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Visual field asymmetries in visual word form identification

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ABSTRACT

Visual performance across the visual fields interacts with visual tasks and visual stimuli, and visual resolution decreases as a function of eccentricity, varying at isoeccentric locations. In this study, we investigated the extent of asymmetry and the rate of change in visual acuity threshold for visual word form (VWF) identification at horizontal and vertical azimuths across the fovea, and at eccentricities of 1°, 2°, 4°, 6° and 8° for 10%, 20%, 40%, and 80% contrast levels, to determine whether and how the eccentricities, meridians, and contrasts modulated the VWF identification acuity threshold. The stimuli were 16 traditional Chinese characters of similar legibility. Participants pressed a key to indicate the character presented, either monocularly or binocularly, at one of 21 randomly selected locations. A staircase procedure was used to determine the threshold, and a multiple linear regression model was used to fit the linear cortical magnification factor (CMF). We found that (1) the asymmetry was most pronounced on the vertical and superior azimuths, (2) the asymmetry between the right and left azimuths was not significant, (3) the CMF was significantly smaller on the vertical azimuth than on the horizontal azimuth, (4) the CMF was smaller on the superior vertical azimuth than on the inferior azimuth, and (5) monocular viewing and low contrast enhanced the CMF difference between azimuths. In conclusion, vertical and horizontal azimuths, location of eccentricity, contrast levels of word symbols, and monocular/binocular viewing have different effects on visual field asymmetry and cortical magnification factors.

1. Introduction

Visual word identification is essential for reading. It depends on central vision, including the fovea, which encompasses the central 2° of the visual field, to perceive fine details of the word, and the parafoveal regions of the retina, which extend approximately from 2 to 5 degrees to the right or left side of fixation, to support and facilitate word identification in a normal observer (Rayner, 1975, Veldre, Reichle, Yu, & Andrews, 2023a). However, low vision people with a central scotoma due to anterior and/or posterior visual pathway deficits have to adopt either an eccentric retinal location or the preferred retinal locus (PRL) for visual word identification (Crossland, Culham, Kabanarou & Rubin, 2005, Trauzettel-Klosinski & Reinhard, 1998). For example, patients with age-related macular degeneration develop a PRL that is most commonly located in the nasal and superior quadrants of the retina, and less in the inferior and temporal quadrants (Erbezci & Ozturk, 2018, Sunness & Applegate, 2005). The distance between the PRL and the fovea can be up to 13 degrees or more (Erbezci & Ozturk, 2018). Therefore, patients with central scotoma may need to use superior, inferior, or beyond parafoveal retinal regions to identify visual words. Thus, understanding the factors and how they affect word recognition beyond the fovea would be important from a clinical perceptive.

Visual acuity and eccentricity play crucial roles in determining word recognition abilities beyond the fovea (Veldre, Reichle, Yu, & Andrews, 2023b). Human visual performance, including visual acuity, for the same stimulus deteriorates with retinal eccentricity in a variety of visual tasks due to degraded spatial sampling in cones, ganglion cells, and neurons of visual cortex (Levi, Klein & Aitsebaomo, 1985, Levi, Klein & Aitsebaomo, 1984, Strasburger, Rentschler & Juttner, 2011). However, if one scales the size of visual stimuli with eccentricity, the performance for visual stimuli in the peripheral visual field will be similar to that in the fovea (Strasburger et al., 2011). This scaling factor is called the cortical magnification factor (*M*), defined as the area of the primary visual cortex activated by a stimulus in one degree of visual angle (Daniel & Whitteridge, 1961). Directly measuring *M* in humans is complex, as another common and psychophysically based scaling factor,

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E_2, which represents the eccentricity (E) that a stimulus diameter has to be doubled to maintain similar foveal performance (Beard et al., 1997), is usually substituted to characterize the relationship between visual performance and its connection to the spacing of anatomical units (Beard, Levi & Klein, 1997, Levi et al., 1985, Levi et al., 1984).

In addition to visual acuity and eccentricity, visual performance also depends on the quadrant of the visual field the stimulus is projected to (Veldre, et al., 2023). At the same eccentricity, visual performance is usually better along the horizontal meridian (HM) than along the vertical meridian (VM) (horizontal–vertical anisotropy/HVA), and better along the lower vertical meridian (LVM) than along the upper vertical meridian (UVM) (vertical meridian asymmetry/VMA) (Barbot, Xue & Carrasco, 2021, Carrasco, Talgar & Cameron, 2001, Himmelberg, Winawer & Carrasco, 2020, Karim & Kojima, 2010, Rubin, Nakayama & Shapley, 1996). These visual perceptual asymmetries across the visual fields are presented in numerous visual tasks that assess the spatial resolution and contrast sensitivity of the visual system (Barbot et al., 2021, Himmelberg et al., 2020), but they are much smaller in some other tasks, such as orientation discrimination (Fuller, Rodriguez & Carrasco, 2008). As a result, the extent of eccentricity effects and visual field asymmetry varies with task demand. Understanding these asymmetries and the influence of visual tasks could be important for developing visual tests and visual rehabilitation programs for people with problems in spatial vision (Kerkhoff, 2000, Tsai, Liao, Jang, Hu & Wu, 2016).

