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CLINICAL INVESTIGATION

Measurement of paracentral stereopsis using a new method with the binocular open perimeter *imovifa*® in normal adults

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Abstract

Purpose No method to quantitatively evaluate stereopsis within the 15° visual field has been clinically established. We developed a program to measure paracentral stereopsis and evaluated its feasibility in visually normal participants.

Study design Experimental investigation

Methods Ten visually normal volunteers with stereopsis of 60 arcseconds or better were included. The Stereo Eccentricity Analysis (SEA) program for stereopsis measurement across the visual field was integrated into the binocular visual field analyzer *imovifa*®. Subjects with established binocular stereopsis detected a stereoscopic circular target presented with crossed disparity on random dots at the fovea, 3°, 5°, 10°, and 15° on the 45°, 135°, 225°, and 315° meridians. The subjects performed two tasks for measurement in the periphery: a detection task by pressing the response button when the circular target was perceived and a localization task by tilting a joystick to indicate in which quadrant the circular target was perceived. The duration of the target presentation was 500 ms.

Results The stereo thresholds at 0° and 3° did not significantly differ. The thresholds at 10° and 15° were significantly higher than at 0° ($P < 0.01$). While no inter-individual threshold difference was observed at the fovea, the difference was large at 15°. The stereo thresholds for the detection and localization tasks also did not differ significantly.

Conclusion With the SEA program, paracentral stereopsis can be measured and the stereo threshold increases with eccentricity. The SEA program appears to be a feasible clinical method to evaluate paracentral stereopsis.

Keywords Stereopsis · Visual field · Binocular disparity · Paracentral stereopsis · Perimeter

Introduction

When the eyes fixate on an object, a slight misalignment occurs between the two retinal images (i.e., binocular disparity) because the two eyes are horizontally separated. By fusing the misalignment, binocular stereopsis is derived and depth perception happens, consequently leading to the perception of the external world in three dimensions. Binocular stereopsis plays an essential role in individuals' quality of life (QOL) in tasks such as judging distances, grasping items, and driving.

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In cases of unilateral retinal diseases [1–5] and glaucoma [6–8], the vision and visual field impairments owing to the disease can have a substantial impact on patients' stereopsis. Reportedly, reduced stereopsis is associated with the degree of visual field loss progression in glaucoma and could be useful for early detection of the disease [9]. In some glaucoma cases, parafoveal and peripheral field loss precede visual acuity deterioration and reduced stereopsis could occur earlier in the visual fields outside the fovea than in the fovea. Deteriorated stereopsis is even observed in glaucoma patients with a normal threshold of differential light sensitivity [8]. These observations suggest that a quantitative assessment of stereopsis outside the fovea may reflect the progression of visual field impairment in a more accurate fashion and aid in the early detection of the disease.

The significant impact of visual acuity and visual field impairments on patient's QOL has also been reported [10–13]. The involvement of the upper or lower visual field loss in traffic accidents observed in glaucoma patients [14]

suggests the possible decline in peripheral stereopsis and the resultant impact on patients' QOL. Psychophysical experiments report that the stereo threshold differs between the central and peripheral visual fields and is higher in the periphery [15–19]. Although binocular stereopsis at the fovea has been investigated in some clinical studies, to our knowledge, no study has evaluated stereopsis outside the fovea in cases with eye diseases. A clinical method that measures paracentral stereopsis will help understand whether and how patients with retinal diseases or glaucoma can process binocular disparity outside the fovea and if stereopsis outside the affected central field is compromised or preserved, as well as the impact of the reduced paracentral stereo vision on patients' daily living.

We developed a program, "the Stereo Eccentricity Analysis (SEA) program" that measures paracentral stereopsis. The SEA program is integrated into the binocular open field imaging system *imovifa*®, which is clinically used for visual field testing under binocular viewing. With the SEA program, random dot stereograms (RDSs) are displayed in front of the observer's two eyes and the test target can be presented to any test location in the visual field, similar to the target presentation in other visual field testing.

In this study, we aimed to validate the feasibility of the new quantitative method for measuring foveal and paracentral stereopsis in visually normal adults.

