

The effect of dot size in random-dot stereograms on the results of stereoacuity measurements

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Research article

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Abstract

Background The aim of this study was to evaluate the effect of the size of the dots in random-dot stereograms on the results of stereoacuity measurements.

Methods A stereopsis measurement system was created using a phoropter and two 4K smartphones. Three dot sizes, including 1×1 pixel, 6×6 pixels, and 10×10 pixels (equivalent to 0.17min arc, 1 min arc and 1.68 min arc arc, respectively), were used to form random-dot arrays, and each test pattern had one Lea symbol hidden within it. The resulting stereograms were tested on 30 subjects with normal acuity and stereoacuity.

Results Stereoacuity measured with the 1-pixel dots was significantly worse than that measured with the 6-pixel dots (Wilcoxon signed ranks test, $Z=-4.903$, $P < 0.001$) and the 10-pixel dots ($Z = -4.941$, $P < 0.001$). No significant difference was found between 6-pixel dot and 10-pixel dot stereograms ($Z = -1.000$, $P = 0.317$).

Conclusion The size of the dots in random-dot stereograms affects the test results significantly when the dots are too small for the eye to resolve.

Background

Random-dot stereograms (RDS) are widely used in the clinical evaluation of stereopsis. The advantage of this technique is that it eliminates monocular clues more thoroughly than contour based stereo tests. In clinical practice, the stereopsis to detect contour based stereo target, e.g. the circle pattern in the Fly Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA), is considered as “local” ; while the stereopsis to detect random dot based stereo target, e.g. the Pacman hidden in TNO stereotest (Lameris Ootech BV, Ede, Netherlands), is considered as “global” [1]. The neural processing of “local” and “global” stereopsis may be different. However, the two mechanisms cannot be entirely separated [2]. In neurophysiology research field, local and global stereograms may be determined by the number of dots contained within the stereogram. A small number of dots expressing in a pattern should be considered as “local”. On the contrary, plenty of dots existing in a pattern should be considered as “global”. In this point of view, a test pattern consisted of a small amount of random dots, may also be considered as “local” [3]. In Gantz’s research, the density of RDSs lower than 0.39% may be considered as “local” stereo targets, otherwise, it may be considered as “global” stereo targets [4].

In the Frisby stereotest (Stereotest Ltd ,Sheffield, UK) [1,5], the shape to be perceived is hidden in an array of randomly arranged triangles of varying sizes, but the shape is distinguished by a real difference in depth, and can be perceived without the help of any other appliance. In the random-dot E stereo test (Vision Assessment Corporation, Illinois, USA) [1,5], the letter E is hidden in a random dot array, but can be perceived with the aid of polarising spectacles that divide the images seen by the two eyes. In the TNO test [1,5], the test shapes are disks with a missing sector, with the two stereo elements printed in red and green for viewing with red/green anaglyph stereo glasses. Although the measurements are all based on

detecting minimum disparities a subject could distinguish, the test result evaluated with different stereotests may differ from each other. [6]: For example, the stereoacuity measured with the TNO test is worse than the acuity measured with other methods, either in a normal population [7] or in patients with abnormal binocular vision [8]. The mechanisms underlying these differences have not been clearly established [9].

Whether the size of the dots in a RDS could affect the test result? In Henriksen's study, the size of half-matched RDSs (half the dots in RDS are correlated and half are anticorrelated) was set at 0.025° , 0.05° and 0.075° respectively. They found that psychophysical performance decreases with smaller dot size, and stated that smaller dots might decrease the local correlation variability [10]. A previous study has confirmed that the increasing dot size may increase the accuracy to detect binocular disparity - although slightly, but significantly [11].