Whereas perceptual asymmetries have been investigated in numerous studies (Barbot et al., 2021, Beard et al., 1997, Fuller et al., 2008, Strasburger et al., 2011), little is known about the effect of perceptual asymmetries on visual word form (VWF) identification. Although an advantage of the right visual field over the left visual field for letter and word stimuli has also been observed in some studies (Josse & Tzourio-Mazoyer, 2004, Veldre, et al., 2023), most studies of peripheral vision have been based on the detection or discrimination of simple visual stimuli (Strasburger et al., 2011), or have presented stimuli on either one or two of meridians. These findings provide only a limited explanation of how a complex visual word is processed across different meridians and eccentricities. However, VWF identification is a fundamental ability for reading, so understanding how VWF identification changes as a function of meridians and eccentricity would be helpful in vision rehabilitation for people with central scotoma or central visual field deficits.

In this study, we presented Chinese characters of similar legibility (Tsai, Jang, Liao & Chen, 2019) to evaluate how visual performance of VWF identification varies in terms of acuity threshold at different iso-eccentric locations along the vertical and horizontal azimuths. Furthermore, during reading, the text will have different contrasts or the same reading material will have different levels of contrast at different ambient luminance. Therefore, another aim of the present study was to investigate whether variations in contrast levels— characters presented at high, medium, and low contrast levels—across the visual fields could be a potential factor affecting the visual performance fields. The manipulation of contrast levels of complex characters, rather than conventional high-contrast and simple optotypes, to measure the performance fields was employed in this study to provide a framework for how people identify characters in the center and periphery, highlighting the importance in clinical application (Tsai et al., 2016). In addition, in clinical conditions, some patients will only reserve the function of one eye or inhibit the function of the other eye to gain better binocular vision, so we also investigated how E_2 changes with eccentricity in monocular and binocular viewing conditions. Given the complexity of visual stimuli that influence perceptual asymmetry (Strasburger et al., 2011), we hypothesized that both HVA and VMA would become more pronounced in VWF identification with increasing eccentricity and decreasing contrast levels. Finally, this study describes the calculation of psychophysically based cortical magnification E_2 in VWF identification.

2. Material and methods

2.1. Participants

Five participants (3 females, 2 males, mean ages 29.2 ± 4.3 years) participated this study. All participants were recruited from the National Taiwan University campus and had experience in psychophysical experiments. The monocular and binocular visual acuity of the participants were normal or corrected to normal (20/25 or better). None of them had known ocular problems that could affect visual performance. All procedures were reviewed and approved by the Institutional Review Board of the Taipei City Hospital, and all tests were conducted in accordance with the tenets of the Declaration of Helsinki. Informed consent was obtained from each participant when they understood the procedures of this study.

2.2. Apparatus

Visual stimuli were displayed on a ViewSonic monitor (G90fB 19″) driven by a MacBook Pro with an Intel HD Graphics 3000 display card. The stimuli were generated by Psykinematix software with the Mono 10.8 bits bit-stealing method to reach 10-bit contrast resolution (Beaudot, 2009). The gamma correction was performed with the Psykinematix software and Eye-one Display 2 together. The monitor resolution was 1280 (H) x 1024 (V), and the refresh rate was 85 Hz.

2.3. Visual stimuli

The stimuli consisted of five groups of traditional Chinese characters. Each group contained 2 to 3 characters. In total, 15 characters of similar legibility were used in the experiments. The characters in each group had similar spatial configurations and stroke densities (Table A1 in Appendix). Stroke density was defined as the ratio of the number of pixels in the strokes to the number of pixels in the character image. These characters were evaluated using three methods (the contrast thresholds for character identification, the patterns of confusion matrices, and the pixel ratios of the bitmap images) to verify that they were similar in legibility (Tsai et al., 2019).