Materials and methods

Subjects

Visually normal volunteers from the Kindai University Hospital, excluding staff members from the ophthalmology department, were recruited. The inclusion criteria were: under 40 years of age, best corrected visual acuity of 1.2 or better (−0.1 logMAR equivalent), normal stereopsis of 60 seconds of arc (arcseconds) or better and normal ocular alignment and ocular motility. Ten subjects (3 females; age, 23–39 years) were included. Before the experiment, all the subjects received the random dots stereo test and tests for VA, eye position, and eye movement. Refractive errors (spherical) were -1.94 ± 1.33 D OD and -1.91 ± 1.42 D OS. The study protocol was compliant with the Declaration of Helsinki and approved by the Ethics Committee of Kindai University (No. R03-245). Written informed consent was obtained from all participants after an oral explanation of the nature and potential consequences of the study.

Apparatus

The binocular open field perimeter *imovifa*® (CREWT Medical Systems, Inc.) for visual field testing [20] was used for target presentation in this study. The device has two separate optical systems for the left and right eyes and each has a wide-angle lens system. The target was presented on a Quad High-Definition (QHD) transmissive liquid crystal display (LCD) with a high-intensity light-emitting diode (LED) backlight. Using the distortion function and field curvature corrections, targets can be accurately presented within 30° from the fovea. Target presentation and eye monitoring are independently performed for each eye. The device also has a telecentric optical system to equalize the central and peripheral light intensities. To fuse the images in the two eyes for the binocular viewing test condition, one-meter angle convergence is required.

Stimuli, test locations, and background

The RDSs were programmed using the Mersenne-Twister algorithm (Makoto Matsumoto and Takuji Nishimura) with random numbers between 0 and 255 generated and assigned to each pixel of the QHD LCD screen. One pixel corresponded to a stereo display resolution of 200 arcseconds. The test target was a stereoscopic circle with crossed disparity, which could be perceived by subjects with established binocular stereopsis (Fig. 1). The circular target with binocular disparity was presented at the fovea, 3°, 5°, 10°, and 15° on the 45°, 135°, 225°, and 315° meridians. A total of 17 test locations within the central 15° visual field were tested. Table 1 shows the circular target's sizes and binocular disparity magnitudes that varied with the tested eccentricities. The mean luminance levels for the four quadrants of the RDSs background were set to the same level, and the average tone of the RDSs was controlled to a grayscale of 128.

Tasks and procedure

The stereo threshold was first measured at the fovea. A composed figure of four rhombuses horizontally and vertically spaced at a visual angle of 2° from each other was used as the fixation target. The size of each rhombus was 0.5°. The subject was corrected for refractive error as needed and instructed to fixate on the fixation target and press the response button when the circular target was perceived in the center of the fixation target. In the subsequent measurement in the paracentral visual field, a cross figure of 0.5° was used as the fixation target and the subject was asked to perform two tasks, a detection task and a localization task. In the detection task, the subject was instructed to fixate on the center of the cross figure and press the response button when perceiving the circular target projected onto the paracentral visual field. In the localization task, the subject was asked to indicate in which quadrant the circular target was observed by tilting a joystick. To ensure that the subject fully