Whatever the test symbol or the test procedure, the RDS used in the clinic are simpler than that conducted in a laboratory environment. We adopted our newly designed stereoacuity measurement system, a phoropter combined with two 4K smartphones [12], to explore the effect of the size of the dots in RDS. Extremely small dots far smaller than the recognition resolution of an ocular of a human being were utilized. For some stereotest, e.g Random dot E test, the examined distance could be prolonged to obtain a finer stereo threshold. The visual angle of the dots in the background may reduce to an unrecognizable level. The aim of this study was to evaluate the possible difference of stereopsis tested with RDSs composed of different size of dots.

Methods

Evaluation of stereoacuity with RDS of different size

Test system

A novel stereopsis measurement system was developed, using a phoropter (VT-10, Topcon Corp, Tokyo, Japan) and two Sony smartphones (Sony Xperia Z5 Premium Dual E6883, Sony Mobile Communications Inc. Tokyo, Japan) (Figure 1). At a test distance of 65 cm with this system, a 1-px (pixel) disparity of two images equates to an angular disparity of $10''$ (arcsec, second of arc), which makes it possible to test stereoacuity with a resolution of $10''$.

Test symbols

A program written in C# was used to produce all test targets. The test symbol imitated the Random Dot 3 Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA). Lea symbols (house, circle, square and apple) were used as the test targets, solid filled, hidden in random-dot stereograms. The random dots were chosen to be square rather than circular because of the limitations of the screen pixel arrangement of the smartphones. Black dots and white dots constituted test pictures, and the proportion of them was 1:1 (dot density 50%).

Three dot sizes were used to construct the random-dot arrays, including 1-px (1×1 px, equivalent 0.17 min arc at 65cm, similarly hereinafter), 6-px (6×6 px, 1 min arc), and 10-px (10×10 px, 1.68 min arc). Each test pattern included a symbol hidden within it. Two test images were created. The first image included four lines ranging from 8-px disparity to 5-px disparity, while the second image included four lines ranging from 4-px disparity to 1-px disparity. The detail was shown in Figure 2.

Test procedure

After tested with an auto-refractor (KR-8900PA, Topcon Corp, Tokyo, Japan), the subjects were examined with a phoropter to determine the diopter and the best corrected visual acuity (BCVA), after which the two 4k smartphones were attached to the near vision rod. The test distance was 65cm. With the aid of two 5.5^Δ base out Risley prisms, two smartphones could be fused as one image (Figure 1). The subjects were asked to identify the forms hidden in the random dot stereograms, from left to right, top to bottom. The last correct answer for each size of dot was recorded as the stereoacuity of the subject.

Subjects

A total of 30 subjects were enrolled, 11 men and 19 women, with ages of 20–31 (25.3 ± 3.8) years. The corrected visual acuity of each eye was at least 0 logMAR, and the stereoacuity was at least 40", as measured by the Fly Stereo Acuity Test. The study was conducted at the Second Hospital of Jilin University in China. The research protocol followed the tenets of the Declaration of Helsinki, and was approved by the ethics committee of the Second Hospital of Jilin University (No. 2017-89).

Statistical analysis

All data were processed using PASW Statistics 18.0 (IBM SPSS Inc.). Because the data did not satisfy tests for normality of distribution, nonparametric tests were carried out. The Friedman test was used to analyse the differences among the groups, with $P < 0.05$ used as the threshold for statistical significance. The Wilcoxon signed ranks test was used to compare the differences between pairs of groups. Because three comparisons were conducted, $P < 0.017$ (0.05/3) was used as the threshold for statistical significance.

Measurement of the dot size of RDS utilized in the clinic

TNO stereotest, Randot Stereotest (Stereo Optical Company, Inc. Illinois, USA), Butterfly Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA), Pass Test 3 (Vision Assessment Corporation, Illinois, USA), Random Dot E Stereotest, Random Dot Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA), Random Dot 2 Stereo Acuity Test (Vision Assessment Corporation, Illinois, USA) and Random Dot 3 Stereo Acuity Test were chosen. A scanner (ScanMaker S260, Microtek International, INC. Shanghai, China) was used to scan the pictures in a resolution of 3200×3200. TNO stereotest was scanned directly. Other 7 tests were all based on polarizing technique, which means the tested image actually contained two polarization pictures, for which the polarization direction of them was perpendicular to each other.

