# The influence of simulated visual impairment on distance stereopsis

**Lu Liu** Department of Optometry, The Second Hospital of Jilin University, Changchun, China

**Lingxian Xu** Department of Optometry, The Second Hospital of Jilin University, Changchun, China

**Bo Yu** Department of Optometry, The Second Hospital of Jilin University, Changchun, China

**Lingzhi Zhao** Department of Optometry, The Second Hospital of Jilin University, Changchun, China

**Huang Wu** Department of Optometry, The Second Hospital of Jilin University, Changchun, China

**The intricate interrelationships between visual acuity (VA) and stereopsis depend on an array of factors, incorporating the nature of vision impairment, its manifestation (monocular versus binocular), and the classification of stereopsis test symbols used. The objectives of this study were to methodically dissect these multifaceted interactions by simulating a diverse range of vision loss conditions. Thirty medical students with normal vision were subjected to simulated vision loss through opacification and blurring methodologies. Stereopsis was assessed at a distance using both contour-based and random-dot-based symbols under equal binocular and varied monocular VA conditions. In this study, opacification consistently affected stereopsis more than blurring at equivalent VA reductions. However, this difference was absent in contour-based symbols under binocular vision impairment conditions. Significant differences in stereopsis emerged between monocular and binocular vision within the opacification contour-based groups. These differences were less evident in the opacification and blurring groups using random-dot-based patterns. In terms of symbols, the contour-based test demonstrated superior results to the random-dot-based test, particularly under decreased VA. In sum, the method of VA reduction and the choice of stereogram significantly impact distance stereopsis outcomes. This understanding can guide clinical assessments of stereopsis in individuals with varying visual impairments.**

## Introduction

The intricate field of vision science encompasses numerous components that collectively shape human visual perception. Two key aspects, visual acuity (VA) and stereoacuity, fundamentally determine our visual capabilities. VA usually quantified via Snellen fractions or LogMAR (logarithm of the minimum resolution angle), indicates the eye's proficiency at discerning fine details at a specified distance (Lakshminarayanan, 2016). This critical determinant of vision quality is broadly employed in clinical and research environments to diagnose and manage a range of visual disorders (Freundlieb, Herbik, Kramer, Bach, & Hoffmann, 2020). In contrast, stereoacuity signifies the minimum depth difference discernible caused by binocular disparity—the minor dissimilarity in the two retinal images ascribed to the horizontal separation of the eyes (Howard, Rogers, Howard, & Rogers, 2012). Optimal

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stereoacuity affords us depth perception, augmenting our three-dimensional (3D) interpretation of the world.

Extant research delineates a robust correlation between these two parameters (Atchison et al., 2020). In a study, Sodhi, Gautam, Sharma, Anand, & Sodhi (2021) improved distance and near VA of 84 subjects with low vision using low vision aids. It was found that an increase in distance best-corrected VA seems to enhance stereopsis for distance, although the improvement may not be statistically significant. In contrast, an improvement in near best-corrected VA significantly improves stereopsis for near objects. This relationship is ascribed to the inherent intertwining of VA and stereoacuity.

Further substantiating this, Atchison et al. (2020) and Quaia, FitzGibbon, Optican, & Cumming (2018) found an association between diminished VA and impaired stereoacuity. The study suggested that decreased VA, often resulting from prevalent conditions such as amblyopia, can considerably affect stereoacuity. Additionally, an exploratory study conducted by Çakır et al. (2019) revealed that enhancing VA could potentially improve stereoacuity in patients with both refractive accommodative esotropia and amblyopia.

Stereopsis is typically categorized into two types based on the distances used for measurement: near stereopsis and distance stereopsis (Lew & Coates, 2022). Near stereopsis is the ability to perceive depth from binocular disparities in the near visual field. When an object is within close range, the eyes necessitate convergent rotation to maintain focus on the object, resulting in relatively large binocular disparity—the subtle difference in the images perceived by the two eyes (Han, Jiang, Zhang, Pei, & Zhao, 2018; Hess, 2019). Such conditions enable a high-resolution depth perception, facilitating intricate manipulation of objects and execution of tasks that demand precise hand-eye coordination. Conversely, distance stereopsis pertains to depth perception for objects located further away (Adams et al., 2005). In this scenario, the eyes are almost parallel, exhibiting minimal or no convergence (Young, Sueke, Wylie, & Kaye, 2009). Stereopsis is often less effective at longer distances because of the reduced disparity between the images perceived by the two eyes. Under these circumstances, alternative depth cues, including size, perspective, and motion parallax, assume greater importance for perceiving depth at longer distances (Bloch, Uddin, Gannon, Rantell, & Jain, 2015; Howard, Rogers, Howard, & Rogers, 1996; Zhu, Fan, & Zhang, 2022).

In this investigation, our emphasis lies on distance stereopsis. We aim to examine the relationship between VA and stereopsis in light of three pivotal variables: the modality of induced vision loss (opacification versus blurring), the state of vision diminution (monocular versus binocular), and the types of stereopsis test symbols (contour-based versus random-dot based).

Opacification and blurring serve as two distinct methodologies utilized to simulate vision loss. In this experiment, we use an ultraviolet (UV) printer to deposit white ink at various concentrations onto transparent acrylic plates, a procedure designed to mimic opacification comparable to differing degrees of form deprivation. Conversely, blurring means artificial blurring of vision with fogging methods identical to the naturally occurring state of myopia (Kaufman, 1980). Use of positive lenses can cause distant objects to appear blurred, consequently reducing distance VA. Both methodologies affect a reduction in VA. However, when vision loss is comparably induced, it remains uncertain whether these two types of vision loss differentially affect stereopsis.

The influence of monocular and binocular vision reduction on stereopsis measurement is multifaceted (Goodwin & Romano, 1985; Schmidt, 1994). A diminution in vision in one eye can adversely impact depth perception and the capacity to accurately estimate distances, due to the two eyes no longer supplying comparable clear images for the brain to process and contrast (Manoranjan, Shrestha, & Shrestha, 2013). This can lead to difficulties in executing tasks that demand precise depth perception. However, monocular cues may still provide a rudimentary sense of depth (Mehringer, Wirth, Roth, Michelson, & Eskofier, 2022). The effect on stereopsis could potentially vary, depending on the severity of the vision reduction and the individual's capacity to adapt and rely more on monocular cues. A decreased vision in both eyes could also diminish stereopsis and depth perception. Yet, if the decrease in vision is uniform in both eyes, some degree of stereopsis may be maintained (Donzis, Rappazzo, Burde, & Gordon, 1983; Goodwin & Romano, 1985). This preservation is attributed to both eyes still supplying comparable blurred images that can be contrasted to estimate depth. However, if the decrease in vision differs significantly between the two eyes, it may disrupt fusion faculty and, consequently, stereopsis (Hairol, Arusulem, & Ying, 2017; Nabie, Andalib, Khojasteh, & Aslanzadeh, 2019).

