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Research article

# Factors affecting depth perception and comparison of depth perception measured by the three-rods test in monocular and binocular vision

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ABSTRACT

*Purpose:* The purpose of this study was to explore the effects of factors affecting depth perception of moving objects using a modified three-rods test, which can be used at longer distances than the conventional one, and to compare differences in the results between binocular and monocular vision.

*Methods:* This study included 24 volunteers (10 women, 14 men; mean age, 35.2 years; standard deviation, 6.8 years; range, 22–56 years). We measured depth perception using a modified three-rods test under eight different conditions and investigated the factors affecting depth perception using a linear-effect model.

*Results:* The results identified test distance, binocularity, masking, and direction of movement as significant factors affecting depth perception of a moving object.

*Conclusions:* The current study successfully determined factors affecting depth perception using the three-rods test with a moving object and the results should contribute to further clinical and social applications of the three-rods test.

## 1. Introduction

Depth perception is the ability to identify the three-dimensional spatial layout of objects and surfaces in our surroundings. The human visual system is sophisticated in its use of depth information and can integrate a number of cues, taking into account each cue's reliability and applicability for the current operational task. Sources of information for the detection of depth can be grouped into two categories: monocular cues (cues available from the input of just one eye) and binocular cues (cues that require input from both eyes). Binocular cues include binocular disparity and vergence. Monocular cues consist of static information including relative size, perspective, interposition, lighting, and focus cues (image blur and accommodation) as well as dynamic information such as motion parallax [1].

Binocular disparity, one of the most reliable cues to depth, refers to the difference in image location of an object seen by the left and right eyes resulting from the eyes' horizontal separation. When binocular disparity is unavailable, for example when one eye is patched, depth perception is strongly impaired. In such conditions, the defocus blur produced by an object out of an eye's plane of focus could potentially provide the visual system with the same information, since blur and disparity derive from the same geometry [2]. However, these cues likely operate over different ranges, and whether the visual system uses blur as a depth cue is debated [3, 4].

Driving tasks are characterised by dynamic situations in which moving vehicles are operated in an environment with both static and moving objects. Several vision-related tests are employed routinely for individuals to qualify for a driver's license [5, 6, 7, 8]. The three-rods test is used to examine depth perception, and it is used routinely to qualify for a driver's license in Japan in addition to visual acuity (VA) testing. The test examines a kind of dynamic stereopsis in response to a moving rod at 2.5 m. Previous reports have shown that the results of a commercially available three-rods test (Electric Depth Perception Tester, AS-7JS1, Kowa, Tokyo, Japan), which is used during drivers' tests in Japan, was correlated with those of the static stereopsis tests including the distance Randot stereotest, TNO, and Titmus Stereotests, although it is not as accurate as those ophthalmic tests [7]. The authors reported that the three-rods test might be an appropriate screening test of depth perception in the general population. However, a search of the PubMed® database by the National Center for Biotechnology Information on June 29, 2020, did not identify any report on how or to what extent the loss of depth cues

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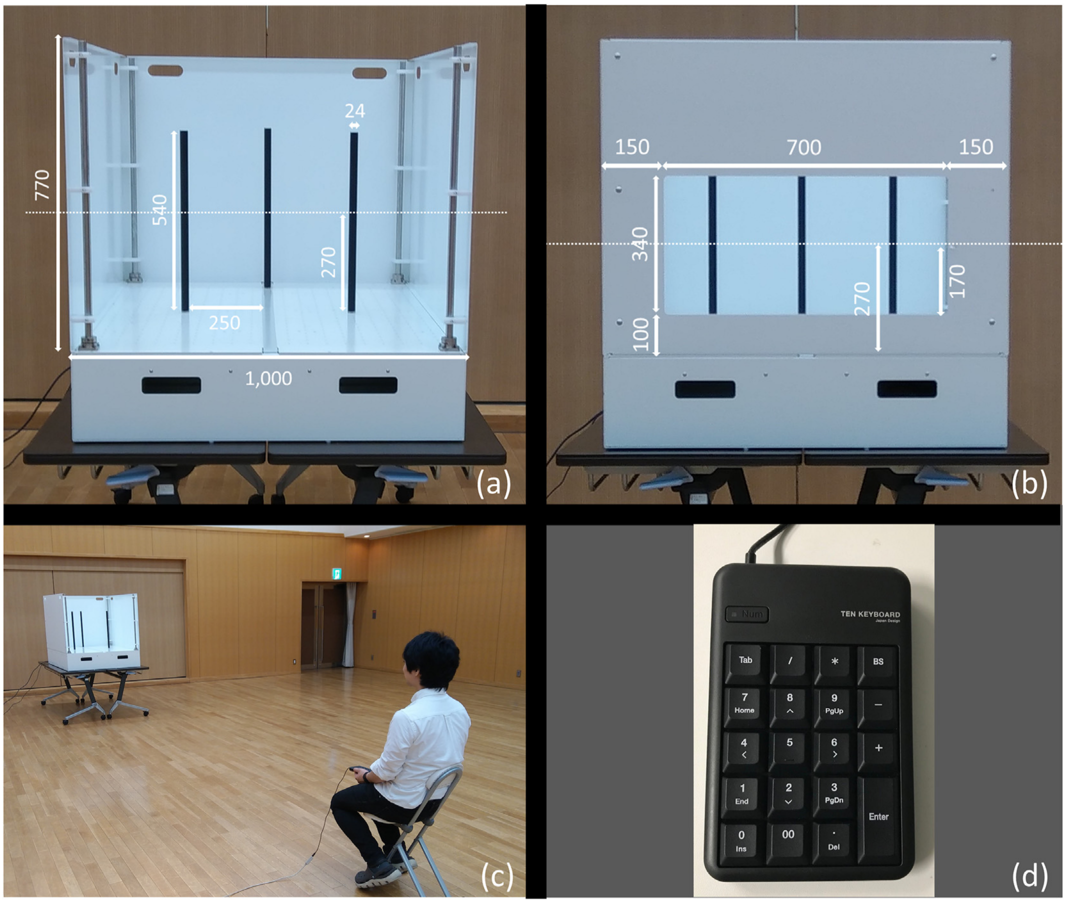