The test card was scanned twice covering by a polarizing glass plate. The polarizing orientation of the glass was perpendicular during the two scans which keeping the same polarization direction as original images. Two clear images would be decomposed by this manner. A 600×600 frame was used to cut the image 10 times randomly in the random dots background region, and to find the smallest short diameters of the dot in the areas. The size of the dot was measured by counting the number of px occupied in the narrowest diameter.

Specifically analyzed images selected: TNO stereotest, the 19th edition, the first image for plate 8; Randot Stereotest, the first image in large homogeneous areas; Butterfly Stereo Acuity Test, the random dot pattern for butterfly; Pass Test 3, 60" test card; Random Dot E Stereotest, card with letter E; Random Dot Stereo Acuity Test, the first image in section A page 1; Random Dot 2 Stereo Acuity Test, the first image in section A page 1; Random Dot 3 Stereo Acuity Test, the first circle in section A page 2. The measurement method was relied on subjective judgment. The form of the dots was different from test to test. For instance, the dots in the background of TNO stereotest were irregular, while the examiner should catch the smallest dot in the view window and measure the narrowest diameter.

Results

Stereoacuity evaluation of RDS of different size

The median stereoacuities for the 1-px group, 6-px group, and 10-px group were 50", 30", and 30", respectively (Figure 3). Using the Friedman test, a significant difference was found among the three groups ($Chi-square=57.532$, $P<0.001$). Using the Wilcoxon signed ranks test to detect differences between the groups: 1-px group versus 6-px group, $Z=-4.903$, $P<0.001$; 1-px group versus 10-px group, $Z=-4.941$, $P<0.001$; 6-px group versus 10-px group, $Z=-1.000$, $P=0.317$. Using the significance level $P<0.017$ set before the comparisons, the stereoacuity of the 1-px group was significantly worse than those of the other two groups, while no significant difference was found between the 6-px and 10-px groups.

Measurement of the dot size of RDS utilized in the clinic

The measured results were shown in table 1. At a checking distance of 40cm, the visual angle of the smallest diameter of the dot expressing in the background was from 0.8 min arc to 1.8 min arc.

Discussion

The random-dot stereogram is the most used method of evaluating stereoacuity. Several tests widely used in research or the clinic are based on this technique. Different designs of the test shapes, or differences in the random dots, may lead to differences in the results of methods. In Simon's view, the poorer stereoacuity measured by the Frisby test may be caused by the widely spaced random elements, which make the contour of the stereofigure discontinuous with the surrounding pattern [13]. Gantz and

Bedell found that the effect of dot density on stereothresholds was significant [4]. However, dot size is another factor that may affect the test result [11, 14]. Forty years ago, Pitblado studied the cerebral asymmetry with the aid of RDS. To recognition of cyclopean shapes, left visual field (right hemisphere) superiority was observed when the small dots comprised the stereogram; with large dots, performance was better in the right visual field (left hemisphere). The size of the dots was 2.6 min arc, 3.8min arc and 6.8min arc viewed at 100cm. The study also showed that increasing the dot size in the random background could slightly, but significantly, enhanced distinguish accuracy with the smaller binocular disparity [11]. Henriksen adopted a stereogram named half-matched to detect the stereo threshold. The research showed that large dots produced stronger responses than small dots, and psychophysical performance decreased with smaller dot size [10].