Stereopsis is assessed through a variety of tests that employ diverse types of stimuli (Chopin, Silver, Sheynin, Ding, & Levi, 2021). Two common types are the contour-based stereopsis tests and random-dot-based stereopsis tests (Vancleef et al., 2017). Contour-based stereopsis tests use figures with discernible, defined contours (Garnham & Sloper, 2006). However, these contour-based tests exhibit a limitation: they potentially permit recognition with monocular cues (such as identifiable shapes, contours, or apparent blur), leading to false-positive results for stereopsis (Garnham & Sloper, 2006). On the other hand, random-dot-based stereopsis tests present the observer with a field of random dots, with a subset of these dots offset in one image compared to the other,

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thus generating disparity. This subset is arranged into a shape or figure that appears in depth when viewed binocularly. The random dot stereogram (Rado, Sari, Buzas, & Jando, 2020) serves as a typical example of this test type. The impact of the test form—contour-based versus random-dot-based—on stereopsis measurement after a decrease in VA remains an area of uncertainty.

Vision loss can arise from an array of causes, often associated with diverse ocular diseases, injuries, or conditions affecting the refractive media, such as cataracts, corneal diseases (Devi, Kumar, Marella, & Bharadwaj, 2022), whether in one or both eyes, can detrimentally impact stereopsis (Tong et al., 2021). Should one eye exhibit significantly poorer VA than the other, it can impede the brain's capacity to integrate the two slightly disparate images from each eye into a single 3D image, thereby disrupting stereopsis (Bourne et al., 2013; Saydah, Gerzoff, Saaddine, Zhang, & Cotch, 2020). Significant uncorrected refractive errors and anisometropia can impact stereopsis, as well as defocused, blurred images can influence distance stereoacuity. In the natural progression of diseases, the multitude of variables makes it challenging to precisely ascertain the effect of a specific factor on stereoscopic vision. Therefore opacification films with different concentrations of white ink were used to simulate the impact of varying degrees of form deprivation on vision (Lapp et al., 2023). Fogging is a technique used to induce out-of-focus vision, thereby simulating the blurring of myopia (Gawecki, 2019). Both opacification and blurring reduce VA, but their impact on vision differs: the former primarily causes a significant reduction in contrast, whereas the latter predominantly results in the blurring of shapes (Kaufman, 1980; Zhang et al., 2022).

Although the contour-based and random-dot–based stereograms might exhibit minimal differences in individuals with normal VA, it's worth noting that in clinical settings, random dot stereograms are often favored. They are believed to provide a more accurate representation of a patient's genuine stereopsis because of the minimal presence of monocular cues. However, as VA deteriorates, differences between the two methods may become evident. In the context of clinical eye diseases leading to vision impairment, it raises an essential question: Which method more precisely mirrors a patient's actual stereopsis state?

In this investigation, we have implemented a phoropter and a polarized 3D display to establish a distance stereopsis test system. The objective is to juxtapose the results of stereopsis tests conducted under various conditions: differing methods of simulating vision loss, monocular and binocular vision decrease, and varying forms of stereo test symbols. Through this comparative analysis, we aim to provide additional insights into the complex dynamics of stereopsis under various conditions of visual impairment.

## Methods

### Participant

This quantitative observational study included a sample of 30 participants aged 22 to 28 (24.83 ± 2.05) years old who were recruited from the medical undergraduate and postgraduate community at the second hospital of Jilin University, informing potential participants about the upcoming research experiment conducted by our research group, interested individuals were invited to sign up for participation voluntarily. Each participant had a VA of no less than 0 LogMAR in each eye and a stereoacuity of no less than 40″, as verified with the Fly Stereo Acuity Test (Vision Assessment Corporation, Elk Grove Village, IL, USA). Before participation in the study, a written, informed consent was obtained from all participants. The study protocol adhered to the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Second Hospital of Jilin University (No. 2020-110).

### Test apparatus

The experimental apparatus utilized in this study consisted of a polarized 3D display (AOC d2367PH, 23 "16:9 Full HD 3D [1920 × 1080]; Admiral Overseas Co., Taipei, Taiwan) for the visual representation of 3D symbols. This monitor boasts a dot pitch of 0.265mm. The optimal observational distance was strategically set at 3.4m, a configuration that equates to a one-pixel distance to 16 seconds of arc (").

A phoropter (TOPCON VT-10; Topcon Corp, Tokyo, Japan) served as the primary instrument for assessing stereopsis (Figure 1). The original linear polarized lens, incompatible with the circular polarization principle of the 3D display, necessitated modification. Accordingly, the standard ± 0.12DC astigmatic lens assembly was

Figure 1. Schematic diagram of distance stereopsis inspection.

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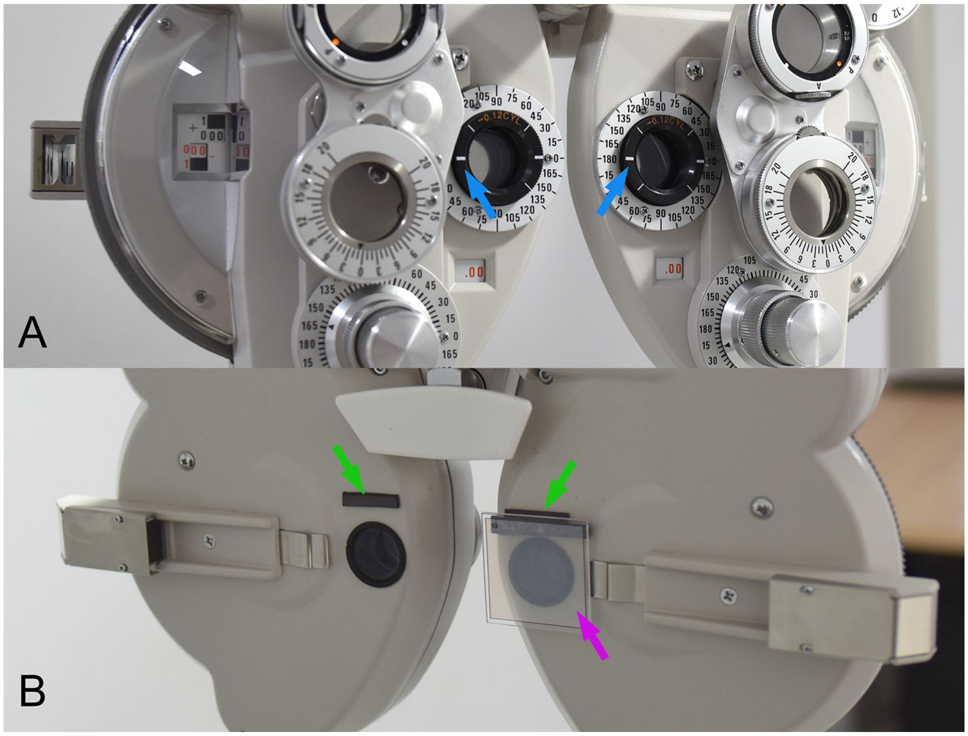

Figure 2. Schematic diagram of a phoropter modified for testing purposes. (**A**) A pair of circularly polarized lenses, modified with −0.12DC astigmatic lens auxiliary accessories (indicated by the blue arrows). The astigmatic lenses originally located behind the attachment have been replaced with circular polarizing films. Polarizers' orientations are calibrated to align optimally with the 3D display when set on the 180° axis, consequently providing the best 3D display effect. (**B**) Two magnetic strips affixed to the backplate of the phoropter (indicated by the green arrows). During the examination, these magnetic strips facilitate the attachment of opacification cards of varying concentrations (indicated by the purple arrows) to the area behind the peephole, thereby allowing modifications of the inspection conditions as required.

retained, but the astigmatic lens itself was substituted with a circular polarized lens. By positioning two circular polarized lenses with appropriate angles over the left and right viewing apertures of the phoropter, 3D effects could be generated in conjunction with the polarizing display (Figure 2A). A magnetic strip was affixed to the phoropter's backplate to facilitate the attachment of auxiliary devices, allowing for effortless adherence of compatible equipment (Figure 2B).