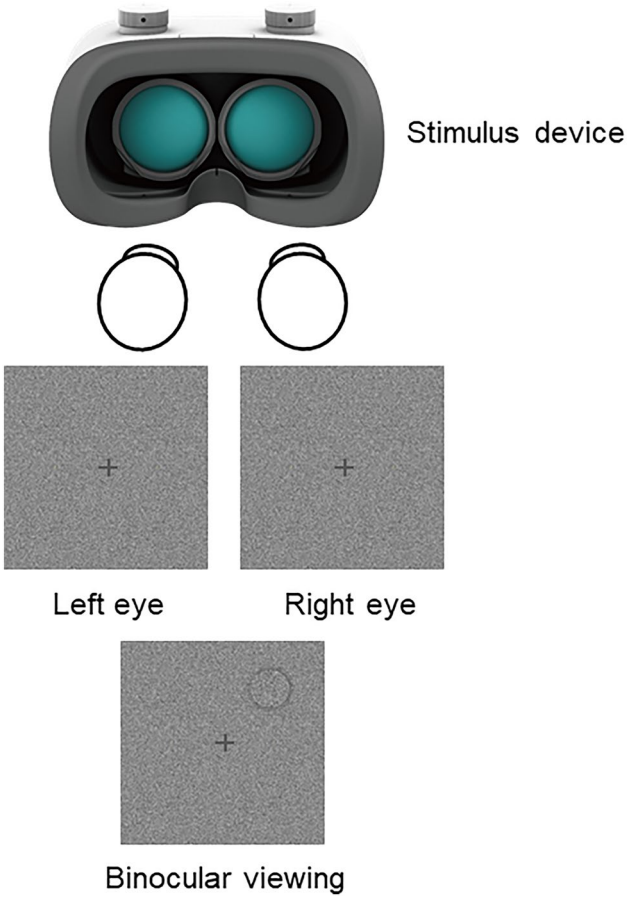

Fig. 1 Schematic of the paracentral stereo test. The RDSs are displayed in front of the two eyes and a circular test target with binocular disparity can be presented to any test location within the 15° visual field. Only the examinees with established binocular stereopsis can perceive the circular target. RDS, random set stereograms

Table 1 Test conditions

Eccentricity	Target size	Binocular disparity magnitude
0°	1°	0″ 200″
3°	2°	0″ 200″
5°	2°	0″ 200″ 400″
10°	5°	0″ 400″ 600″ 800″
15°	6°	0″ 400″ 600″ 800″

understood the instructions, a brief demonstration was given prior to conducting the measurement.

Before beginning the test, the examiner checked the subject's fusional condition in both eyes. The fixation target which was projected to each eye would appear as one if fused and as two if not. The stereoscopic vision test was performed following the confirmation of the fused fixation target. The examiner also checked fixation during the test by monitoring the eye positions with an infrared camera. In each test, new RDSs were generated and the SEA program constantly displayed the same RDSs in front of the subject's eyes, creating a disparity ranging from 200 to 800 arcseconds in front of the tested eye. The duration of each target presentation was 500 msec and a gray background was shown for 2 seconds between each target presentation. In each test, the 17 locations were randomly tested with a stimulus disparity that varied with the test location. The test was performed three times with two intervals of at least five minutes each. The median of the three detected thresholds for each test location was used as the stereo threshold for that test location. If the subject indicated perception of the circular target while no target was presented (i.e., a figure with zero disparity was presented), the response was considered a false positive response. The correct answer rates for the four quadrants obtained in the localization task were also assessed.

Statistical analysis

Data were analyzed using BellCurve for Excel (Social Survey Research Information Co., Ltd.). The stereo threshold differences between the detection and localization tasks were analyzed by the Wilcoxon signed-rank test. The stereo threshold differences among the eccentricities (at the fovea, 3°, 5°, 10°, and 15°) were analyzed by the Kruskal-Wallis test and the Bonferroni/Dunn test. $P < 0.05$ was considered statistically significant.

Results

The stereo threshold differences between the detection and localization tasks

Figure 2 shows the detected stereo thresholds at the 17 test locations in the two tasks, no significant threshold difference was seen between the tasks ($P = 0.735$, Wilcoxon signed-rank test; Fig. 2). The average false-positive rates were 7.1% and 5.1% for the detection and localization tasks, respectively. The localization task had a high correct response rate of 97.2%.

The stereo threshold differences among the five eccentricities

Figure 3 shows the subjects' median stereo thresholds at the 5 eccentricities in the detection and localization tasks. All subjects had a stereo threshold of 200 arcseconds at the fovea and 3°. No significant threshold differences were observed within 5°, either in the detection or localization task. Compared to the threshold at the fovea, significant threshold