**Figure 1.** Photographs of our modified measurement system, with lengths expressed in millimetres. (a) The front view of the measurement system without masking of the ends of the central rod. The eye level of the participant is set at the dotted line. (b) The front view of the measurement system with masking. (c) The test scene under binocular conditions without masking. (d) The wired keypad. The enter key is used to stop the central rod.

affects the results of the three-rods test, although there are drivers in the real world with varying degrees of visual impairment.

In addition, the examination distance is fixed at 2.5 m in this test, which might be too close as a test distance for driver's vision. Considering this, we developed a modified three-rods test that is basically the same as the three-rods test used in previous studies except for the changeable test distance up to 20 m and explored the factors affecting depth perception measured using the three-rods test in normal subjects.

## 2. Participants and methods

### 2.1. Participants

The inclusion criteria were an active driver's license holder who drove in daily life at least four times/month, age over 19 years, and normal motor and visual function. The exclusion criteria were a best-corrected VA of 0.15 LogMAR or worse in both eyes, a Mini-Mental State Examination (MMSE) score less than 24 points, and near stereovision over 80 arcseconds.

### 2.2. Ethics statement

The Institutional Review Board and Ethics Committee of the Keio University School of Medicine approved this study (approval number, 20160382) and the methods were performed in accordance with the Declaration of Helsinki. All participants provided written informed consent. The study protocol was registered with the UMIN Clinical Trials Registry (UMIN000026519).

### 2.3. Visual function tests

Monocular and binocular distance visual acuities and binocular distance functional VA were measured with corrective lenses (eyeglasses, contact lenses, or none) that the participants used in their daily life. Functional VA is an average of VAs that were measured continuously for 60 s using a functional VA tester (AS-28, Kowa, Tokyo, Japan). The details of the measurement have been described previously; functional VA can reflect quality of vision more precisely than conventional VA in various situations [9, 10, 11, 12, 13, 14, 15]. The Stereo Fly test (Stereo Optical Company, Inc., Chicago, IL, USA), performed at a distance of 40 cm was used to evaluate near stereopsis. The Rosenbach test was used to easily determine the dominant eye. The test procedure was as follows. First, the examinees were instructed to extend their arms in front of them and created a triangular opening between their thumbs and forefingers by placing their hands together at a 45-degree angle. Second, with both eyes open, they were instructed to center this triangular opening on a distant object, such as a wall clock or a door knob. Third, they were instructed to close their left eye. If the object remained centered, their right eye (the open eye) was their dominant eye. If the object was no longer framed by their hands, their left eye was the dominant eye.

**Table 1.** Patient profiles (n = 24).

| Parameter | Mean ± SD |
|---|---|
| Age (y) | 35.2 ± 6.8 |
| Female sex, n (%) | 10 (41.7%) |
| Dominant eye, right, n (%) | 17 (70.8%) |
| UDVA (logMAR), | |
| Dominant eye | 0.62 ± 0.53 |
| Non-dominant eye | 0.65 ± 0.55 |
| CDVA (logMAR) | |
| Dominant eye | -0.16 ± 0.03 |
| Non-dominant eye | -0.14 ± 0.05 |
| Subjective refraction (spherical equivalent) (D) | |
| Dominant eye | -2.703 ± 1.987 |
| Non-dominant eye | -2.609 ± 2.148 |
| Subjective astigmatism(D) | |
| Dominant eye | -0.594 ± 0.477 |
| Non-dominant eye | -0.760 ± 0.701 |
| Titmus stereo test | In all participants, |
| Fly | (+) |
| Animal | 3/3 |
| Circle | 9/9 |
| Binocular fuunctional visual acuity (logMAR) | -0.03 ± 0.10 |
| MMSE | 29.6 ± 0.6 |

D, diopters.
UDVA: uncorrected distance visual acuity.
CDVA: corrected distance visual acuity.
MMSE: Mini Mental State Examination.