As shown in Fig. 1, the visual display consisted of a circular aperture window with a radius of 12 degrees and luminance of 90 cd/m^2, while the background luminance outside the circular aperture was 73 cd/m^2, and a black fixation cross (0.2° × 0.2°; < 1 cd/m^2) presented in the center of the screen. During the measurement, one of the 15 characters was randomly selected and presented at a random test location. The total of 21 test locations included the fovea and the 1°, 2°, 4°, 6° and 8° eccentric locations on the upper, lower, right, and left (or nasal and temporal in the monocular condition) azimuths. This design allowed measurement of VWF identification performance as a function of acuity threshold in the units of degree of visual angle (DVA) at the fovea and 20 isoeccentric locations. The initial character sizes for the psychophysical measurements at different eccentric locations were different. The sizes were 0.5 degree of visual angle at the fovea and 0.7, 0.9, 1.2, 1.5, and 1.8° visual angles at the 1°, 2°, 4°, 6° and 8° eccentric locations, respectively. Participants viewed the display at a distance of 50 cm with their head position stabilized by a chin rest.

2.4. Procedure

Prior to the experiment, participants were given sufficient time to familiarize themselves with the test characters. Participants then sat in a darkened room for 3 min to adapt to the luminance of the room before the practice trials began. Since performance in peripheral vision is highly influenced by practice (Levi et al., 1985), participants were given approximately one hour of practice to achieve stable performances in both the monocular and binocular viewing conditions.

Characters were presented at one of four contrast levels: 10 %, 20 %,

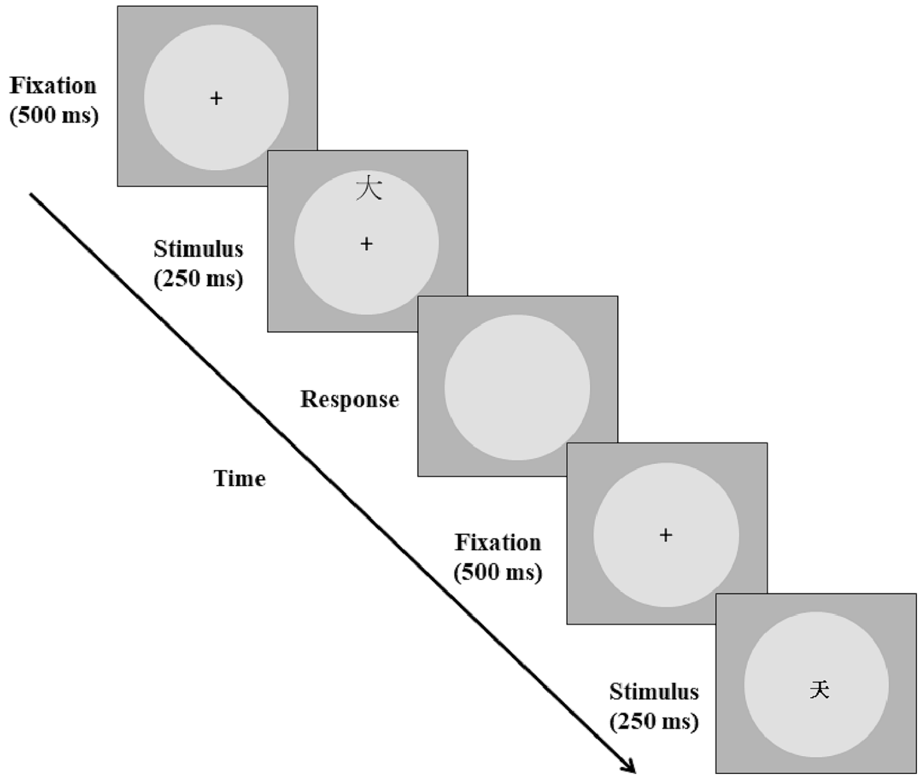

Fig. 1. Trial sequence.

40 %, or 80 %. There were three runs for each contrast condition, for a total of 12 runs for the entire experiment (3 runs x 4 contrast levels = 12 runs). Each run contained 21 interleaved staircases for all of the 21 locations across the vertical (superior and inferior) and horizontal (right and left, or nasal and temporal) azimuths. Each participant performed all 12 runs binocularly and then the other 12 runs monocularly on different days. In the monocular conditions, stimuli were presented only to the dominant eye as determined by the Miles test (Miles, 1930).

Fig. 1 depicts the trial sequence. In each trial, the duration of stimulus presentation was 250 ms, which was deemed sufficient for participants to identify the characters while minimizing the influence of saccadic eye movement (Chan & Lee, 2005, Trauzettel-Klosinski, Biermann, Hahn & Weismann, 2003). The task of the participant was to fixate at the central fixation point and to press a key to indicate the character they perceived. The 15 different characters were labeled on a standard computer keyboard. These characters were arranged in close proximity based on their similarity in configuration. The arrangement of the 15 characters on the keyboard began at the left side of the A and Z keys and extended to the right side, ending at the K and M keys. Prior to the start of the formal experiment, all participants were required to familiarize themselves with the positions of the characters on the keyboard. In addition, participants were instructed that if they should look at the keyboard during the task, they had to refocus their eyes on the fixation point on the screen before button pressing.

