to avoid motion and parallax being used as a depth cue. The height of the headrest was adjusted so that the height of the eyes matches the height of the viewing window.

Three rods inside the apparatus were presented to the subjects only during measurements. Between measurements, the viewing window of the apparatus was manually covered by a cardboard panel. The direction of movement and the position of the center rod at the start of each measurement was not fixed and were chosen randomly.

The subject is asked to press the switch when he/she feels that the three rods are lined up in a row. The erred distance between the planes of the fixed rods and movable center rod was recorded as a plus or minus value (in mm) when the center rod was in backward or forward positions relative to the fixed rods, respectively. Three measurements are taken as one set of measurements, and the mean of absolute values of measured erred distances was used for analysis.

Four sets of measurements were taken under binocular condition, followed by two sets of measurements under monocular condition, and then one set of measurements under blind condition. Measurement in the monocular condition is done first by the subject's dominant eye, followed by the non-dominant eye. In the non-blind conditions, the measurement starts when the cardboard panel covering the viewing window is manually removed by the experimenter. On the other hand, in the blind condition, the subject was only verbally informed of the signal to start the measurement, and the subject keeps both eyes closed during the measurement.

The width of the central movable bar in the original test was 3 mm in diameter, but the test was also conducted under conditions where this was thickened to 5 mm in diameter (Fig. 1b). To increase the width of the center movable rod, a hollow cylindrical silicon tube with an inner diameter of 3 mm and an outer diameter of 5 mm was placed over this rod, and the surface of this silicon tube was painted to have a similar color and texture as the fixed two peripheral rods. Under this condition, two binocular measurements were performed, followed by two monocular measurements.

Four consecutive sets of binocular measurements were taken in all 68 subjects. Of these, 50 continued testing in the monocular and blind conditions. After at least 7 days, 24 of these 50 subjects were tested in conditions with a modified bar width.

Statistical analysis

All data processing and statistical analysis were performed using Python (v3.7). Statistical tests are as described in text and figure legends.

Results

Practice effects on the error distance in three-rods test

To investigate whether there is a practice effect in the three-rods test, we first performed 4 sets of consecutive measurements under binocular condition. We found a significant decrease in error distance in the third set compared to the first set (Fig2a. Nemenyi post-hoc test following Friedman test; $p = 0.006$). Since the legal acceptance criterion for the three-rod test in Japan is set at less than or equal to 20 mm, we further divided the data set into two groups: those whose average error distance in the first set was less than or equal to 20 mm (pass group) and those whose average error distance was greater than 20 mm (fail group). In the fail group, as in the overall group, there was a significant decrease in error distance between the first set and the third set (Fig2b. Nemenyi post-hoc test following Friedman test; $p = 0.005$). However, in the pass group, there was no significant change in the score due to the repetition of measurement (Fig2c. Friedman test; $p = 0.241$). The fail group consisted of 14 subjects, of which 9, 10, and 10 reached scores within the acceptance criteria on the second, third, and fourth measurements, respectively. Taken together, these results indicate that scores of subjects who failed in the first set of measurements improved with repetition, indicating the practice effect in the three-rods test.

Effects of monocular cues on the depth perception in three-rods test

We next examined the ability to perceive depth using only monocular cues in the three-rods test. We measured erred distances under the monocular condition and compared them with the erred distances under the binocular and the blind conditions (Fig. 3). Of the 68 subjects who performed continuous measurements under the binocular condition, 50 subjects continued to perform measurements under the monocular condition. In the monocular condition, one set of measurements was performed first by the dominant eye and then by the non-dominant eye. We found that the erred distances under the monocular condition were significantly longer than those in the binocular condition, indicating the existence of binocular cue in the three-rods test (Fig3a. Nemenyi post-hoc test following Friedman test; $p < 0.001$ for binocular and dominant eye, $p = 0.005$ for binocular and non-dominant eye). Both the dominant eye and the non-dominant eye under monocular conditions performed better than the blind conditions (Fig3a. Nemenyi post-hoc test following Friedman test; $p < 0.001$ in each of the blind and other conditions). There was no significant difference in the results between the dominant and non-dominant eyes (Fig3a. Nemenyi post-hoc test following Friedman test; $p = 0.900$).

To test the ability to perceive depth by monocular cues, we performed one set of measurements under the blind condition following the measurement by the monocular eye. We found that both binocular and monocular conditions performed significantly better than blind condition (Fig3a. Nemenyi post-hoc test following Friedman test; $p < 0.001$ in each of the blind and other conditions). In blind condition, only 8 out of 50 subjects reached the passing criterion, whereas 19 and 23 subjects reached the passing criterion by the dominant and non-dominant eyes, respectively. These results indicate that there is an approximate 40% chance of passing the test with the monocular eye alone.