Most of the smallest dot size of RDS involved in previous literature were larger than normal recognizability (Snellen VA) of 1 min arc, such as 2.2 min arc in Gray's study [16], 1.8×2.7 in min arc in Ito's study[17], 3.5 min arc in Tortter's research [18], and 5 min arc in Stevenson' work [19], etc.. In our experiment, the smallest dot, 1×1 px, with the visual angle of 0.17 min arc, was far smaller than recognition resolution of a normal subject. Generally speaking, the RDSs designed for the clinic were relatively simpler than those used in the laboratory environment mentioned above. The design of our RDSs was similar with common stereotests utilized in the clinic except the test pattern with smallest dots.

The test result of RDS established with extremely small dots was significantly lower than those composed with larger dots. Blur may be one of the reasons. Recognizability is a measurement of the resolution power of the eye to distinguish adjacent points [20]. Assuming that two 1×1 px black dots separated by a 1×1 px white dot, if an observer could distinguish these two black dots, his/her VA should not be lower than 0.17 min arc. Actually the resolution could not be achieved by a normal eye. A subject with normal VA (about 1 min arc) cannot make out these two dots, but may only see one blurred dot. Under this circumstance, the background composed of extremely small random dots may express as a mottled grey background. The blurred retinal image reduces local contrast. The decreased contrast causes a decrement in stereoacuity [21]. Schmidt [22] induced blur with the aid of lenses and found stereoacuity deteriorated 1.341 times faster than Snellen acuity tested under binocular blur conditions and 3.77 times faster under the monocular blur. Crowding may be another factor to influence the test result. The minimum separation from adjacent elements, 1 min arc or more could avoid crowding [23]. Obviously, 0.17 min arc (1 px interval) was too small.

The density of dots in our experiment was 50%, which means the number of black dots and white dots (also could be considered as the background) was equal. Some literature adopted this type of dot dense [11, 24, 25]. Banks believed that low density of dots might lead to a decreased stereopsis. When the dot density increased, the stereo resolution improved and leveled off at a certain value. The levelled off density depended on the amount of blur, that is, 4–5 cycles/° with no blur, 1–2 cycles/° with low blur, and 0.7–1 cycle/° with high blur. It also depended on the stimulated location when meeting with retinal eccentricity, that is, about 2 cycles/° at the fovea, nearly 1 cycle/° at the intermediate eccentricity, and approximately 0.3 cycle/° at the largest eccentricity tested [26].

The stereopsis measurement carried out in the clinic are not as complicated as those utilized in a laboratory environment. The test patterns are relatively simple and the target symbols are easy to be distinguished. After all, young children should not be excluded from a certain test. The RDS used in the clinic vary from the size, the density and the shape of the dots. Piano et al. [27] studied 5 commonly used RDS in the clinic and found a significant difference existing between TNO and Frisby stereotest. It is unwise to attempt to use stereotests interchangeably to test subjects. The test value of most of the stereotest used in the clinic is not consecutive but section by section. The test result of Howard-Dorman apparatus is linear continuous, however, the instrument is seldom used in the clinic. Manner of discontinuous measurement value brings a great trouble when comparing between different tests. For example, the test value 240" measured with TNO stereotest of a subject did not mean that the stereo threshold of the people was 240", but in a field between 240" and 120" (not including 120"). Similarly, a test value 200" tested with Preschool Randot Stereotest means the stereoacuity of the subject was located in a field between 200" and 100" (not including 100"). It should not confirm that the subject whose measurement value was 200" in Preschool Randot Stereotest was better than that of a subject got a 240" value in TNO test. A large overlapping region existed between 120" to 240" in TNO and 100" to 200" in Preschool Randot Stereotest.