After key pressing, the next trial would begin after a 500 ms interval, in which a fixation point was presented at the center of the screen. Throughout the experiment, the participants were instructed to fixate on the fixation point at all times and to avoid eye movements when the stimulus was presented. Auditory feedback was given to indicate correct or incorrect responses after each response.

Character acuity thresholds for the 21 locations were measured with an interleaved multiple 3 down–1 up staircase procedure; i.e., character size was decreased after three correct responses and increased after one wrong response. The relative size decrement rate was 50 % of the current size before the first reversal and 12.5 % after that. The size increment rate was always 25 %. The staircase for each location was terminated after 6 reversals. The initial character size of the staircase depended on the eccentricity. The acuity threshold for each run was calculated as the average of the last five reversals. At each location, the threshold measurement was repeated three times. We reported the average of the three repetitions.

Participants performed a VWF identification task. First, participants were presented with a central cross to assist fixation throughout the trial. When the character was presented on the central cross, the fixation point would disappear. Note that a total of 21 locations along either the vertical or horizontal azimuths at the fovea and at eccentricities of 1°, 2°, 4°, 6° and 8° of visual angle were presented in a given trial, and only one of these locations was represented by a character. Participants reported which character they saw.

2.5. Data analysis

Participants' performances on VWF identification for four contrast levels, 21 locations, and monocular or binocular conditions are presented as descriptive statistics. The results of acuity thresholds are reported as mean ± standard deviation (SD) and expressed in terms of degrees of visual angle. The visual performance of the HM is the average along the right (positive direction of the x-axis) and left (negative direction of the x-axis) HM in the binocular condition, or nasal and temporal HM in the monocular condition. The visual performance of the VM is the average along the upper VM (positive direction of the y-axis) and lower VM (negative direction of the y-axis), respectively. To assess HVA and VMA at specific contrast levels and eccentricity angles, two-way repeated measures ANOVAs and Fisher's LSD as post-hoc comparison were used to compare the results of each experimental subset.

A multiple linear regression was used to examine the relationships between acuity thresholds and eccentricities for each of the 16 conditions (four contrast levels and four azimuth conditions). The dependent variable was acuity threshold. The independent variables were eccentricity, contrast level (dummy variable: 0 to 3 for contrast of 80 %, 40 %, 20 %, and 10 %, respectively), azimuth (dummy variable: 0 to 3 for x-axis (+), x-axis (−), y-axis (+), and y-axis (−), respectively), interaction between contrast level and eccentricity (dummy variable: contrast level * eccentricity), and interaction between meridian and eccentricity (dummy variable: meridian * eccentricity). The relationships between the acuity thresholds, ω_T, and eccentricities, E were as

$$\omega_T = \omega_{T0} * (1 + E/E_2) \tag{1}$$

where ω_{T0} is the acuity threshold in the center of the fovea, and E_2 represents the cortical magnification factor (Kao & Chen, 2012, Levi et al., 1985). Estimating the cortical magnification factor as a function of eccentricity was an intuitive way to describe the visual-cortical architecture of the primary visual cortex or higher visual cortex in visual word form identification. The Wilcoxon signed ranks test was used to check for differences in E_2 values between nasal and temporal meridians tested in the monocular condition. Statistical significance was set at < 0.05 probability.

All analyses were performed in IBM SPSS Version 25 (SPSS Statistics V25, IBM Corporation, Somers, New York). The statistical significance level for all the tests was set at a P-value < 0.05, two-tailed. Scatter plots and corresponding regression lines were established in the statistical software R (version 4.3.0) with the package ‘ggpubr’.

3. Results

3.1. Extent of asymmetries along the horizontal and vertical meridians

Figs. 2 & 3 (also see Table A2 in Appendix for the numerical representations) depicts the descriptive data of the mean acuity threshold for VWF identification at various locations and at different contrast levels for both the binocular and monocular viewing conditions. As eccentricity increases and contrast decreases, mean acuity thresholds also increase across all test conditions. Monocular acuity thresholds were larger than those tested binocularly, even in the high contrast condition. Acuity thresholds were larger along the vertical azimuth, with the largest threshold observed along the upper vertical azimuth. These effects were supported through ANOVA analysis for both binocular and monocular viewing conditions, focusing on the measurements of upper VM, lower VM, HM and VM. Detailed omnibus results are shown in Table 1. In summary, the main effects of contrast, eccentricity, and meridian were all statistically significant for binocular upper VM vs. lower VM, monocular upper VM vs. lower VM, binocular HM vs. VM, and monocular HM vs. VM. The interaction between meridian and eccentricity was also significant in all conditions.