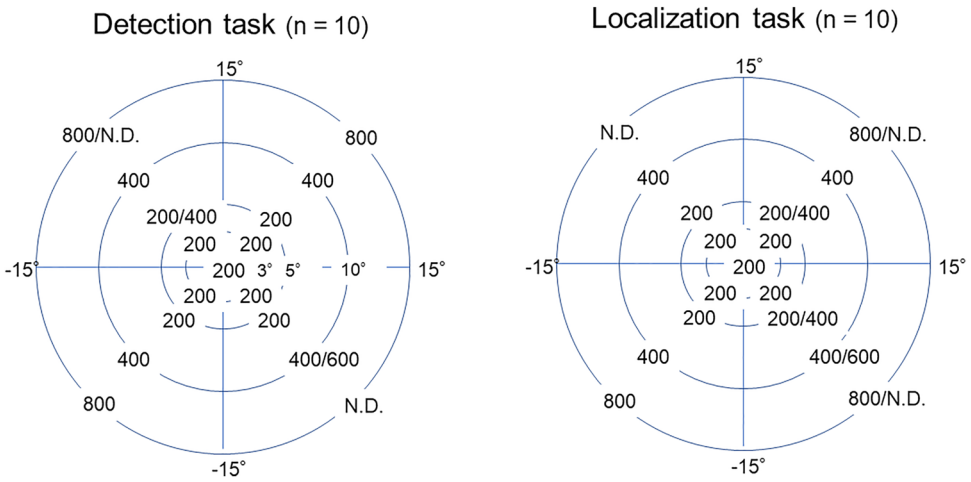

Fig. 2 The stereo thresholds at the seventeen test locations for the detection and localization tasks. N.D., not detectable

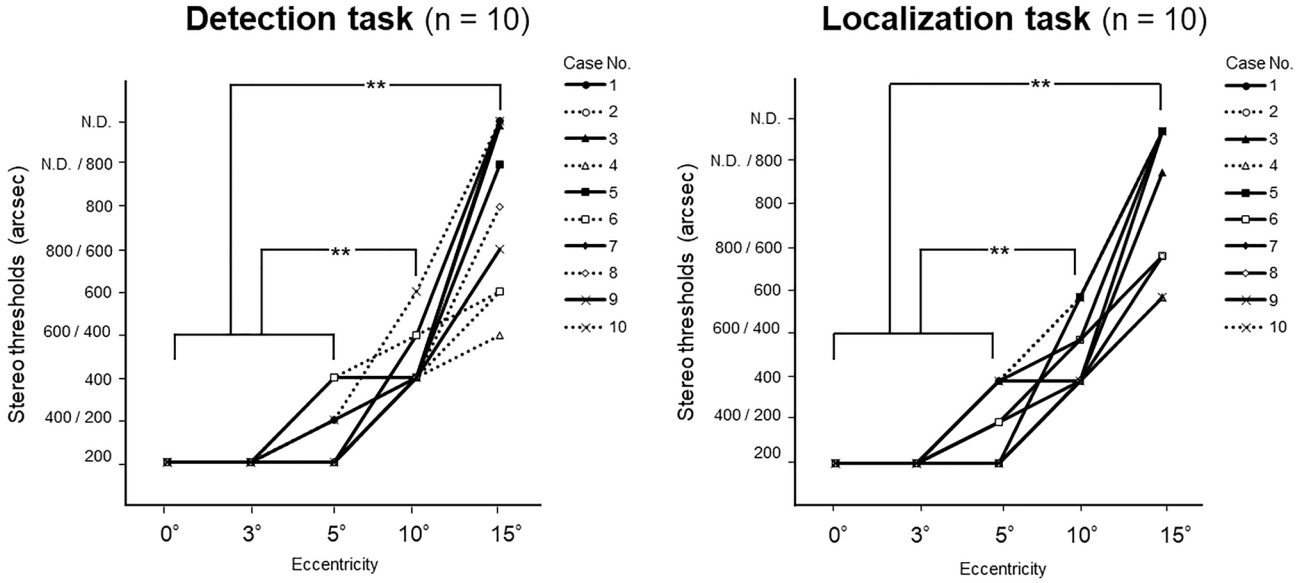

Fig. 3 The stereo threshold comparison among the five eccentricities. In the detection task, the subject fixates on the fixation target in the center and presses the response button when the circular target is detected in the paracentral visual field. In the localization task, the subject uses a joystick to indicate in which quadrant he or she has detected the circular target. N.D., not detectable. $^{**}P < 0.01$

differences were observed at 10° and 15° ($P < 0.01$ by the Kruskal-Wallis test and $P < 0.01$ by the Bonferroni/Dunn test).

The inter-individual threshold differences at the four eccentricities

At the fovea and 3°, no discernible inter-individual threshold differences in the two tasks were observed. However, the differences became more evident as the eccentricity increased. At 15°, the inter-individual threshold differences ranged from 400 arcseconds to "not detectable" (N.D.) and 4 of the 10 subjects showed undetectable for both tasks (Fig. 4).