Comparing stereopsis between different stereotests should be cautious. However, testing and following up with the same stereotest make the value comparable. In our experiment, eight RDSs were all carried in the clinic. The dot size at 40 cm was greater than or equal to 1 min arc in 6 out of 8 RDSs, while the dot size was close to 1 min arc (0.8 min arc) in the other 2 RDSs. The test result may be affected by reducing the dot size when increasing the test distance. An RDS composed of extremely small dots may underestimate the stereo threshold according to our experiment. However, no significant difference of stereopsis was found when evaluating stereoacuity with another two different size of dots (6-px versus 10-px). This consequence was different from the literature mentioned above. The discrepancy may result from different design of test patterns, different test procedure and different test environment. This reminds us whatever designing or using RDS to test stereopsis, that the smallest dot size in the background should be larger than the recognizability for the subject at test distance. Otherwise, underestimating stereo threshold may appear. Nevertheless, the size of the dots is not the larger the better. Monocular clues become obvious with larger dots because the outline of the target symbol tended to be discerned at this circumstance.

The limitation of our study is that the participants recruited were in a relatively narrow age range, which may lead to possible age bias. All of them were young doctors, nurses and students from our department. Another limitation was that the relative influence factors, such as dot density, was not included into the study. More thorough research should be conducted in future.

Conclusion

Although the disparities of the stereo targets setting in the RDS are the test unit to evaluate the stereo threshold, the effect of the dots composing of the background should not be totally neglected. It is

recommended to avoid adopting the random dots whose sizes are much smaller than the recognizability of the subject. Otherwise, underestimating the stereo threshold should arise under the circumstances.

Abbreviations

arcsec: second of arc

BCVA: best corrected visual acuity

MAR: Minimum angle of resolution

min: minute

px: pixel

RDS: Random-dot stereograms

TNO: The Netherlands Optical Society

Declarations

Ethics approval and consent to participate

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).

Consent for publication

Not applicable.

Availability of data and materials

All the raw data of this article is shown in [additional file 1: Raw data \(stereoacuity\). xls](#). The data of personal identity information will not be made available in order to protect the participants' privacy.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

HW and LZ participated in the design of the study. HW and LZ participated in the data collection. HW performed the statistical analysis of the data. All authors read and approved the final manuscript.

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Table

Table 1 The dot size in 8 stereotests

Name of Stereotest	Dot Size	
	mm	min arc at 40cm
TNO stereotest	0.20	1.8
Randot Stereotest	0.10	0.8
Butterfly Stereo Acuity Test	0.15	1.3
Pass Test 3	0.12	1.0
Random Dot E Stereotest	0.13	1.1
Random Dot Stereo Acuity Test	0.13	1.1
Random Dot 2 Stereo Acuity Test	0.13	1.1
Random Dot 3 Stereo Acuity Test	0.09	0.8

Figures



Figure 1

Stereoacuity measurement system. A test system consisted of a phoropter and two 4K smartphones.