The results of the post-hoc comparison among eccentricities are denoted in Fig. 2 (A) to (H) for the binocular condition and Fig. 3 (A) to (H) for the monocular condition. For a more detailed numerical comparison result (F and *p*-value) between the positive direction and negative direction of the x-axis, as well as between the positive direction and negative direction of the y-axis, and between HM and VM, see Table A3, A4 and A5, which are provided as additional materials to the graphs. For the binocular condition, the asymmetries were not apparent between right HM and left HM ($F_{(1,4)}$ from 0.33 to 1.69, all p > 0.05). VMA (upper-lower vertical difference, lower VM vs. upper VM) was found at three contrast levels (10 %, 20 %, and 80 % contrast) and multiple eccentricity locations (within post-hoc comparisons), including 6° and 8° at 10 % contrast ($F_{(1,4)} = 18.90$, p = 0.012), 6° at 20 % contrast ($F_{(1,4)} = 13.14$, p = 0.022), and 1° and 6° at 80 % contrast ($F_{(1,4)} = 140.69$, p < 0.001).

HVA (horizontal and vertical difference, HM vs. VM) was observed across 4 contrast levels and continuous ranges of eccentricity (within post-hoc comparisons), including 2° to 8° at 10 %, 20 %, and 80 % contrast ($F_{(1,4)} = 241.84$, p < 0.001; $F_{(1,4)} = 475.63$, p < 0.001; $F_{(1,4)} = 59.33$, p = 0.005) and 4 to 8° at 40 % contrast ($F_{(1,4)} = 92.47$, p = 0.002).

For the monocular condition, shown in Fig. 3, no significant differences between the right and left meridians were found for most of the evaluation conditions. VMA (lower VM vs. upper VM) was observed at three contrast levels (10 %, 20 %, and 40 % contrast) and multiple eccentricity locations (within post-hoc comparisons), including 6° and 8° at 10 % contrast ($F_{(1,4)} = 7.85$, p = 0.049); 2°, 6°, and 8° at 20 % contrast ($F_{(1,4)} = 19.54$, p = 0.012); and 6° at 40 % contrast ($F_{(1,4)} = 9.75$, p = 0.035). Although the main effect of the meridian at 80 % contrast was not significant ($F_{(1,4)} = 4.32$, p = 0.106), significances of the 2° and 8° eccentricities were still observed in post-hoc comparisons (p = 0.037 and 0.036).

HVA (HM vs. VM) was also observed across 4 contrast levels and continuous ranges of eccentricity (within post-hoc comparisons), including 2° to 8° at 10 % and 40 % contrast ($F_{(1,4)} = 56.30$, p = 0.002; $F_{(1,4)} = 34.63$, p = 0.004) and 1° to 8° at 20 % and 80 % contrast ($F_{(1,4)} = 152.35$, p < 0.001; $F_{(1,4)} = 89.24$, p < 0.001).

3.2. Estimated linear cortical magnification factor

The VWF identification acuity thresholds and regression lines at different eccentricities and contrast levels are shown in Fig. 4 for the binocular condition and Fig. 5 for the monocular condition. The size thresholds were plotted for four contrast levels. At the high contrast levels (80 % and 40 % contrast), the estimated threshold and trend were similar, and apparent changes were observed in the lower contrast conditions (20 % and 10 % contrast). The adjusted R^2 values were 0.83 (p < 0.001) for the binocular condition and 0.84 (p < 0.001) for the monocular condition.

The relationships between size threshold and eccentricity was fit with the Eq. (1). This allowed us to estimate the size threshold at the center of the fovea, ω_{T0}, and the cortical magnification factor, E_2, from the data. The parameter ω_{T0} was the same for the whole dataset whereas E2 was allowed to change with meridian. The solid lines in Figs. 4 & 5 are fits of this equation.

x-axis: eccentricity (deg), y-axis: estimated visual acuity (degree of visual angle, DVA). x (+): positive direction of x-axis; x (−): negative direction of x-axis; y (+): positive direction of y-axis; y (−): negative direction of y-axis. The dots are values obtained from the VWF (visual word form) identification task.

x-axis: eccentricity (deg), y-axis: estimated visual acuity (degree of visual angle, DVA). x (+): positive direction of x-axis; x (−): negative direction of x-axis; y (+): positive direction of y-axis; y (−): negative direction of y-axis. The dots are values obtained from the VWF (visual word form) identification task.