## Test symbols

All stereograms used in this study were constructed using a C# programming framework. Our contour-based stereogram simulation drew upon the quantitative component of the Fly Stereopsis Test (The Stereo Optical Company, Inc., Chicago, IL, USA). A stereo target was randomly assigned to one of four positions: upper, lower, left, or right within a circle. The stereoscopic target becomes perceptible if the subject's stereopsis threshold value exceeds the set disparity. As a crossed disparity configuration, all stereo symbols were designed to appear as if they were protruding from the plane (Figure 3A).

The simulation of random-dot-based symbols replicated the quantitative portion of the Random Dot 3 Stereo Acuity Test (Vision Assessment Corporation). A large circle encompassed four smaller circles. One target circle was set with cross disparity, whereas the remaining three control circles were set with non-cross disparity. If the subject's disparity threshold fell below the set disparity, they could perceive one circle projecting from the test plane, whereas the other three appeared to be within the plane. The task required of the subject was to pinpoint the position of the target circle. The minimum size for the random dots was established at 6 × 6 pixels (with a visual angle equivalent to 0 LogMAR), ensuring full recognition of each dot (Figure 3B).

## Test page description

In this experiment, the disparity range for the stereoacuity test was set from 1 pixel (equivalent

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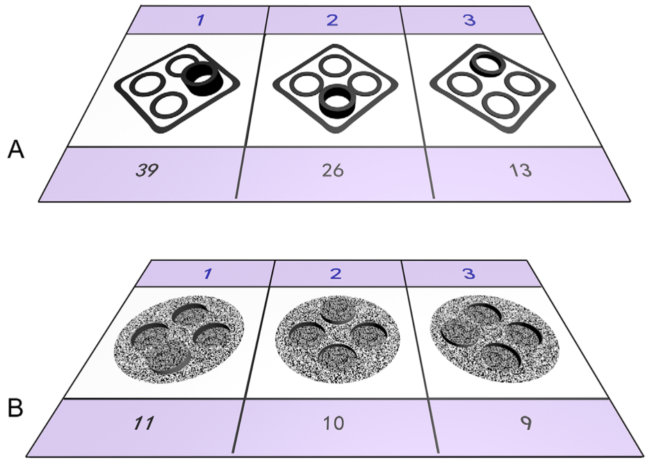


Figure 3. 3D simulation diagram of the visual target. (**A**) Contour-based symbols: This diagram represents the first-grade test page with predetermined disparities of 39 pixels (stereo circle positioned to the right), 26 pixels (stereo circle located at the bottom), and 13 pixels (stereo circle positioned at the top). (**B**) Random-dot—based symbols: This diagram showcases one of the third-grade test pages with established disparities of 11 pixels (stereo circle situated at the bottom), 10 pixels (stereo circle positioned at the top), and 9 pixels (stereo circle located to the left).

to 16") to 39 pixels (equivalent to 624"), with the arc second value obtained by multiplying the pixel count by 16. Using a three-step menu mode allowed for precise control over the subjects' stereopsis measurement accuracy to within 1 pixel (16") throughout the test range. Each test page contained a horizontal arrangement of three test charts.

For the first level, a single test page was presented, with disparities set at 39, 26, and 13 pixels, respectively. The second level encompassed three test pages, each showcasing disparity at different values: 38, 34, 30 pixels; 25, 21, 17 pixels; and 12, 8, and 4 pixels.

The third level comprised nine test pages, each displaying a sequence of disparities as follows: 37-35 pixels, 33-31 pixels, 29-27 pixels, 24-22 pixels, 20-18 pixels, 16-14 pixels, 11-9 pixels, 7-5 pixels, and 3-1 pixels. Detailed visual representations of these levels are provided in Figure 4.

## Opaque plate production

An UV printer (Sonpoo 3060 printer, Shenzhen Songpu Industrial Group Co., Ltd., China) was used to print white ink at varying concentrations onto transparent acrylic plates. This process aimed to mimic opacification akin to differing severities of form deprivation. The printing densities were scaled from 1% to 20% at increments of 1%, thereby establishing a total of 20 distinct concentrations. Two identical plates were produced for each concentration, resulting in a total of 40 plates.

Each acrylic plate measured 4 × 4 cm and was affixed with a magnetic strip on its upper section, facilitating adherence to the corresponding magnetic strip located on the phoropter's back panel. Once positioned, the plate effectively covered the sight hole in its entirety (Figure 2B)

## Test procedure

### *Determination of VA in blurring*

The standard optometry protocol was used to ascertain the subject's refraction, followed by the placement of corrective lenses into the sight hole of the phoropter. For the right eye, the left eye was occluded, and positive lenses were successively added to the right eye to fog VA until reaching a value of 0.6 LogMAR. Gradual unfogging ensued with the recording of the spherical power when the VA reached 0.5 LogMAR (noted as A). This procedure was further continued, with the recording of spherical power corresponding to each subsequent VA values of 0.4 LogMAR (B), 0.3 LogMAR (C), 0.2 LogMAR (D), 0.1 LogMAR (E), and 0 LogMAR (F), as detailed in Figure 5. Should the VA change by two lines due to a 0.25DS adjustment, a 0.12DS auxiliary lens was recommended to ensure adherence to VA requirements.

For the left eye, the right eye was occluded, and positive lenses were added in front of the left eye until a VA of 0.6 LogMAR was attained. The values corresponding to the same VA thresholds as the right eye were recorded as a, b, c, d, e, and f, respectively, as depicted in Figure 5.

### *Determination of VA under varying degrees of opacification*

The test procedure was almost the same as determining VA in blurring but altered the method of changing VA from blurring to opacification. The opacity concentration was recorded at each of the same VA thresholds as in the blurring test (U, V, W, X, Y, Z for the right eye, and u, v, w, x, z for the left eye), as illustrated in flowchart Figure 6. When a 1% concentration adjustment triggered a two-line VA change, the superposition of two opaque plates of different concentrations was used to satisfy the VA requirements. Notably, in our test, the impact on VA was such that $(n\% + 1\%) < (n + 1)\ \%$, where n represented the concentration within the test range.