Of these 50 subjects, there were two subjects with suppression in one eye due to anisometropia or exotropia and had no binocular stereopsis. These two subjects were able to reach the passing criteria in three out of four measurements and two out of four measurements under the binocular condition respectively. In the monocular condition, they all reached the passing criteria in all measurements of the three-rods test. In addition, there was one subject whose binocular stereopsis was poorer than 60 arcsec in other clinical stereotests (Titmus Stereo Test, Randot Stereo Test, and New Stereo Test). The subject exceeded the passing criteria in all measurements under both binocular and monocular conditions. (Fig3b,3c)

Our results indicate that the three-rods test has a statistically significantly higher probability of reaching the passing criteria even under monocular conditions compared to blind conditions. Although the small sample size did not allow us to show a statistical significance, the results suggest that even humans with no or inferior binocular stereoscopic function may have a higher pass rate than chance. Taken together, our results indicated the existence of both binocular and monocular cues as factors that affect results in the three-rods test.

Effects of rod width on the depth perception in the three-rods test.

It is known that some kinds of monocular cues allow us to determine relative distance and depth. These include relative size, interposition, linear perspective, aerial perspective, light and shade, and monocular motion parallax¹⁹. We investigated what type of monocular cue is used in the three-rods test. In the three-rods test, subjects know before the start of the measurements that the widths of all the rods are equal. We hypothesized that subjects use the cognitive information that all rods are the same width as a monocular cue. To test this hypothesis, we modified the width of the central movable rod from 3mm to 5mm and performed measurements under binocular and monocular conditions. First, two sets of measurements were performed under the binocular condition, followed by two measurements under the monocular condition using one of the dominant and non-dominant eyes. This measurement was done on 24 of the 50 people who had done all the measurements.

The results showed that neither of the two monocular conditions differed significantly from the blind condition (Fig4a. Nemenyi post-hoc test following Friedman test; $p = 0.680$ for blind vs dominant eye, $p = 0.900$ for blind vs non-dominant eye). Furthermore, in the monocular condition, no subject could score above the criterion for both the dominant eye and the non-dominant eye. (Fig4a)

We also compared the results of the measurements before and after changing the width of the central rod. Changing the width of the rod did not result in significant changes in the measurements under binocular condition (Fig4b. Nemenyi post-hoc test following Friedman test; $p = 0.887$). In contrast, the use of the wider rod significantly increased the error distance compared to the measurements when the width of rods is equal under the monocular condition (Fig4b. Nemenyi post-hoc test following Friedman test; $p = 0.0012$) and resulted in no significant difference between the monocular condition and the blind condition (Fig4b. Nemenyi post-hoc test following Friedman test; $p = 0.784$). These data demonstrate that when the width of the rod is increased, the binocular cue is preserved but the monocular cue is lost, thus indicating that the equal width of rods is a potent monocular cue in the three-rods test.

Of these 24 subjects who performed experiments under conditions where the width of the rods was wider, two of the three people with weak or no stereopsis participated (Fig4c, see also Fig. 3b and c). When the width of the central rod was made wider, neither subject could pass the criterion in all cases in contrast to the results using the normal width of the rod. This result suggests that these subjects passed the criterion in the three-rod test with the normal width of the rod by using the information of equal width of rods as a monocular cue.

Effects of the interpupillary distance on the performance of the three-rods test

Stereopsis is typically quantified by stereoacuity, which is the threshold angular disparity that can be seen in binocular vision. One of the factors which affect stereoacuity is the interpupillary distance (IPD)²⁰. The angular disparity depends on IPD, and the larger IPD would give subjects a better depth perception, which may result in a smaller erred distance in the three-rods test.

To examine this, the mean error distance was plotted against IPD for the normal rod condition and the wider rod condition. The mean error distance in three-rods test showed low correlation with IPD in both normal rod condition (Fig5a. Pearson correlation; $n = 68$, $r = 0.102$, $p = 0.409$) and wider rod condition (Fig5b. Pearson correlation; $n = 24$, $r = 0.067$, $p = 0.756$). These results indicate that differences in IPD in the physiological range do not make a significant difference in the results of the three-rods test.

Correlation between the results of the three-rods test under various conditions and clinical stereopsis tests.

Finally, to investigate the reproducibility and correlation between the three-loss test and the clinical stereopsis test under various conditions, we calculated the Spearman correlation coefficient between each test. (Fig6)

There was a significant positive correlation between the results of the first and second sets of the normal three-rods test performed under binocular condition (Fig6a. Spearman correlation; $n = 24$, $\rho = 0.67$, $p = 0.0003$). However, we did not find a significant correlation between these results and the results of clinically used stereotests. The same result was observed when the width of the rod was increased or tests were done under monocular or blind conditions.