The properties of ω_{T0} and E_2 in the binocular condition were similar, as shown in Fig. 6 (A) and (B). The values of parameter E_2 showed a tendency to depend mainly on the meridians rather than on contrast levels. Fig. 6 (C) and (D) show the values of the parameters ω_{T0} and E_2 for the monocular condition. The value of parameter ω_{T0} was linked to contrast levels; when the contrast decreased, the value of ω_{T0} increased. Although the E_2 values of the temporal meridian were smaller than those of the nasal meridian (monocular), and the E_2 values of the left meridian tended to be smaller than those of the right meridian (binocular), there were no significant differences between the temporal and nasal meridians (Z = -1.83, asymptotic significance (2-tailed) = 0.068), or between the right and left meridians (Z = -1.83, asymptotic significance (2-tailed) = 0.068).

The E_2 values were similar across the vertical meridian in both monocular and binocular conditions, while the E_2 values of the temporal meridian were smaller than those of the nasal meridian, and the E_2 values of the left meridian tended to be smaller than those of the right meridian. The smallest E_2 values were found across the upper meridian, followed by the lower meridian.

Parameters (ω_{T0} and E_2) for adjusting the character size at different eccentricities, meridians, and contrast levels in the binocular condition ((A) & (B)) and monocular condition ((C) & (D)). ω_{T0} is the size