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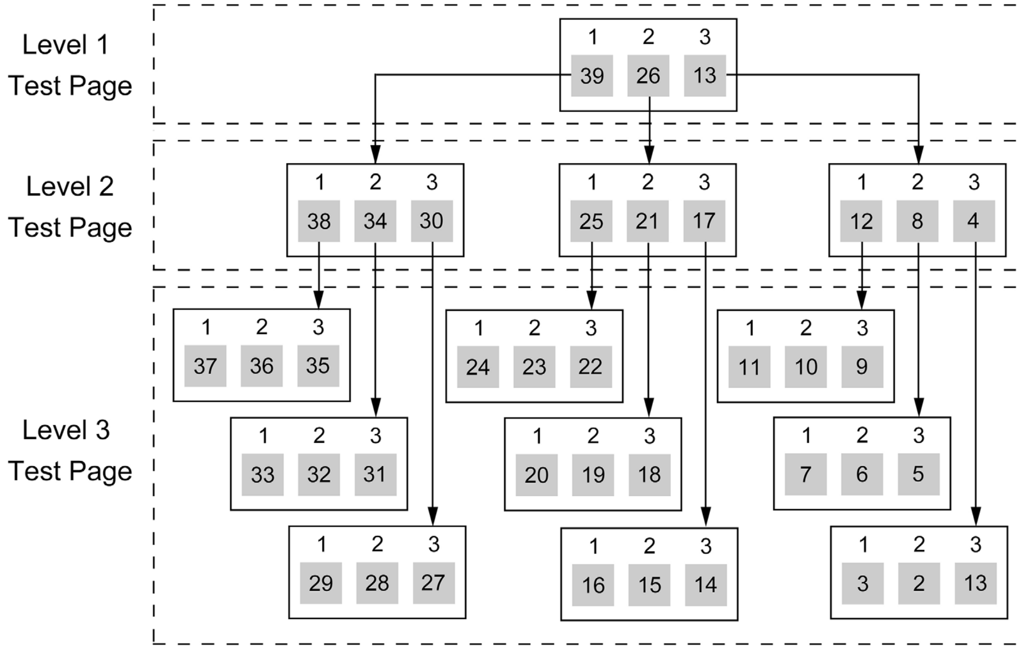


Figure 4. Flow chart of three-level menu stereopsis inspection.

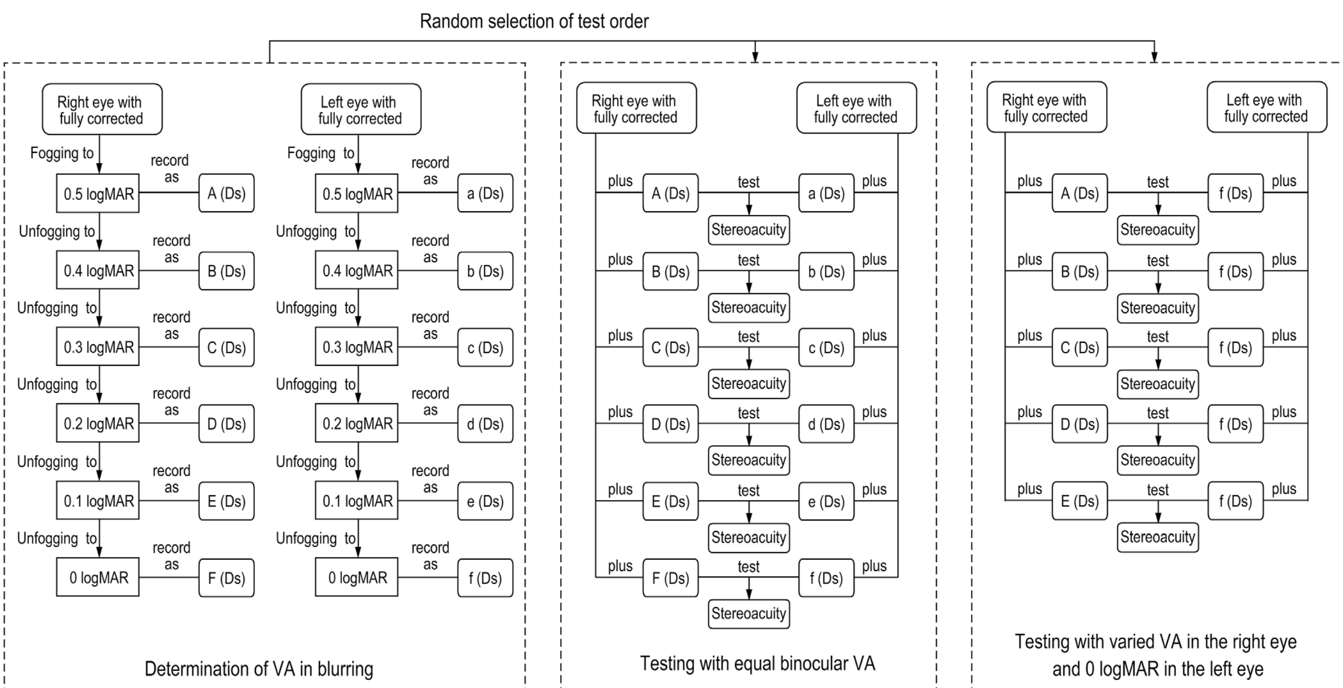


Figure 5. Flow chart of test in blurring.

### *Evaluation of stereoacuity*

Stereoacuity was determined through a three-tier menu mode (Figure 4). The subject was initially asked to observe the test page of the first grade. If the individual failed to identify the stereo target, the result was recorded as 1000". However, if the participant was able to correctly distinguish the stereo target, the pixel number of the minimum disparities optotype discernible was determined, followed by progression to the corresponding next grade test page. The subject's stereoacuity could be accurately identified through this three-tier menu approach.

For instance, if a subject were only able to recognize a disparity of 39 pixels, the subsequent step would

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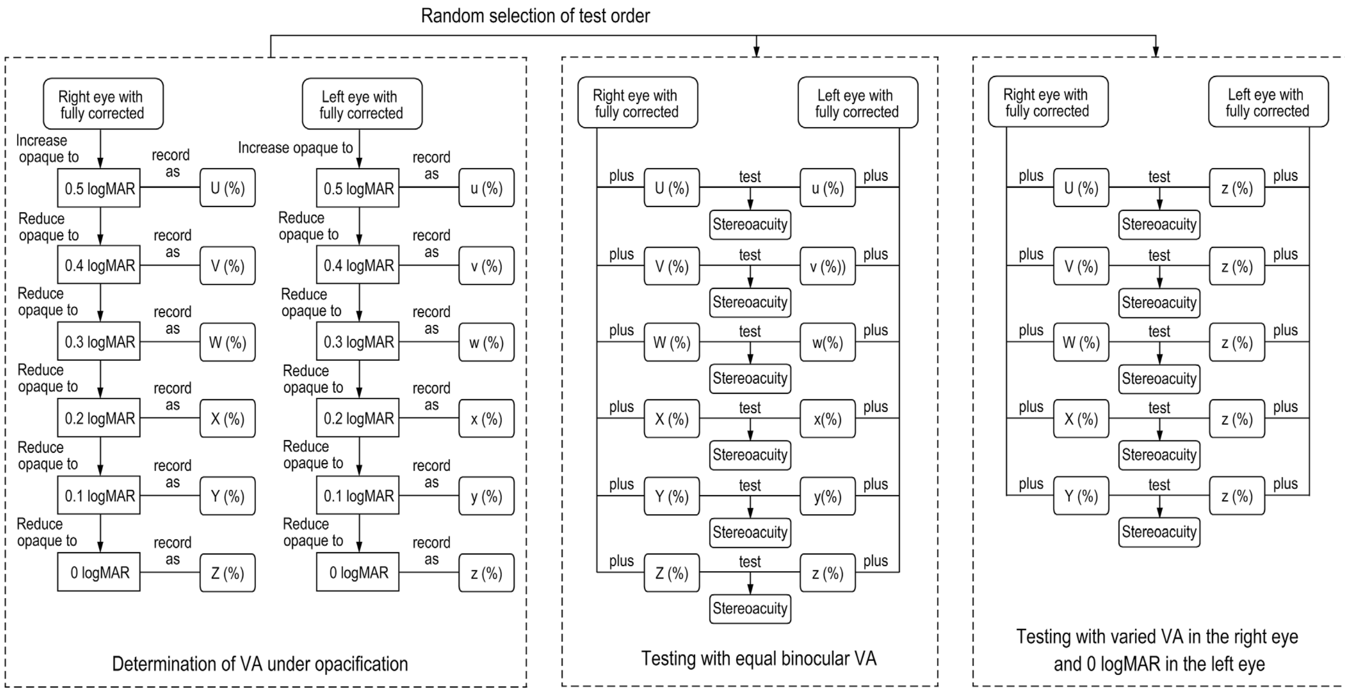