Discussion

We have measured the stereo thresholds at the fovea and in the paracentral visual field using the binocular open perimeter *imovifa*® with the developed SEA program. The results show a significantly higher threshold with increasing eccentricity and a threshold of 800 arcseconds at 15°. Furthermore, the stereo thresholds for the detection and localization tasks did not significantly differ, indicating that a detection task alone would be sufficient

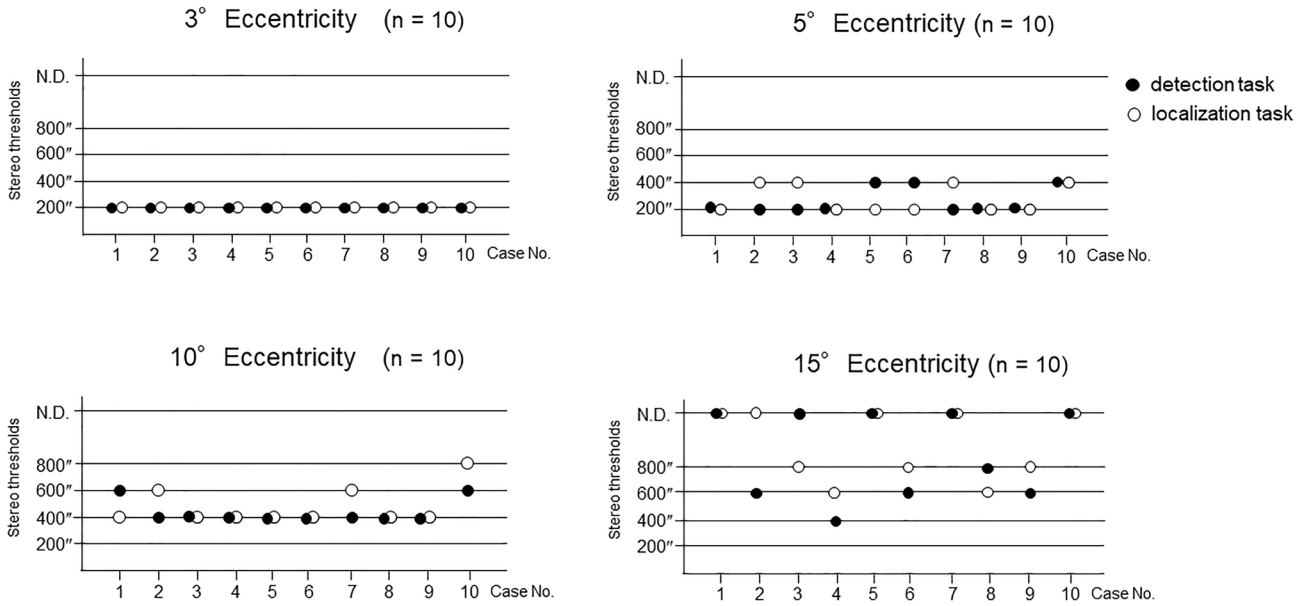

Fig. 4 The inter-individual threshold differences at the four eccentricities

for stereo threshold measurement. These results suggest that *imovifa*® with the introduced SEA program can be a feasible clinical method to evaluate stereoscopic vision.

Previous studies on peripheral stereopsis have conducted psychophysical experiments to investigate the relationship between eccentricity and stereo thresholds [15–19] and conclude that the stereo threshold is higher with increasing eccentricity. The threshold difference between the fovea and periphery becomes evident beyond the 10° periphery and can reach a level of 4-10 times depending on the experimental conditions [15–19]. Another study that used CyberDome to investigate peripheral stereopsis reports an average stereopsis of 725 arcseconds at 20° eccentricity [21]. Using a RDS target size that took account of the resolution difference between the foveal and paracentral visual fields, like those previously reported, the stereo threshold also increased with eccentricity in this study.

We reported that glaucoma patients' monocular sensitivities under monocular and binocular vision are different and that monocular sensitivity under binocular vision is affected differently by binocular interaction owing to the sensitivity disparity between both eyes [22]. This implies the possible effect of the sensitivity disparity on the establishment of stereopsis in these eyes. Currently, the clinical evaluation of stereopsis in patients with eye diseases is based on the results for the fovea. Because no method to evaluate stereopsis outside the fovea has been established, the effect of a disease on patient's paracentral stereopsis and the possible connection between the level of visual field loss and the stereo threshold are yet to be clarified. Paracentral stereopsis measured using the new method could provide information regarding these issues.