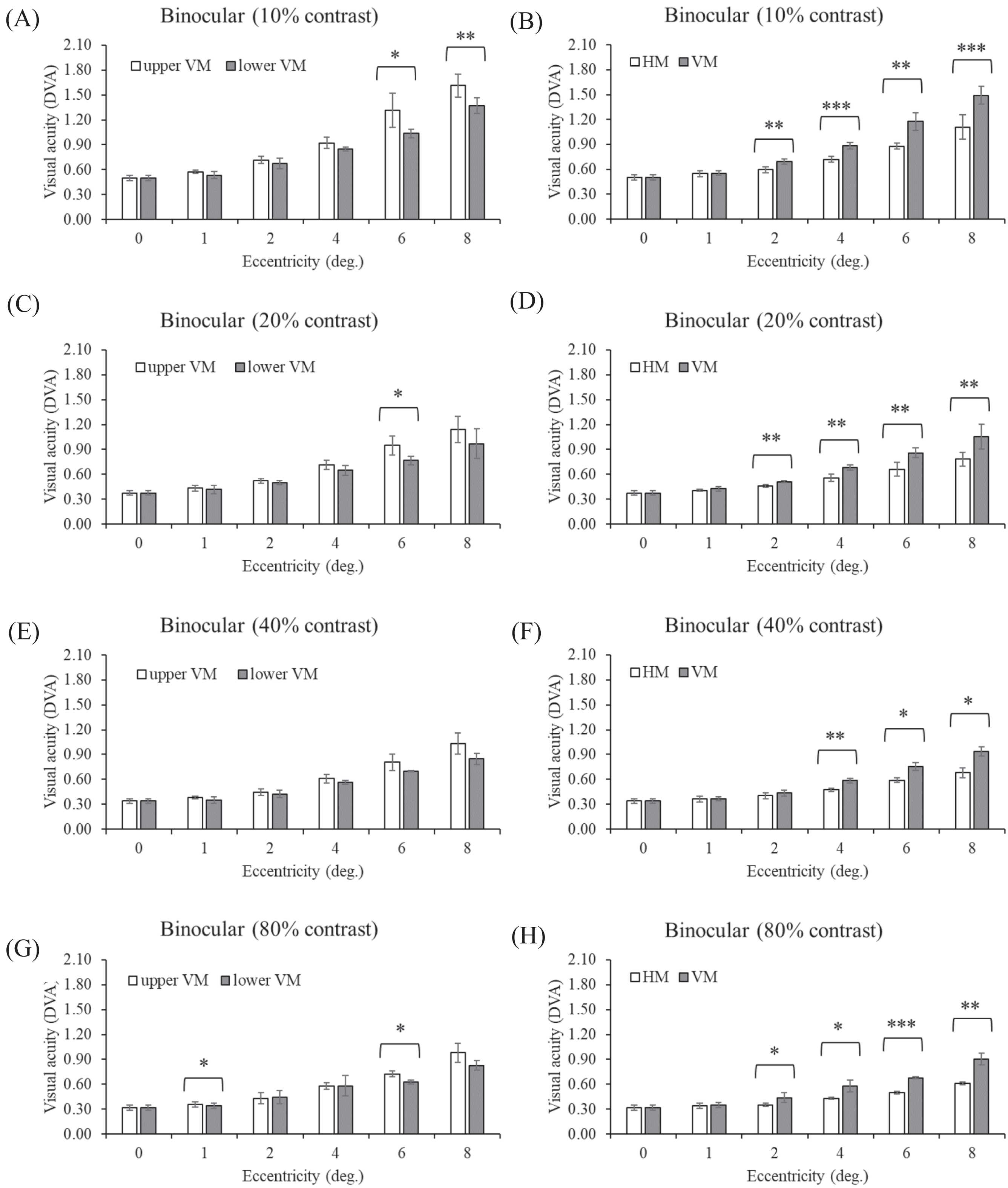

Fig. 2. Effects of eccentricity, meridian, and contrast on VWF identification acuity threshold in the binocular viewing condition. These are results averaged across all participants. The x-axis shows the degree of eccentricity, and the y-axis shows the mean VWF identification acuity threshold. Error bars depict ± 1 standard deviation (SD). Significant differences in post-hoc comparisons are indicated by asterisks: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. HM: horizontal meridian, the average of the same eccentricity angle along the x (+) and x (−); VM: vertical meridian, the average of the same eccentricity angle along the y (+) and y (−); DVA: degree of visual angle.