### *2.4. Cognitive function*

The Japanese version of the MMSE (MMSE-J, Nihon Bunka Kagakusha Co., Ltd.) was used to evaluate cognitive function.

### *2.5. Evaluation of depth perception using the modified three-rods test*

Depth perception was measured using our modified measurement system, which is comprised of three vertical rods that are 24 mm in diameter and 540 mm long (Figure 1a, b).

The design and structure of the system were basically the same as the three-rods test used previously [6]. Due to the viewing distance being greater than in the standard three-rods test, the apparatus was scaled up in size so that it would have the same optical size (at a maximal distance of 20 m) as the apparatus in the standard three-rods test. The structure and size of the system are shown in Figure 1. The two peripheral rods are fixed on the floor at the same distance from the participant, and the central rod moves toward and away from the participant at a speed of 50 mm/s. The top and bottom ends of the central rod can be hidden from the participant with a fenestrated panel. We defined the measurements without the fenestrated panel as an unmasked condition (Figure 1a). In contrast, the measurement performed using the panel was defined as a masked condition (Figure 1b). We also defined binocular measurements as a binocular condition and monocular measurements as a monocular condition.

The participants kept their heads straight and still without the heads being fixed ans sat on a chair at distances of 2.5, 5.0, 10.0, 15.0, and 20.0 m from the line linking the two peripheral rods. The height of each participant's eyes was aligned 270 mm from the floor of the measurement box by adjusting the chair height, so that the eyes were level with the vertical center of the central rod. Each participant wore earplugs during measurements to avoid hearing any sound cues. The central rod started to move at a distance set randomly between 250 and 500 mm from the extension line of the two peripheral rods, from the examinee's side or the other side. All experiments were performed in a gymnasium with the air-conditioning set at a comfortable level and illumination brighter than 370 lux.

The direction of movement of the central rod was announced before each examination and the participants were instructed to push a button to stop the central rod when they recognised that it had reached the same distance as the two peripheral rods; the test can be performed by observing the point at which the top and bottom of the three bars aligned. After three practices, each participant completed the task for six measurements for three trials in each direction. The minimal distance from the central rod to the line linking the two peripheral rods then was recorded (Figure 1c, d). The measurements were obtained under eight conditions: unmasked binocular vision, masked binocular vision, unmasked monocular vision, and masked monocular vision, all done for both directions of movement (toward and away from the participant). Measurements obtained during each of the eight conditions were repeated at distances of 2.5, 5.0, 10.0, 15.0, and 20.0 m.

### *2.6. Statistical analysis*

The values are expressed as the means ± standard deviations unless otherwise specified. The error distances and test distances were converted to logarithmic values for the statistical analyses because the error distances were not normally distributed. Median values were compared using the Wilcoxon signed-rank test, conducted using IBM SPSS Statistics Version 24 software (Armonk, NY, USA).

The factors affecting error distances were estimated by a linear mixed effect model, conducted in SAS Version 9.4 (Cary, N.C., USA). Age, sex, test distance, binocular functional VA, direction of movement of the central rod and use of masking were treated as fixed effects, and each participant was treated as a random effect, to obtain point estimates and 95% confidence limits. The binocular VA and the dominant eye and nondominant eye VAs were not used because of multicollinearity. The correlation structure was assumed to have compound symmetry.