With the developed SEA program introduced in this study, stimuli with different magnitude of disparities could be presented at any location across the visual field. Furthermore, the use of RDSs helped eliminate monocular depth cues so that stereo thresholds solely based on binocular disparity could be measured. The subjects performed two tasks for paracentral threshold measurement: a simple detection task by pressing the response button and a more complicated localization task that required correct answers. The results showed no significant difference between the thresholds for these two tasks and a high correct answer rate of 97.2% for the more complicated localization task. These observations suggest that the detection task, easy for young children and the elderly, would be sufficient for threshold measurements. Considering the resolution differences between the central and paracentral visual fields, the target size was determined according to the tested eccentricity; spaces between the presented targets were also set to avoid overlapping in this study. This could eliminate the influence of the resolution difference as much as possible, as only the impact of eccentricity on the stereo threshold was evaluated.

We selected *imovifa*® as the device for the paracentral stereopsis measurement mainly for three reasons. First, the features of the separated optical systems and background displays for the left and right eyes and the test condition under fused binocular vision [20, 22] have rendered it well-suited for precise stereo threshold measurement. Second, *imovifa*® has already been established in clinical use as a perimeter for differential light thresholds. The integration

of the SEA program in this study enabled the seamless execution of both visual field and stereopsis assessments using the same device. Finally, it is difficult to detect monocular sensitivity reduction under binocular viewing because of the overlapped left and right visual fields. Stereopsis, which is affected in the regions corresponding to vision loss in either eye, provides a means for detecting a monocular sensitivity reduction even under binocular viewing. A stereo test within the 15º visual field may also serve as a screening tool for the early detection of glaucoma and provide an opportunity to shed some light on the impact of reduced paracentral stereopsis on patients' QOL. These all demonstrated the possible clinical values of a paracentral stereo test.

This study has several limitations. First, the bracketing method could not be applied to the threshold measurement owing to the unknown limit of the binocular disparity in the peripheral vision that could be detected by this device. The current results indicate that it requires a disparity larger than 800 arcseconds to test stereopsis at 15°. The limit of disparity has become clear and with the application of the bracketing method, the program can be further improved for better measurement accuracy. Second, the minimum disparity that could be presented with this device was 200 arcseconds, and thus, foveal stereopsis could have been underestimated. Since visual field testing did not include sensitivity measurements in this study, the presence/absence of the subject's visual field impairments could not be verified. To elucidate the correlation between the paracentral sensitivity and stereopsis will require further detailed investigation. Third, the factor of age was not examined in this study. Reportedly, stereopsis deteriorates after the age of 60 [23], and the ability for stereoscopic depth discrimination also varies in young people [24]. Further investigations regarding the factor of age will be necessary. Finally, the subjects in this study were visually normal participants. Based on the present findings, a quantitative method to assess paracentral and peripheral stereopsis in patients with various ocular diseases is of our future interest.

In conclusion, the paracentral stereo threshold is higher than the foveal threshold, and it decreases toward the periphery. The binocular open field perimeter *imovifa*® installed with the SEA program is a feasible clinical method for evaluating paracentral stereopsis.

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Declarations

Conflicts of interest A. Wakayama, None; C. Matsumoto, Consulting fees, payment or honoraria for lectures, presentations, speakers bureaus, manuscript writing or educational events (CREWT Medical Systems); K. Utamura, None; R. Narita, None; S. Kusaka, None.