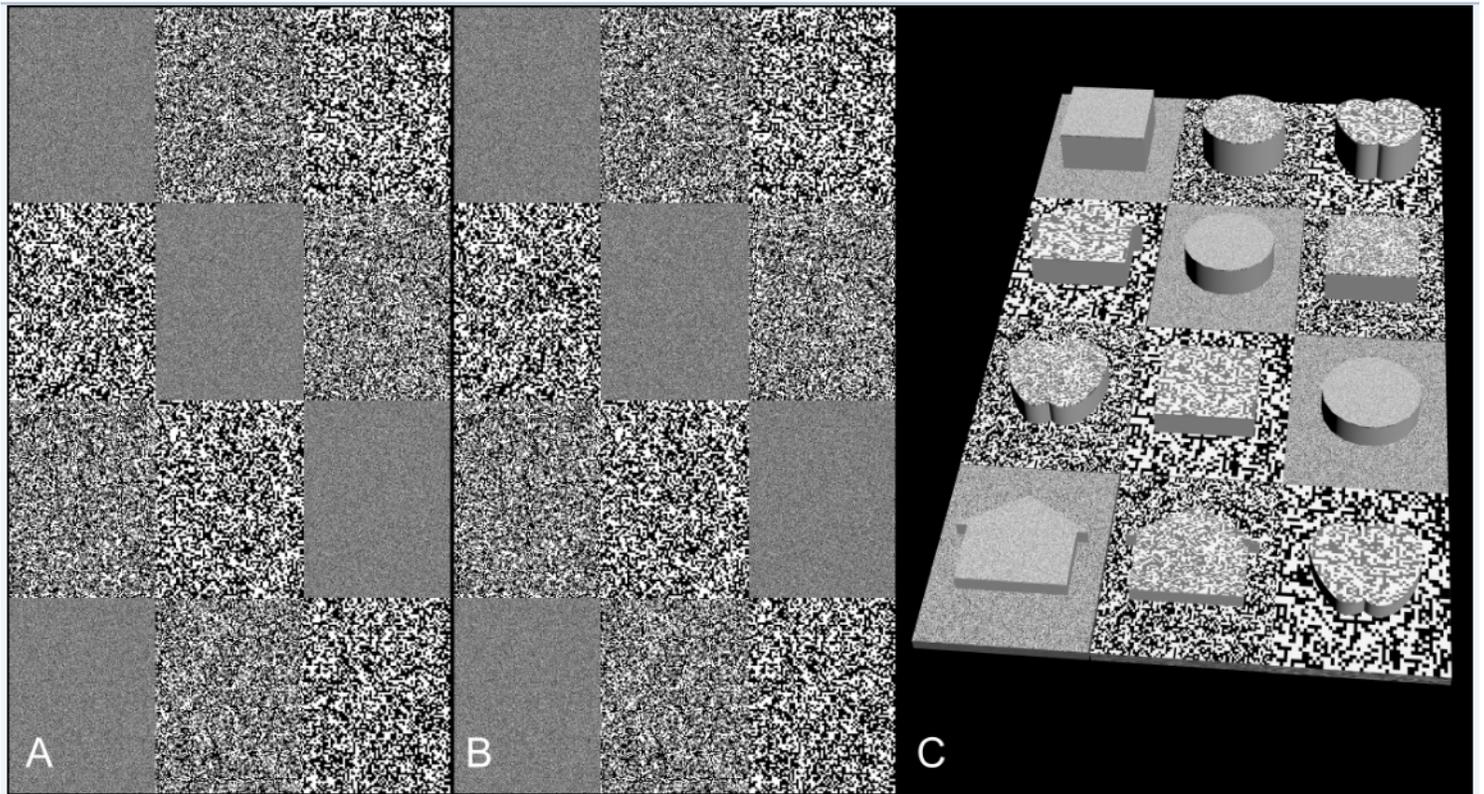


Figure 2

Legend of test image 1 (8 px to 5 px, equivalent to 80" to 50" at 65 cm) This image contains 12 rectangles (720×960 px). The disparities are set 8 px in the first line (the top 3 rectangles); 7px in the second line; 6px in the third line; and 5px in the fourth line. The dot size is 1px, 6px and 10px in the first line; 10px, 1px and 6px in the second line; 6px, 10px and 1px in the third line; 1px, 6px and 10px in the fourth line. The size of the test symbol is 460×460 px for circle, square and apple, the main body of the house is also 460×460 px with the eaves extending another 50px on the left and right side respectively. The target symbols hidden in the rectangles are square, circle and apple in the first line; house, circle and square in the second line; apple, square and circle in the third line; house, house and apple in the fourth line. A is seen by the left eye and B is seen by the right eye. C is the simulation of the percepts generated by the test images A and B. This is an attempt to simulate what a subject might perceive when fusing A and B as one image. The stereo symbols appear to pop out of the background plane.