Figure 6. Flow chart of test under opacification.

involve moving to the first test page of the second grade (comprising disparities of 38, 34, and 30 pixels). If the subject could not discern the stereo target, the disparity was recorded as 624" (39 × 16). Alternatively, if the subject could only recognize a disparity of 38 pixels, progression to the first test page of the third grade (consisting of disparities of 37, 36, and 35 pixels) was made. In the event of the subject failing to identify the stereopsis, a disparity of 608" (38 × 16) was recorded. Should the subject only recognize a disparity of 37 pixels, a disparity of 592" (37 × 16) was noted. Moreover, if the subject discerned disparities of 37 and 36 pixels, the result was recorded as 576" (36 × 16), whereas if the subject recognized all three stereo symbols, a disparity of 560" (35 × 16) was noted.

The sequence of using contour-based or random-dot-based optotypes was randomized. The parameters used in the test are delineated as follows:

#### *Evaluation of stereoacuity with equal binocular VA*

*Determination of VA combination in blurring*: The lenses placed before the right and left eyes were adjusted to “A” + “a” (where “A” denoted the spherical lens power in front of the right eye, and “a” referred to the spherical lens power in front of the left eye), and similarly for “B” + “b”, “C” + “c”, “D” + “d”, “E” + “e”, and “F” + “f”, to sequentially measure the stereoacuity values (Figure 5).
*Determination of VA combination under opacification*: The translucent plates placed before the right and left eyes were set to “U” + “u” (where “U” denoted the concentration of the translucent plate in front of the right eye, and “u” referred to the concentration of the translucent plate in front of the left eye), and similarly for “V” + “v”, “W” + “w”, “X” + “x”, “Y” + “y”, and “Z” + “z”, to sequentially measure the stereoacuity values (Figure 6).

#### *Evaluation of stereoacuity with varied VA in the right eye and 0 LogMAR in the left eye*

*Determination of VA combination in blurring*: The lenses placed before the right and left eyes were calibrated to “A” + “f”, “B” + “f”, “C” + “f”, “D” + “f”, “E” + “f”, and “F” + “f”, which were used in sequence to measure the stereoacuity values, as depicted in Figure 5.
*Determination of VA combination under opacification*: The translucent plates positioned before the right and left eyes were adjusted to “U” + “z”, “V” + “z”, “W” + “z”, “X” + “z”, and “Y” + “z”, which were sequentially used to assess the stereoacuity value, as illustrated in Figure 6.

## Data analysis

The statistical analysis of the data was conducted using SPSS version 26.0 (IBM Corp, Armonk, NY, USA) and GraphPad Prism version 9.0 (GraphPad Software Inc., San Diego, CA, United States). The Shapiro-Wilks test was used to investigate the data

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distribution. A parametric test, more precisely, the paired *t*-test, was used to identify group differences in the data with a normal distribution. However, the nonparametric Wilcoxon signed-rank test was used to compare the two groups. For statistical significance, a significance level of $p < 0.05$ was used.

## Results

The data reflecting simulated VA decline are presented in Table 1. Given that the data did not conform to a normal distribution, the median (M) and interquartile range (IOR) were used to illustrate the data's tendencies toward centralization and decentralization. Table 1 displays the stereoacuity measurements across various VA levels. A general trend of worsening stereoacuity was observed as VA decreased, emphasizing the interrelation between VA and stereoacuity.

The comparison of stereoacuity between the opacification and blurring methods is presented in Table 2 and visualized in Figure 7. Significant differences between monocular and binocular vision within all VA levels with the random-dot–based pattern were found. This observation underscores the nuanced impact of vision loss on stereoacuity, whether one or both eyes are affected. A similar trend was observed in the monocular group with the contour-based pattern. However, no significant difference was found in the binocular group with the contour-based pattern. The differential outcomes between the two patterns suggest that the type of stereogram, in conjunction with the mode of vision impairment (monocular versus binocular), plays a pivotal role in determining stereoacuity outcomes.

Table 3 showcases the comparison of stereoacuity between monocular and binocular VA decreases. This is further illustrated in Figure 8. Significant differences were observed in the opacification group with the contour-based pattern. However, no significant differences were detected between the other groups. This means for the contour-based patterns, the balance state between two opaque patterns proves superior to an unbalanced state in facilitating fusion and maintaining a certain degree of stereopsis.

Table 4 presents a comparison of stereoacuity between random-dot-based and contour-based patterns, further illustrated in Figure 9. When tested under normal VA, the median (IOR) was 32(16) arcsec for the random-dot-based stereoacuity and 32(32) arcsec for the contour-based stereoacuity ($z = -1.706$, $p = 0.088$). A significant difference was observed in the binocular group when opacification and blurring methods

| VA | OMR | OMC | OBR | OBC | FMR | FMC | FBR | FBC |
|---|---|---|---|---|---|---|---|---|
| 0.1 | 72 (64) | 64(80) | 80(64) | 64(48) | 64(32) | 64(48) | 80(20) | 56(48) |
| 0.2 | 104(252) | 144(148) | 128(128) | 80(80) | 80(96) | 80(64) | 88(84) | 80(80) |
| 0.3 | 708(824) | 208(328) | 264(832) | 136(128) | 128(148) | 112(128) | 144(152) | 120(128) |
| 0.4 | 1000(178) | 812(780) | 1000(608) | 200(216) | 240(844) | 216(296) | 288(396) | 208(164) |
| 0.5 | 1000(0) | 1000(540) | 1000(0) | 400(482) | 1000(748) | 376(808) | 1000(620) | 272(812) |

Table 1. Median (interquartile range) of stereoacuity (arcsec) measured at different VA (LogMAR) levels. *Notes:* The following abbreviations were used: (O) Opacification, indicating the use of the opacification method to simulate vision loss. (F) Fogging, denoting the application of the positive lenses fogging method to simulate blurring. (M) Monocular, indicating that while the VA of the left eye remains at 0 LogMAR, the VA of the right eye is induced to decrease. (B) Binocular, signifying that the VA of both eyes is induced to decrease synchronously. (R) Random-dot–based, denoting that the test symbols of stereopsis are random-dot–based. (C) Contour-based, indicating that the test symbols of stereopsis are contour-based.