References

1. Mireskandari K, Garnham L, Sheard R, Ezra E, Gregor ZJ, Sloper JJ. A prospective study of the effect of a unilateral macular hole on sensory and motor binocular function and recovery following successful surgery. Br J Ophthalmol. 2004;88:1320–4.
2. Asaria R, Garnham L, Gregor ZJ, Sloper JJ. A prospective study of binocular visual function before and after successful surgery to remove a unilateral epiretinal membrane. Ophthalmology. 2008;115:1930–7.
3. Verghese P, Tyson TL, Ghahghaei S, Fletcher DC. Depth perception and grasp in central field loss. Invest Ophthalmol Vis Sci. 2016;57:1476–87.
4. Okamoto F, Sugiura Y, Okamoto Y, Hiraoka T, Oshika T. Stereopsis and optical coherence tomography findings after epiretinal membrane surgery. Retina. 2015;35:1415–21.
5. Morikawa S, Okamoto F, Murakami T, Sugiura Y, Hiraoka T, Oshika T. Visual function affecting stereopsis in patients with branch retinal vein occlusion. Eye. 2022;36:457–62.
6. Bassi CJ, Galanis JC. Binocular visual impairment in glaucoma. Ophthalmology. 1991;98:1406–11.
7. Essock EA, Fechtner RD, Zimmerman TJ, Krebs WK, Nussdorf JD. Binocular function in early glaucoma. J Glaucoma. 1996;5:395–405.
8. Gupta N, Krishnadev N, Hamstra SJ, Yücel YH. Depth perception deficits in glaucoma suspects. Br J Ophthalmol. 2006;90:979–81.
9. Adhikari PG, Thapa M, Dahal M. Evaluation of depth perception and association of severity in glaucoma patients and suspects. BMC Ophthalmol. 2021;21:432.
10. Ramulu P. Glaucoma and disability: which tasks are affected, and at what stage of disease? Curr Opin ophthalmol. 2009;20:92–8.
11. Sawada H, Fukuchi T, Abe H. Evaliation of the relationship between quality of vision and the visual function index in Japanese glaucoma patients. Graefe's Arch Clin Exp Ophthalmol. 2011;249:1721–7.
12. Medeiros FA, Gracitelli CPB, Boer ER, Weinreb RN, Zangwill LM, Rosen PN. Longitudinal changes in quality of life and rates of progressive visual field loss in glaucoma patients. Ophthalmology. 2015;122:293–301.
13. Takahashi G, Otori Y, Urashima M, Kuwayama Y. Quality of life improvement committee: evaluation of quality of life in Japanese glaucoma patients and its relationship with visual function. J Glaucoma. 2016;25:e150–6.
14. Kunimatsu-Sanuki S, Iwase A, Araie M, Aoki Y, Hara T, Fukuchi T, et al. The role of specific visual subfields in collisions with oncoming cars during simulated driving in patients with advanced glaucoma. Br J Ophthalmol. 2017;101:896–901.
15. Rawlings SC, Shipley T. Stereoscopic acuity and horizontal angular distance from fixation. J Opt Soc Am. 1969;59:991–3.
16. Blakemore C. The range and scope of binocular depth discrimination in man. J Physiol. 1970;211:599–622.
17. Fendick M, Westheimer G. Effects of practice and the separation of test targets on foveal and peripheral stereoacuity. Vision Res. 1983;23:145–50.
18. Westheimer G, Truong TT. Target crowding in foveal and peripheral stereoacuity. Am J Optom Physiol Opt. 1988;65:395–9.
19. Ghahghaei S, McKee S, Verghese P. The upper disparity limit increases gradually with eccentricity. Vision Res. 2019;19:1–12.
20. Matsumoto C, Yamao S, Nomoto H, Takada S, Okuyama S, Kimura S, et al. Visual field testing with head-mounted perimeter 'imo.' PLoS ONE. 2016;11: e0161974.
21. Mochizuki H, Shoji N, Ando E, Otsuka M, Takahashi K, Handa T. The magnitude of stereopsis in peripheral visual fields. Kitasato Med J. 2012;42:1–5.

22. Wakayama A, Nomoto H, Chiba Y, Matsumoto C, Kusaka S. Effect of sensitivity disparity between the two eyes on pointwise monocular sensitivity under binocular viewing in patients with glaucoma. J Glaucoma. 2021;30:37–43.
23. Zaroff CM, Knutelska M, Frumkes TE. Variation in stereoacuity: normative description, fixation disparity, and the roles of aging and gender. Invest Ophthalmol Vis Sci. 2003;44:891–900.
24. Oishi H, Takemura H, Aoki SC, Fujita I, Amano K. Microstructural properties of the vertical occipital fasciculus explain the variability in human stereoacuity. PNAS. 2018;115(48):12289–94.