A significant positive correlation was found only between Randot stereotest and Titmus stereotest among the clinical stereoscopic tests (Fig6a. Spearman correlation; $n = 24$, $\rho = 0.69$, $p = 0.0002$). We did not find a significant correlation for the other combinations.

Discussion

The present study demonstrated that the result in the three-rods test is affected by repeated measurement. In addition, we showed that this test had both monocular and binocular cues. By using only monocular cues, the average erred distance of 20mm, which is the passing standard for the three-rods test set by various physical examinations conducted in Japan, can be exceeded with a probability of about 40%. We hypothesized that relative size (the information that the examinee was informed before the test that all rods were equal in width) is one of the monocular cues. Based on this hypothesis, we devised a modified three-rods test with a wider central rod. With this modified device, we succeeded in reducing the monocular cue while maintaining the binocular cue in the three-rods test, proving our hypothesis. Furthermore, in both conventional and modified three-rods tests, IPD was not shown to be a factor affecting the results.

A recent study has shown a positive correlation between the three-rods test and stereotests used in clinical practice¹⁶. However, a previous report has suggested that the two-rods-based Howard-Dolman test, which is similar in principle to the three-rods test, may not be able to accurately assess stereoscopic function²¹, suggesting that the three-rods test may not be also able to assess stereoscopic function. In our three-rods test configuration, the test distance is 2.5m. When the subject's IPD is 60 mm, the theoretical disparity threshold corresponding to an error distance of 20 mm in the three-rods test is 39.3 arcsec. Inconsistency between the results of the three-rods test and those of other stereotests has often been reported. Even when the disparity thresholds obtained from other stereotests are far greater than the theoretical disparity threshold of the three-rods test, the actual error distances obtained from the three-rods test tend to be below the legal standard of 20 mm error distance. A similar trend was observed in the previous report¹⁶, suggesting the presence of factors that could skew the results in the three-rods test.

In Japan, the average of the absolute values of the three repeated measurements is used in the three-rods test for aviation workers in the JSDF and automobile drivers in the MLIT. The MLIT uses the average of the five repeated measurements in the test for commercial pilots. However, in the case of commercial pilots, the three-rod test is performed only in the cases of anisometropia, where the refractive powers of the two eyes differ by more than two diopters. For this reason, the average of three measurements is considered to be the standard number of measurements in Japan, and the average of three measurements was used in this study. Our results showed no statistically significant difference between the first and second sets of four consecutive sets of measurements. Therefore, it is considered that the number of measurements of three or five times, which is the unit of one set, is unlikely to distort the results due to obvious practice effects, and these numbers are reasonable. However, since statistically significant differences were observed between the first and third sets, care should be taken to minimize the number of tests performed.

A number of studies investigating the existence of non-stereoscopic cues in commonly used clinical stereotests suggest that the use of monocular cues can help pass these tests^{14,15,22–24}. The previous study has shown that results measured in the three-rod test are affected by several factors¹⁸, but whether monocular cues are used to pass the test criteria has not been explored. Unlike other clinical stereotests that use static planar images, the three-rod test is a dynamic test that uses actual three-dimensional objects. However, our study revealed that both binocular and monocular cues are present in the conventional three-rods test as in other clinical stereotests, and the test results reflect the results of perceptual recognition of both cues. In assessing the stereoscopic function of the subject, it may be preferable to make a comprehensive judgment based on the results of other stereotests as well, rather than using only the results of the three-rods test.

The positive correlation between the three-rods test and clinically used stereotests could not be replicated in this study, and this may be due to the population difference¹⁶. This could also be due to the small number of people who performed all the experiments in our study. The group of subjects in this study was ordinary members of the JASDF who are required to pass physical examinations in terms of visual,

physical, and mental functions. Past reports show that about as high as 30% of the general population has problems with stereopsis²⁵, but in this study, the percentage of people with abnormal stereopsis was small (3 out of 68). Further studies targeting the general population with a larger number of subjects may be necessary to clarify the correlation between conventional and modified three-rods tests and clinically used stereotests.

In conclusion, this study identifies that practice effect and monocular cue are present in the conventional three-rods test and that one of the monocular cues is the evenness of the width of all rods. In the modified version of the three-rods test with a wider central rod we did, binocular cues were not lost, but monocular cues were significantly reduced, and may therefore be useful as a more accurate tool to assess binocular stereoacuity. To demonstrate the usefulness of our method, further studies in the general population are needed. Furthermore, it may be possible to develop a more effective three-rods test in the future, for example, by optimizing the width of each rod.