| | MR | | BR | | MC | | BC | |
|---|---|---|---|---|---|---|---|---|
| VA | *z* | *p* | *z* | *p* | *z* | *p* | *z* | *p* |
| 0.1 | −3.421 | 0.001* | −2.972 | 0.003* | −2.584 | 0.010* | −1.077 | 0.281 |
| 0.2 | −3.355 | 0.001* | −2.889 | 0.004* | −3.098 | 0.002* | −0.360 | 0.719 |
| 0.3 | −4.271 | <0.001* | −3.588 | <0.001* | −3.446 | 0.001* | −0.458 | 0.647 |
| 0.4 | −3.226 | 0.001* | −3.604 | <0.001* | −3.864 | <0.001* | −0.060 | 0.952 |
| 0.5 | −3.182 | 0.001* | −2.437 | 0.015* | −3.040 | 0.002* | −0.203 | 0.839 |

Table 2. Comparative analysis of stereoacuity between the opacification and blurring methods at different VA (LogMAR) levels. *Note:* * $P < 0.05$.

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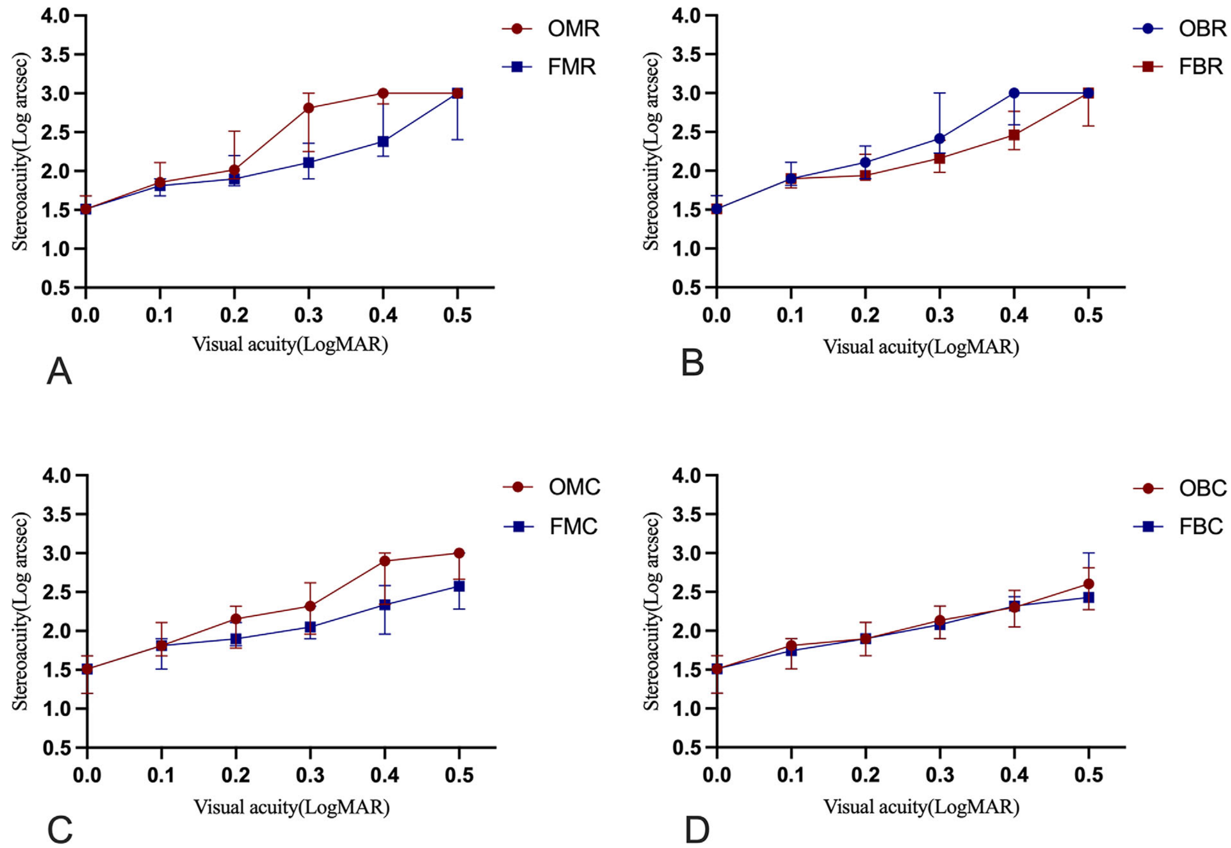


Figure 7. Trend curves are characterized by the relationship between stereoacuity and different VA levels simulated by the opacification and fogging (blurring) methods. (**A**) Monocular VA decreases with random-dot-based stereograms. (**B**) Binocular VA decreases with random-dot-based stereograms. (**C**) Monocular VA decreases with contour-based stereograms. (**D**) Binocular VA decreases with contour-based stereograms. Stereopsis values were transformed to log arcsec values for visualizing. Datapoints and error bars represent the median and quartile of the stereopsis, respectively.

| | OR | | FR | | OC | | FC | |
|---|---|---|---|---|---|---|---|---|
| VA | *z* | *p* | *z* | *p* | *z* | *p* | *z* | *p* |
| 0.1 | −0.466 | 0.641 | −1.395 | 0.163 | −2.353 | 0.019* | −0.178 | 0.859 |
| 0.2 | −0.847 | 0.397 | −1.151 | 0.250 | −3.567 | <0.001* | −0.399 | −0.690 |
| 0.3 | −1.635 | 0.102 | −1.483 | 0.138 | −3.403 | 0.001* | −0.270 | −0.787 |
| 0.4 | −0.267 | 0.789 | −0.990 | 0.322 | −3.902 | <0.001* | −1.138 | −0.255 |
| 0.5 | −1.753 | 0.080 | −1.119 | 0.263 | −3.727 | <0.001* | −0.696 | −0.487 |

Table 3. Comparison analysis of stereoacuity between the monocular and binocular VA (LogMAR) decreasing. *Note:* $^{*}P < 0.05$.

were used to reduce VA. Although no significant differences were found in the monocular group with opacification and blurring methods in the relatively superior VA groups (VA = 0.1 and 0.2 LogMAR in the opacification group and VA = 0.1, 0.2, and 0.3 LogMAR in the fogging group), significant differences were detected in the other groups. The overall trend suggests that stereoacuity tested in the contour-based group was superior to that in the random-dot–based group, particularly in instances accompanied by decreased VA.