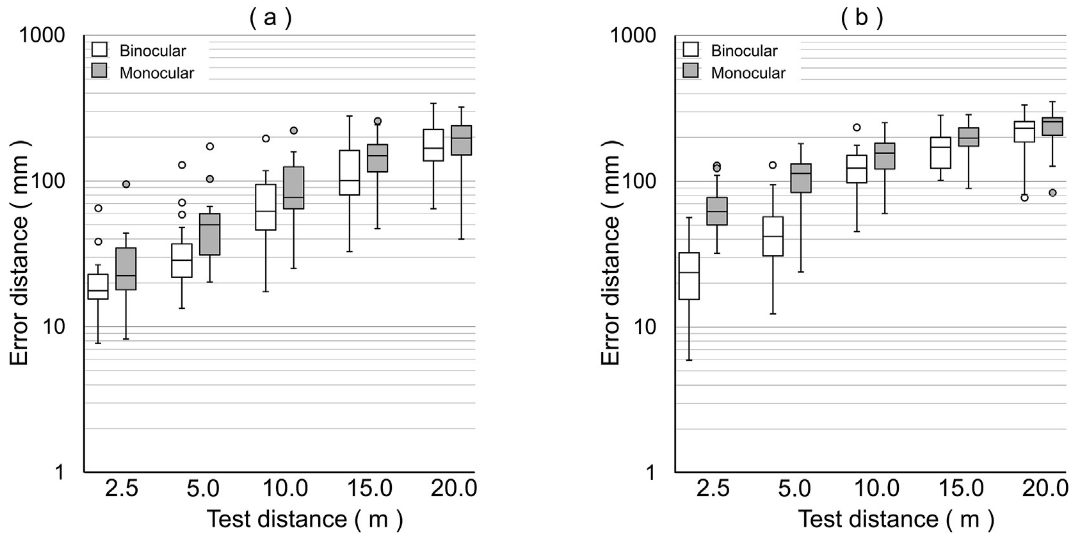


**Figure 2.** Comparison of error distances between binocular and monocular vision under unmasked (a) and masked (b) conditions. The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, 25th and 75th percentiles, and 1.5 times the interquartile range from the median, respectively. The dots indicate outliers.

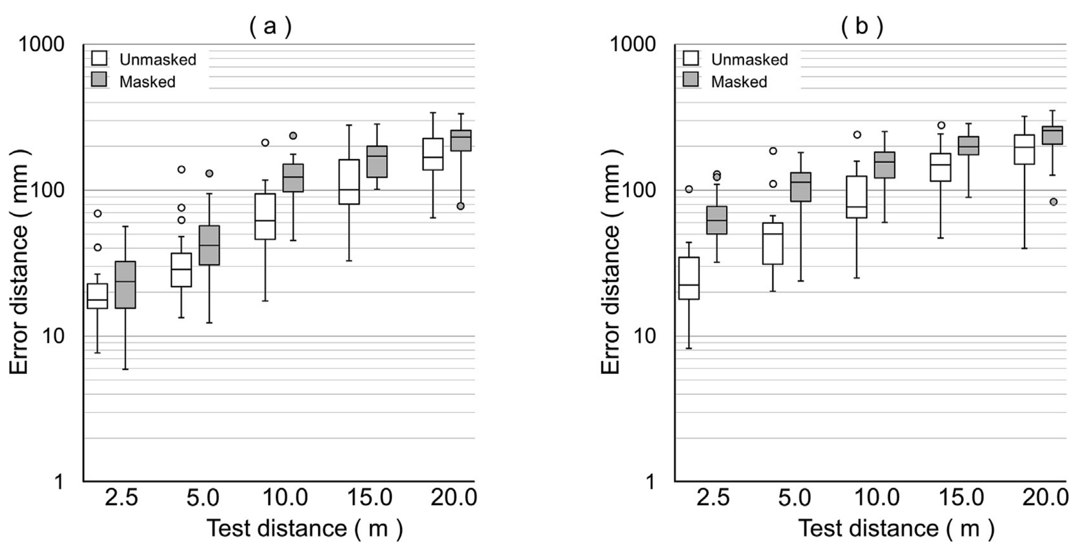


**Figure 3.** The effects of masking that hid the upper and lower ends of the central rods under binocular (a) and monocular (b) conditions. The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, 25th and 75th percentiles, and 1.5 times the interquartile range from the median, respectively. The dots indicate outliers.

The same analyses were performed after normalizing the error distance data for the test distance. The level of significance was set at $P < 0.05$.

## 3. Results

### 3.1. Participants and results of visual and cognitive function tests

This study included 24 volunteers (10 women, 14 men; mean age, 35.2 years; standard deviation, 6.8 years; range, 22–56 years). The participant profiles and the results of visual and cognitive function tests are shown in Table 1.

### 3.2. Factors affecting depth perception

Figures 2, 3, and 4 show participant errors in depth judgements, as a function of test distance, broken down by different conditions, whereas Table 2 summarizes our analysis of the factors affecting the errors in depth judgments using a linear mixed effect model. In this table, the standardized regression coefficients associated with each independent variable give us a measure of how strongly the variables influenced the depth judgments. This analysis shows that test distance was the most relevant factor affecting depth judgements. As seen in all panels of Figures 2, 3, and 4, errors increase with test distance in all conditions. Note however that this is due to the geometry of image formation on the retina, and that if we normalize the error data by the test distance, relative depth errors remain approximately constant across test distance (Figures 5, 6, and 7).