Declarations

Data availability

The datasets obtained and analyzed in this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests in this research.

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Author contributions

A.T. conceived the experiments, A.T. and N.K. conducted the experiments, A.T. analyzed the results, A.T., N.U., and Y.T. wrote the manuscript and produced the figures. All authors reviewed the manuscript.

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Figures

Figure 1

Wide rectangular viewing window at the front surface of normal, conventional three-rods test machine (a) and modified version of the three-rods test with a wider central rod (b). In both cases, three rods are lined

up in a row.

Figure 2

Boxplots of mean error distances. Results of four consecutive sets of measurements performed under binocular condition. (a) Overall population (n = 68) (b) Group of subjects whose average error distance in the first set was less than or equal to 20 mm. (fail group; n = 14) (c) Group of subjects whose average error distance in the first set was greater than 20 mm. (pass group; n = 54) The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, Q1 and Q3 quantiles, and 1.5 times the interquartile range from the median, respectively. Each dot represents scores of individual subjects. Each subject's scores in different conditions are connected by lines. The red dotted line in each figure shows the error distance of 20 mm, which is the pass/fail criterion. **p < 0.01.

Figure 3

Comparison of error distances measured under binocular, monocular, and blind conditions. (a) Boxplots of mean error distances under binocular, monocular (dominant and non-dominant eye), and blind conditions. ($n = 50$) (b) Profiles of three subjects who had problems with stereopsis and their scores on three clinical stereo tests. (c) Error distances in binocular and monocular conditions for three subjects in (b). B1~B4-Sets 1 to 4 under binocular condition. M1-Set1 under monocular condition (= dominant eye). M2-Set2 under monocular condition (= non-dominant eye). The horizontal lines in each box plot, top and bottom end of each box plot, and error bars indicate the median, Q1 and Q3 quantiles, and 1.5 times the interquartile range from the median, respectively. Each dot represents scores of individual subjects. Each subject's scores in different conditions are connected by lines. The red dotted line in each figure shows the error distance of 20 mm, which is the pass/fail criterion. *** $p < 0.005$, **** $p < 0.001$.

Figure 4

Comparison of the error distances measured by the normal and modified three-rod test. (a) Boxplots of mean error distances under binocular, monocular (dominant and non-dominant eye), and blind conditions. Measurements were taken using a modified three-rod test with a wider central rod, except for the blind condition. (n = 24) (b) Boxplots of mean error distances. Both binocular and monocular conditions were measured using the normal and modified three-rod tests, and the average of the first two sets of each condition is shown. For the blind condition, the results are shown for one set of measurements performed using the normal three-rod test. (n = 24) (c) Error distances under binocular and monocular conditions for two subjects who had problems with stereopsis, as measured by the normal and modified three-rod test. B1~B2-Sets 1 and 2 under binocular condition. M1-Set1 under monocular condition (= dominant eye). M2-Set2 under monocular condition (= non-dominant eye). The square dots show the measurement results under the condition of wide rods, and the thin round dots show the measurement results under the condition of normal rod width. The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, Q1 and Q3 quantiles, and 1.5 times the interquartile range from the median, respectively. Each dot represents scores of individual subjects. Each subject's scores in different conditions are connected by lines. The red dotted line in each figure shows the error distance of 20 mm, which is the pass/fail criterion. ***p < 0.005, ****p < 0.001.

Figure 5

Correlation between interpupillary distance (IPD) and error distance in the normal, conventional three-rod test (a) and modified three-rod test with a wider central rod (b).

Figure 6

Heat map showing the Spearman correlation coefficient and significance levels between the results of the three-roads test under several conditions and the results of clinical stereotests. The color bar to the right of the figure displays the mapping of correlation coefficient values to the color map. bset1- Set1 under binocular condition using the normal three-roads test. bset2- Set2 under binocular condition using the normal three-roads test. wbset1- Set1 under binocular condition using the modified three-roads test. wbset2- Set2 under binocular condition using the modified three-roads test. mset1- Set1 under monocular condition using the normal three-roads test. mset2- Set2 under monocular condition using the normal three-roads test. wmset1- Set1 under monocular condition using the modified three-roads test. wmset2- Set2 under monocular condition using the modified three-roads test. blind- Set under blind condition using the normal three-roads test. titmus- stereo threshold quantified by Titmus stereo test. randot- stereo threshold quantified by Randot stereo test. new- stereo threshold quantified by New stereo test. * $p < 0.05$, ** $p < 0.01$, **** $p < 0.001$.