## Discussion

In this research, we delved into the nuanced impact of VA reduction on stereopsis. Specifically,

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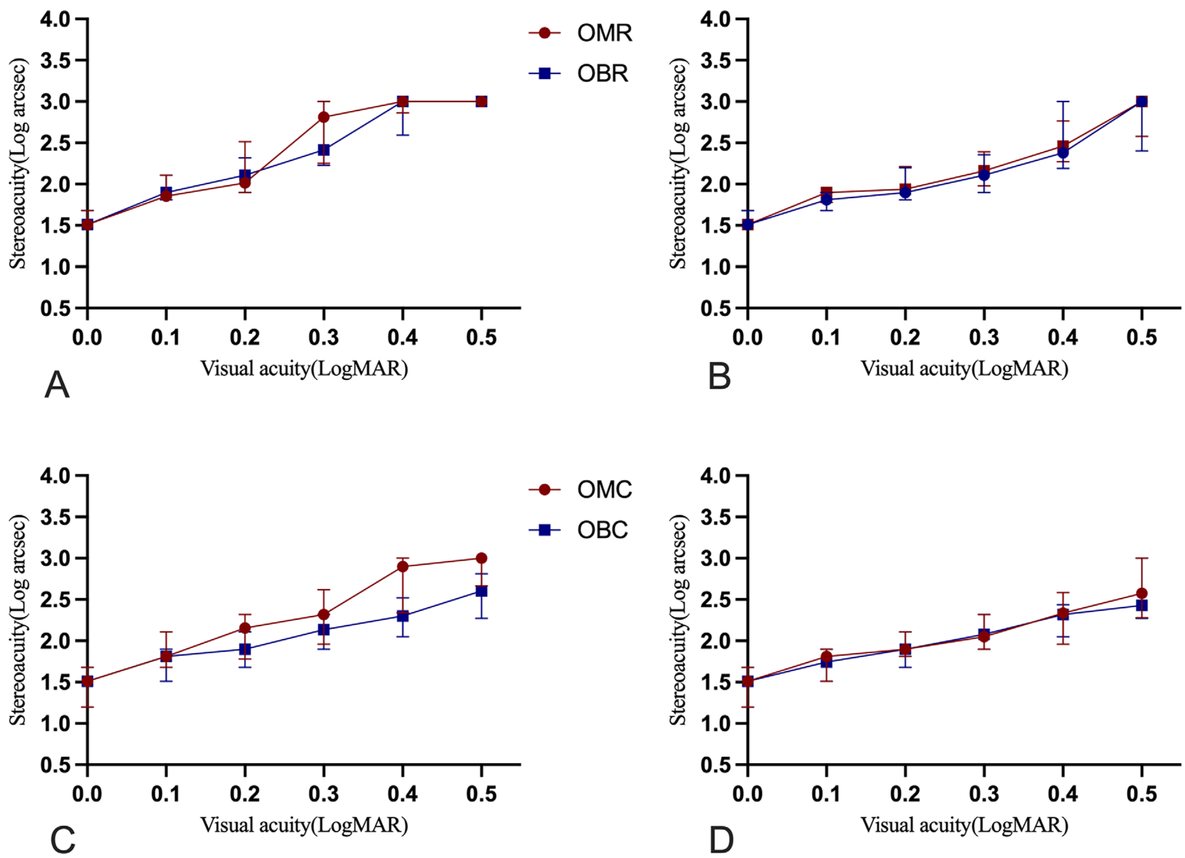


Figure 8. Trend curves are characterized by the relationship between stereoacuity and different decreased monocular and binocular VA levels. (**A**) Opacification method with random-dot-based stereograms. (**B**) Fogging (blurring) method with random-dot-based stereograms. (**C**) Opacification method with contour-based stereograms. (**D**) Fogging method with contour-based stereograms. Stereopsis values were transformed to log arcsec values for visualizing. Datapoints and error bars represent the median and quartile of the stereopsis, respectively.

| | OM | | OB | | FM | | FB | |
|---|---|---|---|---|---|---|---|---|
| VA | *z* | *p* | *z* | *p* | *z* | *p* | *z* | *p* |
| 0.1 | −1.295 | 0.195 | −3.187 | 0.001* | −1.472 | 0.141 | −2.497 | 0.013* |
| 0.2 | −0.913 | 0.361 | −3.381 | 0.001* | −1.123 | 0.261 | −2.318 | 0.020* |
| 0.3 | −2.873 | 0.004* | −4.137 | <0.001* | −1.721 | 0.085 | −2.745 | 0.006* |
| 0.4 | −2.108 | 0.035* | −4.373 | <0.001* | −2.693 | 0.007* | −3.201 | 0.001* |
| 0.5 | −2.194 | 0.028** | −3.772 | <0.001* | −2.635 | 0.008* | −3.101 | 0.002* |

Table 4. Comparison analysis of stereoacuity between random-dot—based and contour-based symbols at different VA (LogMAR) levels. *Note:* $^{*}P < 0.05$.

we examined two distinct methods of simulating vision loss—opacification and blurring—as well as the differences between monocular and binocular vision loss. Furthermore, we explored the effects of two kinds of stereograms: contour-based and random-dot–based.

Opacification had a more pronounced impact on stereopsis compared to blurring, with a notable exception observed in binocular vision loss with the contour-based test. In general terms, opacification led to alterations in contrast while maintaining relatively clear edges of the visual target. Conversely, fogging resulted in edge blurring of the visual target yet induced comparatively minor contrast alterations relative to opacification. For monocular vision impairment, changes in contrast caused by opacification seemed to have a greater influence on stereopsis than edge

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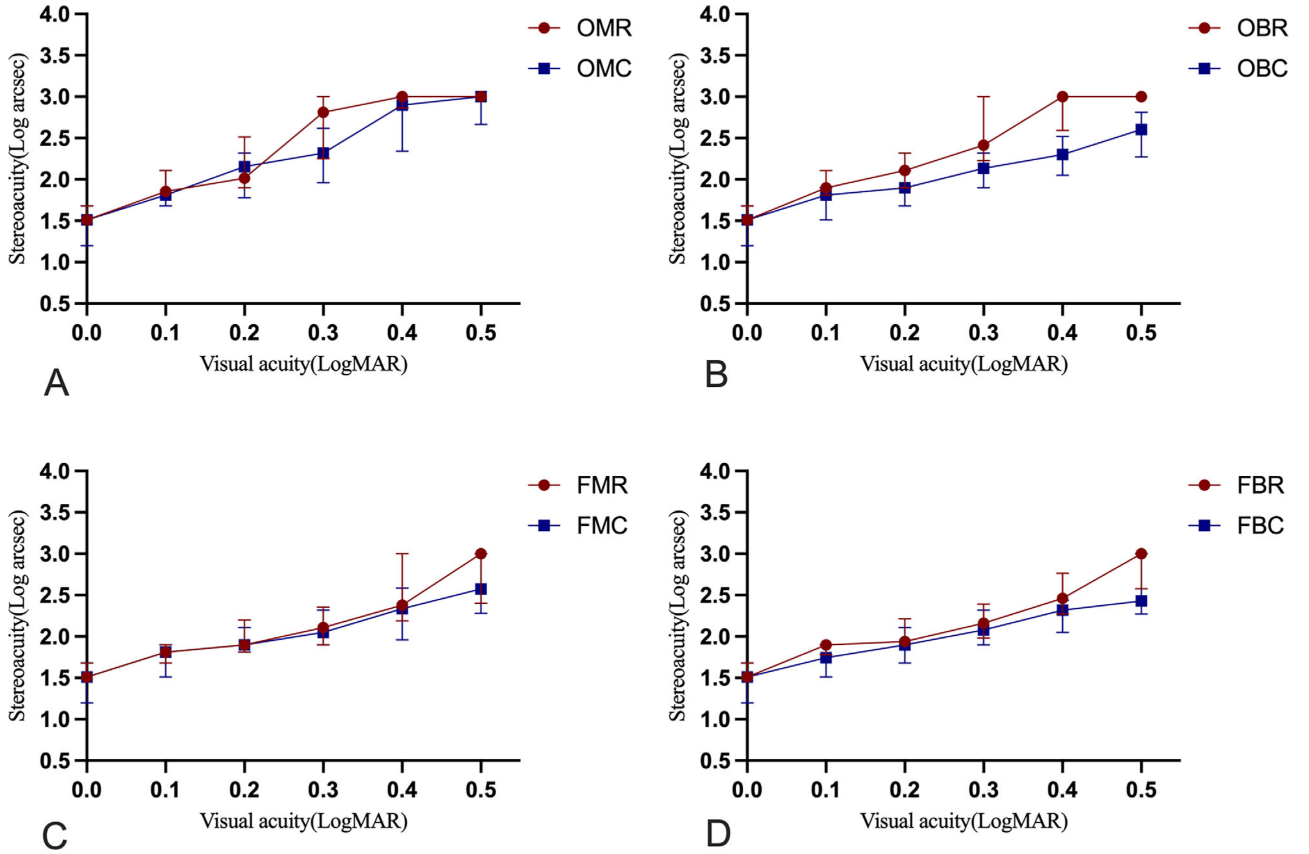