Binocularity, presence of masking, and the direction of movement were all factors also strongly related to errors in depth judgements. Figure 2 shows how the error distance was consistently greater in the monocular condition compared to the binocular condition. This makes sense, since in the monocular conditions participants cannot make use of binocular disparity. Similarly, Figure 3 shows how errors were

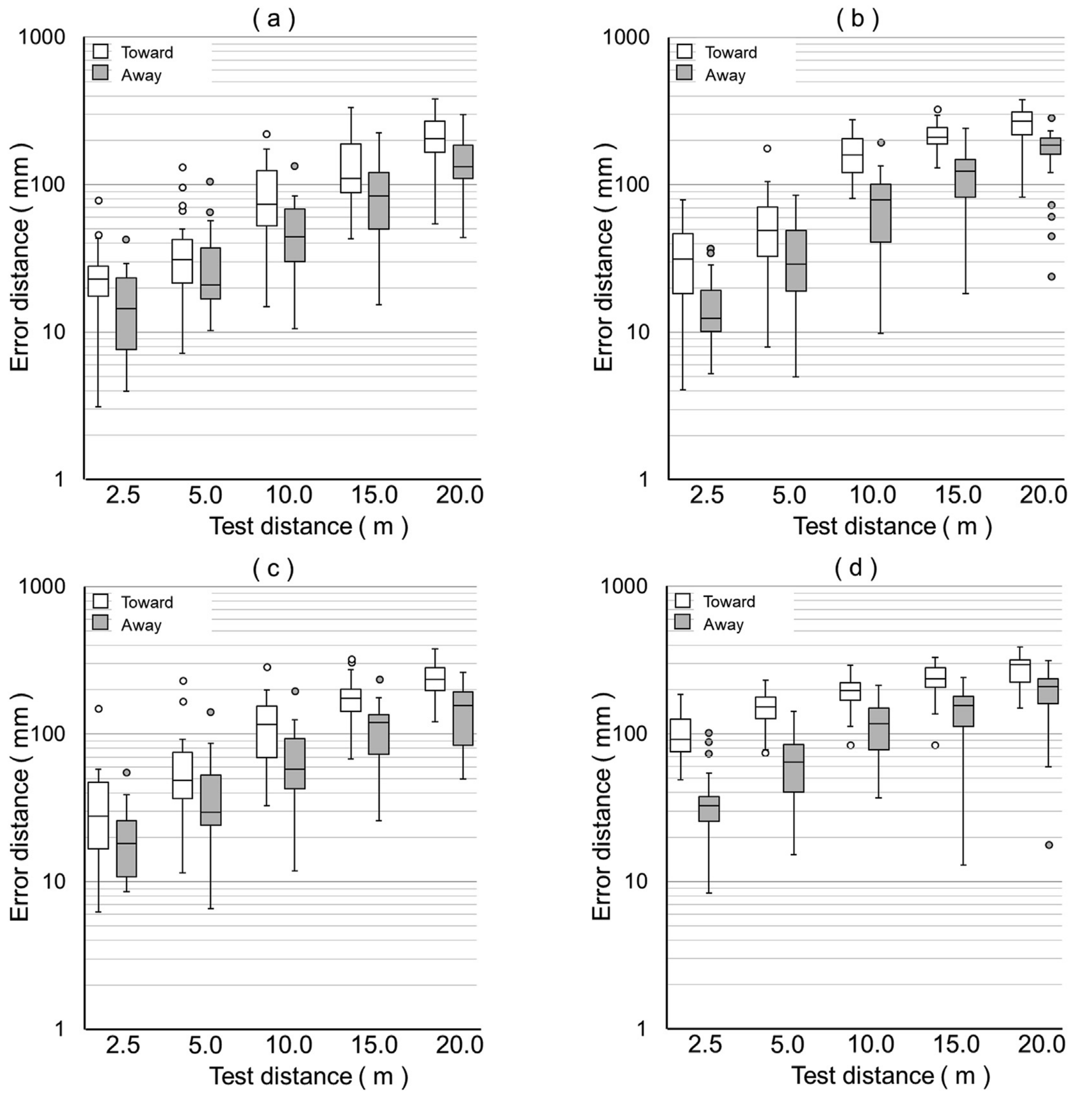


**Figure 4.** Comparison of error distances according to the direction of movement of the central rod under four conditions: binocular vision without masking (a), binocular vision with masking (b), monocular vision without masking (c), and monocular vision with masking (d). The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, 25th and 75th percentiles, and 1.5 times the interquartile range from the median, respectively. The dots indicate outliers.