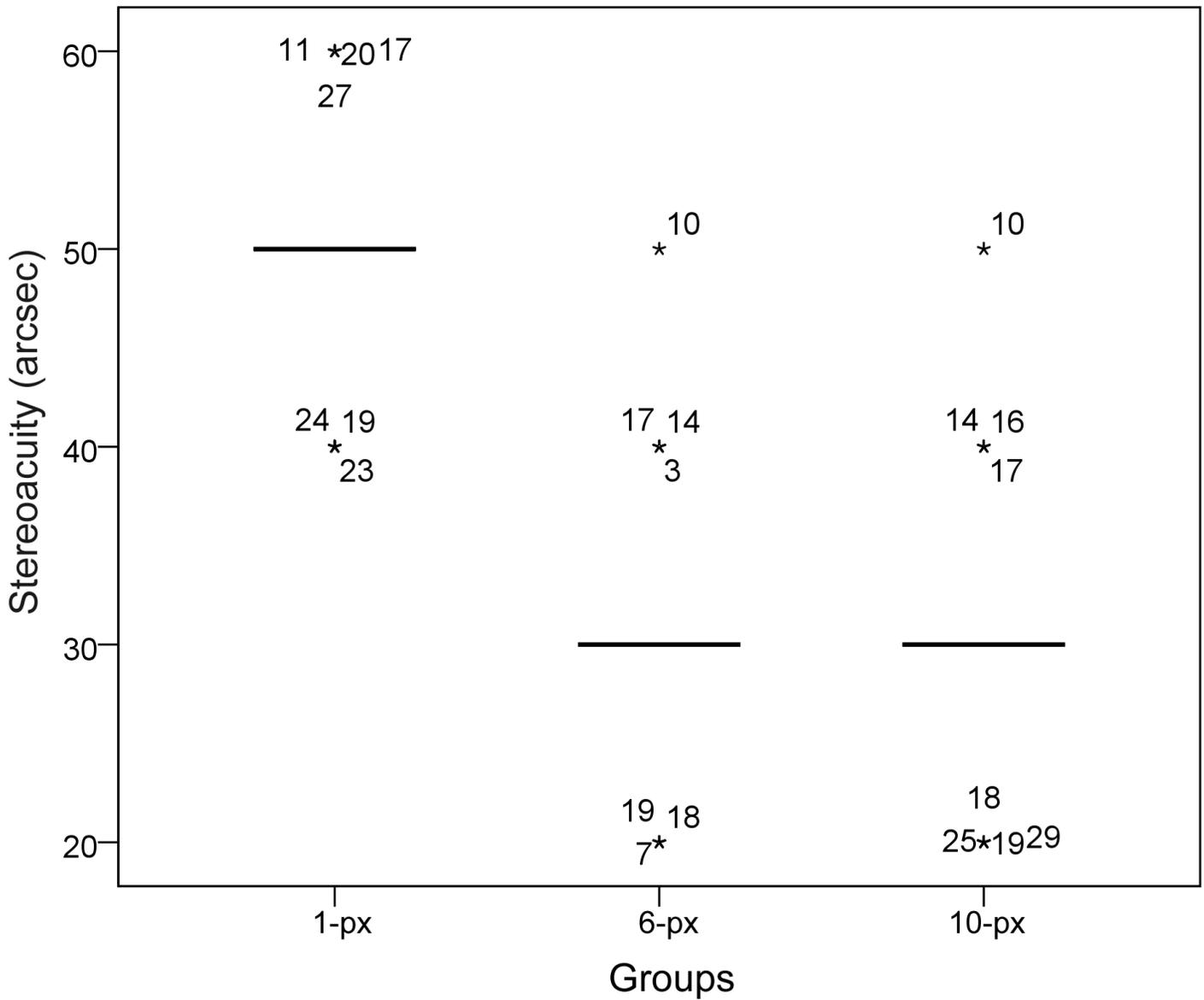


Figure 3

Boxplot of the stereoacuity of three groups. The interquartile range of the three groups was all equal to zero, so the body of the box was changing to a line (the first quartile, the median and the third quartile were the same). The median and interquartile range (M [QR]) of 1-px, 6-px and 10-px was 50 [0], 30 [0], and 30 [0] respectively.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Rawdatastereoacuity.xlsx](#)