Figure 9. Trend curves are characterized by the relationship between stereoacuity tested with random-dot-based and contour-based stereograms at different VA levels. (**A**) Opacification method with monocular VA decrease. (**B**) Opacification method with binocular VA decrease. (**C**) Fogging (blurring) method with monocular VA decrease. (**D**) Fogging method with binocular VA decrease. Stereopsis values were transformed to log arcsec values for visualizing. Datapoints and error bars represent the median and quartile of the stereopsis, respectively.

blur. However, for binocular vision impairment, both opacification and blurring reduced the ability to discern the small dots in the random-dot pattern, hinting at a more substantial influence of opacification on fusion. Yet, for contour-based symbols, the impact differed. Although opacification led to changes in contrast, the edges retained clarity. In contrast, although blurring has a less severe impact on contrast, it results in blurred edges. The relatively clear edges of contour-based symbols in opacification conditions offset the contrast decrease. Simultaneously, the pronounced contrast counterbalanced the blurred edges of the contour-based symbols under blurring conditions. Consequently, when an equivalent binocular vision decline is induced, the difference between opacification and blurring conditions is imperceptible for contour-based symbols. This is consistent with the view of Held, Cooper, & Banks (2012) that blur and disparity are complementary cues to depth.

According to the results, effects on stereopsis from monocular and binocular VA reductions were similar for blurring and opacification groups using random-dot–based patterns. However, differences emerged for the opacification group using contour-based patterns. For random-dot patterns, both conditions blurred the dots equivalently, disrupting fusion. For contour-based patterns, blurring(fogging) influenced fusion similarly whether it affected one or both eyes' images, suggesting a balance between two low-contrast patterns might assist fusion better than an imbalanced state and preserve some degree of stereopsis (Donzis et al., 1983; Goodwin & Romano, 1985). Stereopsis relies on the brain's capacity to contrast images from each eye. If one eye's vision is clear and the other's is blurred, the brain might prioritize the clear image, affecting stereopsis or suppressing the blurrier image (Cooper & Mendola, 2019). A decline in VA in both eyes might blur the overall image, challenging accurate depth perception. However, if the decline is consistent in both eyes, some stereopsis might be retained (Donzis et al., 1983; Lam, Chau, Lam, Leung, & Man, 1996). However, if vision decreases unevenly, binocular disparity and, consequently, stereopsis may be disrupted (Webber, Schmid, Baldwin, & Hess, 2020). The relationship

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between VA and stereopsis isn't necessarily linear, influenced by factors like severity, duration, age at onset, and individual neurological variations (Norman et al., 2008).

Contour-based stereotests use distinct contours, but they may contain monocular cues (Young et al., 2009). In contrast, random-dot-based tests hide a figure within the dots (Chopin, Bavelier, & Levi, 2019; Richards & Kaye, 1974), discernible only binocularly, eliminating monocular cues but posing challenges for very young children or individuals with certain cognitive impairments (Chopin et al., 2019). In a previous study, results from contour-based and random-dot–based tests were similar for participants with normal VA (Zhao & Wu, 2019). However, with VA impairment, contour-based tests outperformed, because dots in random-dot patterns became blurrier, impacting results more than contour-based patterns. It's crucial to differentiate between induced vision loss, which is controlled and temporary, and genuine disease-related vision loss, potentially having different stereopsis effects.

Clinically, numerous eye diseases can lead to vision impairment. Whether it's a vision decline in one eye or both, the repercussion of stereopsis is undeniable. Similarly, both form deprivation and defocus can substantially influence stereopsis. Yet, we posit that the current stereopsis evaluation methods prevalent in clinical practice face challenges in accurately assessing stereopsis in patients experiencing vision loss. For instance, monocular cues in contour-based stereoscopic test charts might lead to overestimating a subject's stereoacuity. On the other hand, the random dot stereogram, commonly used in clinical practice, features extremely small random dots. This can potentially underestimate a subject's stereoacuity if vision reduction hinders their ability to discern these dots. It's pivotal to remember that stereopsis tests are designed to evaluate an individual's disparity resolution capabilities, not their viewing angles. Hence, there's a pressing need to devise a new random dot stereogram. The idea would be to increase the size of the random dots and ensure they're discernible to patients without inadvertently introducing monocular cues due to excessive dot size. Such a design would be fundamental in providing a more accurate assessment of stereopsis in patients with vision loss. This challenge is what we intend to address in our subsequent research endeavors.

The limitations of this study were that a distinction exists between experimentally induced visual impairment and the clinical manifestations of visual impairment, the correlation of which poses a challenge. Specifically, the form deprivation caused by opacification implemented in this study lacks a direct equivalent in real-world clinical conditions, further complicating the extrapolation of our findings to a clinical context. During the testing process, certain factors, which ordinarily exert a negligible effect on stereopsis under normal vision conditions, may potentially influence the measurement outcomes under conditions of diminished vision. For instance, brightness (Liu, Xu, Wang, & Wu, 2021), contrast (Chen, Chen, & Tyler, 2016), and target size may play a role. These variables underscore the complexity of accurately assessing the impact of vision loss on stereopsis and point to the need for further research to elucidate the interplay of these factors fully.

## Conclusions

Our study elucidates the relationship between VA and stereopsis under different vision loss simulations. Stereopsis decline is more pronounced with opacification than blurring. Contour-based tests consistently outperformed random dot stereograms. The impact on stereopsis is notably similar in both binocular and monocular vision loss scenarios. This understanding can guide clinical assessments of stereopsis in individuals with varying visual impairments. The datasets used and analyzed during the study are available in the Supplementary Tables S1 to S8.

*Keywords: simulated visual impairment, stereopsis, monocular, binocular*

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Corresponding author: Huang Wu.
Email: wuhuang@jlu.edu.cn.
Address: Department of Optometry, the Second Hospital of Jilin University, Changchun 130041, China.

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