**Table 2.** Factors affecting the errors in depth judgements using a linear mixed effect model.

| Independent variable | Regression coefficient | Standard error | Standardized regression coefficients | F value | P value |
|---|---|---|---|---|---|
| Age (Years) | -0.016 | 0.009 | -1.878 | 3.527 | 0.076 |
| Sex[†] | -0.361 | 0.147 | -2.453 | 6.019 | 0.024 |
| Test distance [m] | 0.121 | 0.003 | 47.695 | 2274.788 | <0.001* |
| Monocular versus binocular[‡] | -0.424 | 0.033 | -13.035 | 169.919 | <0.001* |
| Masked versus unmasked[§] | -0.509 | 0.033 | -15.643 | 244.719 | <0.001* |
| Direction of movement of the central rod[¶] | -0.606 | 0.033 | -18.601 | 345.997 | <0.001* |
| Binocular DFVA | 1.263 | 0.559 | 2.258 | 5.098 | 0.036 |

*P < 0.05.
DFVA = distance functional visual acuity.
[†] Female = 0, Male = 1.
[‡] Monocular = 0, Binocular = 1.
[§] Masked = 0, Unmasked = 1.
[¶] Toward participant = 0, Away from participant = 1.

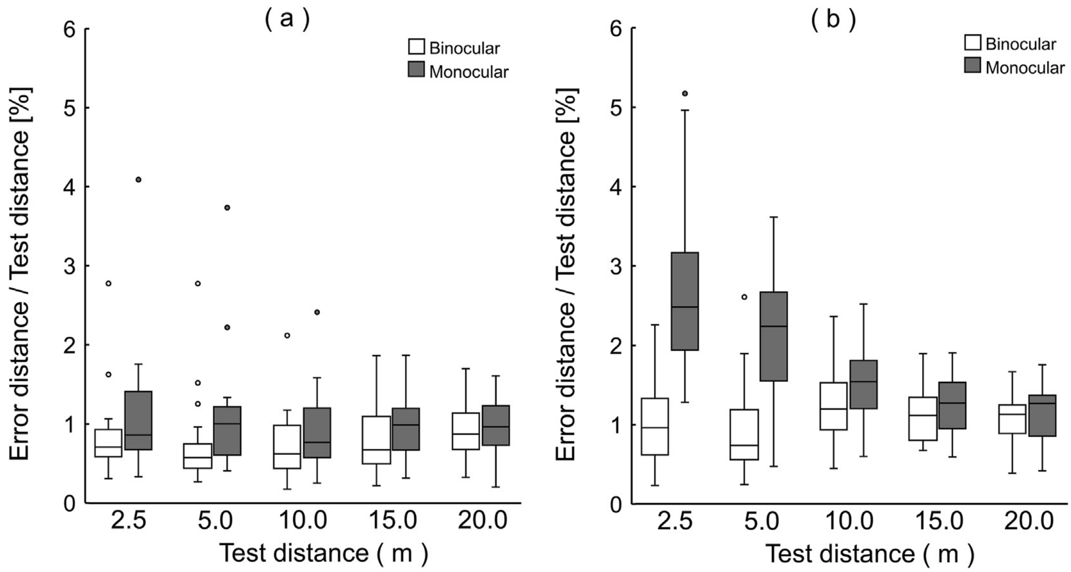


**Figure 5.** Comparison of error distances divided by each test distance between binocular and monocular vision under unmasked (a) and masked (b) conditions. The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, 25th and 75th percentiles, and 1.5 times the interquartile range from the median, respectively. The dots indicate outliers.

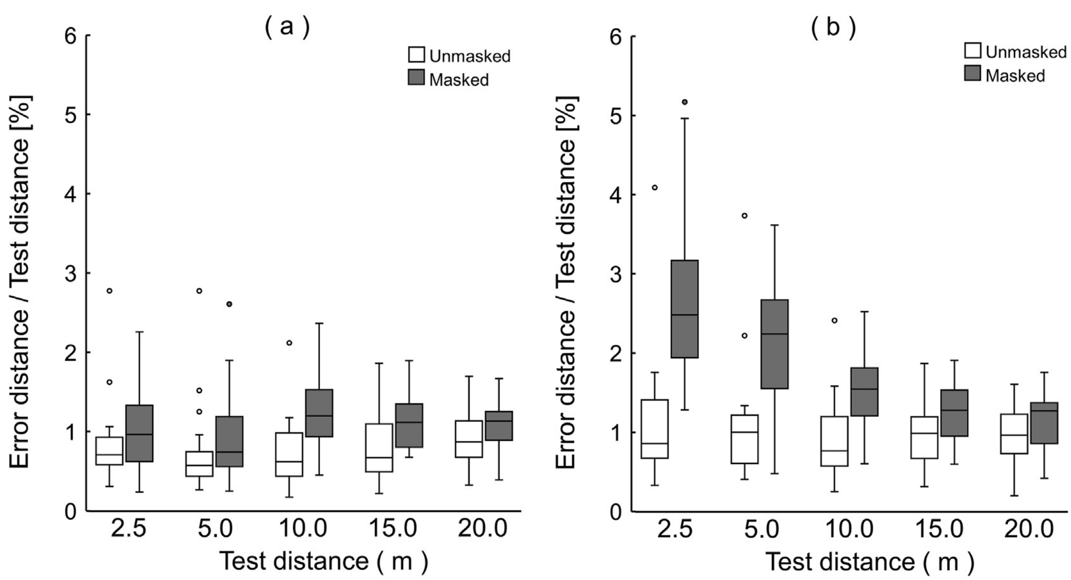


**Figure 6.** Effects of masking that hide the upper and lower ends of the central rods under binocular (a) and monocular (b) conditions compared by error distances divided by each test distance. The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, 25th and 75th percentiles, and 1.5 times the interquartile range from the median, respectively. The dots indicate outliers.

consistently greater in the masked condition compared to the unmasked condition, likely because participants could not base their judgments on whether the top and bottom of the bars were aligned. Finally, Figure 4 shows that depth errors were consistently greater when the target was moving toward the subject and smaller when the target moved away from the subject.

In the linear mixed-effect model, participant sex and binocular distance functional VA were also significantly related to depth errors, although the standardized regression coefficients of those factors were much smaller than those of the four major. More specifically, male sex, and better binocular distance functional VA were associated with smaller errors.

## 4. Discussion

We found that test distance, binocularity, masking, and direction of the moving target were important factors for depth perception measured using a three-rods test at a longer distance compared with the conventional method.

There are many visual sources of information about depth [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. It has become important to understand what information each cue can provide within a particular operational context and how useful that cue is in collaboration with other cues.

In the current study, the test distance significantly affected the error distance. This is for the most part due to the geometry of image formation on the retina, and we've shown that the ratio of depth errors to test

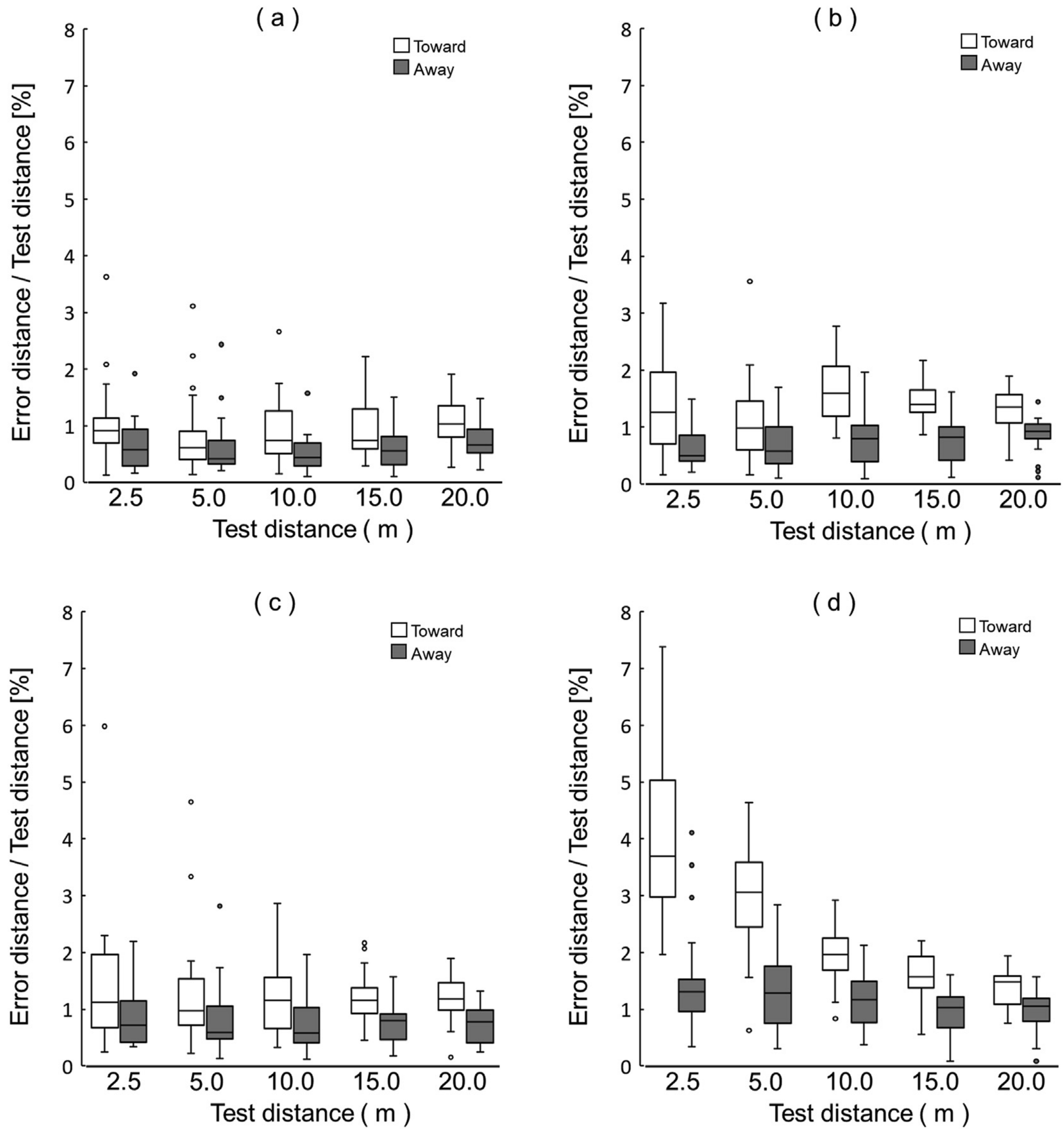


**Figure 7.** Comparison of error distances divided by each test distance according to the direction of movement of the central rod under four conditions: binocular vision without masking (a), binocular vision with masking (b), monocular vision without masking (c), and monocular vision with masking (d). The horizontal lines in each box plot, top and bottom ends of each box plot, and error bars indicate the median, 25th and 75th percentiles, and 1.5 times the interquartile range from the median, respectively. The dots indicate outliers.

distance remains approximately constant across test distances (Figures 5, 6, and 7).

In the current results, male sex and better distance functional VA were associated with less error distance, although the effects of those factors were small. The distance functional VA was expected to be correlated with task performance, such as driving performance [20]. However, no reasonable explanation could be found for the effect of sex, which warrants further investigation in a future study.

The effect of binocularity has been the most thoroughly investigated [1, 9, 10, 13, 15, 16, 17] previously. McKee and Taylor [16] measured binocular and monocular depth thresholds for separating a pair of metal rods presented at 1.22 m and concluded that binocular thresholds were markedly superior to the monocular thresholds in the isolated setting of the target objects. Allison et al. [21] compared monocular and binocular performance on depth-interval estimation and discrimination tasks, at distances of 4.5, 9.0, and 18.0 m and found that binocular vision can significantly improve the accuracy and precision of depth estimation up to 18.0 m. McCann et al. [22] reported that thresholds for binocular viewing were small at all distances and those for monocular viewing were higher than those for binocular viewing at distances of between 15.0 and 20.0 m, beyond which they were similar, while Palmisano et al. [23] reported larger binocular estimates of depth with a lit foreground than in darkness, and further increases as the observation distance increased from 20.0 to 40.0 m. Those studies were conducted for static objects. The three-rods test used in this study has been reported to examine a kind of dynamic stereopsis in response to a moving rod and also to analyse the speed of response by eye-hand coordination to push a button to stop the moving rod. Regarding the validity of the three-rods test, Matsuo et al. previously reported that this test was reproducible and feasible enough for an appropriate screening test of depth perception in the general population, although it is not as accurate as stereo tests used in an ophthalmic practice [7]. The authors also reported that the three-rods test had a better correlation with functional VA tested with both eyes open [6]. Similarly, we also find a relationship between binocular distance functional VA and performance on the modified three-rods test employed in our study.

Our study had limitations. First, the width of the rods was designed in proportion to the conventional three-rods test at 20 m, and the size of the rods was relatively greater at other smaller test distances. In addition, the target speed was too slow considering real driving situations, because it was set at the same speed as the three-rods test used during the driving test in Japan. Second, our results only provided information for viewing distances up to 20.0 m, and results for greater distances would more accurately reflect real-life settings such as that during driving.

## 5. Conclusions

We developed a modified three-rods test with changeable test distances up to 20 m and successfully determined factors affecting depth perception with a moving object, namely, test distance, binocularity, masking, and direction of movement. The results should contribute to further clinical and social applications of the three-rods test.

## Data availability

The anonymized datasets generated during and/or analyzed during the current study are available from the corresponding author if the Ethics Committee of the Keio University School of Medicine provides permission to release the data.

## Declarations

### *Author contribution statement*

I. Iehisa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

K. Negishi: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

M. Ayaki: Analyzed and interpreted the data; Wrote the paper.

K. Tsubota: Analyzed and interpreted the data.

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This work was supported by Hitachi Automotive Systems, Ltd.

### *Competing interest statement*

The authors declare the following conflict of interests: K. Tsubota holds the patent rights for the methodology and the apparatus for the measurement of the functional VA (US patent no. 7470026).

### *Additional information*

No additional information is available for this paper.

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