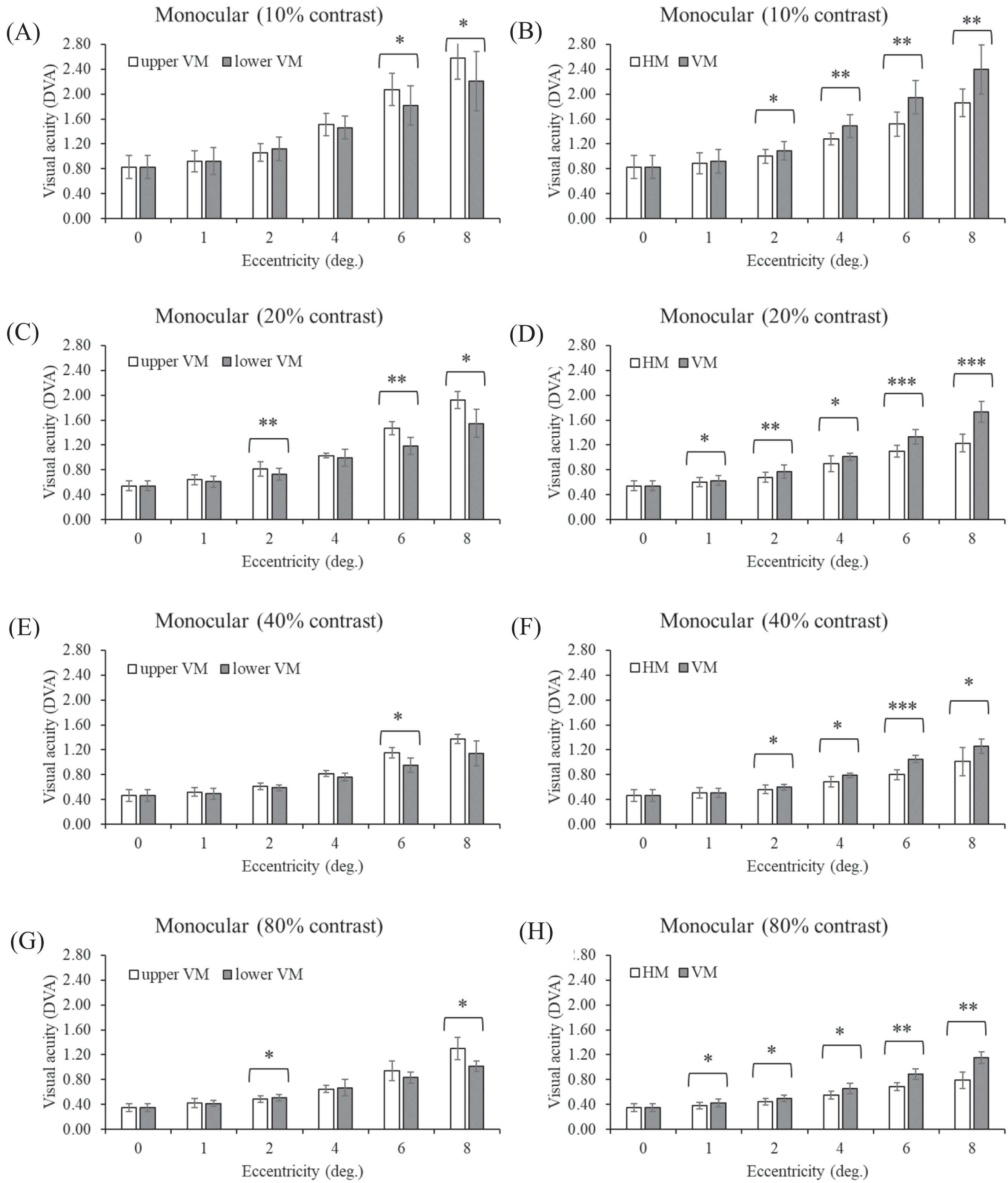

Fig. 3. Effects of eccentricity, meridian, and contrast on VWF identification acuity threshold in the monocular viewing condition. These are results averaged across all participants. The x-axis shows the degree of eccentricity, and y-axis shows the mean VWF identification acuity threshold. Error bars depict ± 1 standard deviation (SD). Significant differences in post-hoc comparisons are indicated by asterisks: * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$. HM: horizontal meridian, the average of the same eccentricity angle along the x (+) and x (−); VM: vertical meridian, the average of the same eccentricity angle along the y (+) and y (−); DVA: degree of visual angle.

Table 1
Omnibus results of the extent of asymmetries along the horizontal and vertical meridians.

Types of Comparison	DF	F	P
Binocular: upper VM/lower VM			
Contrast	(3, 9)	61.45	<0.001
Meridian	(1, 3)	16.88	0.026
Eccentricity	(4, 12)	227.37	<0.001
Contrast * Meridian	(3, 9)	1.49	0.283
Contrast * Eccentricity	(12, 36)	8.97	<0.001
Meridian * Eccentricity	(4, 12)	7.79	0.002
Contrast * Meridian * Eccentricity	(12, 36)	0.52	0.890
Monocular: upper VM/lower VM			
Contrast	(3, 12)	51.00	<0.001
Meridian	(1, 4)	25.54	0.007
Eccentricity	(4, 16)	162.38	<0.001
Contrast * Meridian	(3, 12)	1.08	0.394
Contrast * Eccentricity	(12, 48)	16.96	<0.001
Meridian * Eccentricity	(4, 16)	22.18	<0.001
Contrast * Meridian * Eccentricity	(12, 48)	0.91	0.540
Binocular: HM/VM			
Contrast	(3, 9)	77.66	<0.001
Meridian	(1, 3)	255.79	<0.001
Eccentricity	(4, 12)	163.98	<0.001
Contrast * Meridian	(3, 9)	7.37	0.009
Contrast * Eccentricity	(12, 36)	13.90	<0.001
Meridian * Eccentricity	(4, 12)	39.70	<0.001
Contrast * Meridian * Eccentricity	(12, 36)	1.20	0.318
Monocular: HM/VM			
Contrast	(3, 12)	49.90	<0.001
Meridian	(1, 4)	92.46	<0.001
Eccentricity	(4, 16)	146.19	<0.001
Contrast * Meridian	(3, 12)	13.59	<0.001
Contrast * Eccentricity	(12, 48)	20.62	<0.001
Meridian * Eccentricity	(4, 16)	55.32	<0.001
Contrast * Meridian * Eccentricity	(12, 48)	3.15	0.002

#HM: horizontal meridian, VM: vertical meridian.

threshold in the center of the fovea, and E_2 represents the cortical magnification factor. (HM: horizontal meridian, VM: vertical meridian.).

4. Discussion

The present study examined whether and how the acuity threshold for VWFS identification was modulated by the eccentricities, meridians, and contrasts levels. The study was conducted in both binocular and monocular viewing conditions. Our main finding was that VMA was mainly found at lower contrast levels (20 %, 10 % contrast) and at larger degrees of eccentricity (6° and 8°) independent of monocular or binocular condition. HVA was more apparent than VMA. In both the binocular and monocular conditions, HVA was observed across 4 contrast levels, and starting at about 2° of eccentricity. In addition, for most conditions, no significant identification difference was found between the right and the left meridians in adult participants. Low contrast and the extent of eccentricity can enhance the visual field asymmetry. In this study, the results also provided estimates of the cortical magnification factors for further use in clinical applications (Tsai et al., 2016).

To the best of our knowledge, no previous empirical research has investigated visual word form identification simultaneously across the vertical and horizontal meridians and at high to low contrast levels. Although several studies have employed simple or complex stimuli to specify the limitation and asymmetry in peripheral vision (Barbot et al., 2021, Himmelberg et al., 2020, Strasburger et al., 2011), the identification of Chinese characters is a more complex task than the recognition of Gabor stimuli, letters or Vernier targets. There is a need to understand how such word forms are presented at different meridians and degrees of eccentricity, given the growing demand for visual rehabilitation targeting visually impaired people with a scotoma (Gaffney, Margrain, Bunce & Binns, 2014, Guzzetta, D'Acunto, Rose, Tinelli, Boyd & Cioni, 2010) and whose primary language does not employ Latin letters.

Our results are consistent with previous findings that retinal eccentricity and contrast levels affect the VWF identification thresholds, and with those on the phenomenon of horizontal–vertical anisotropy and

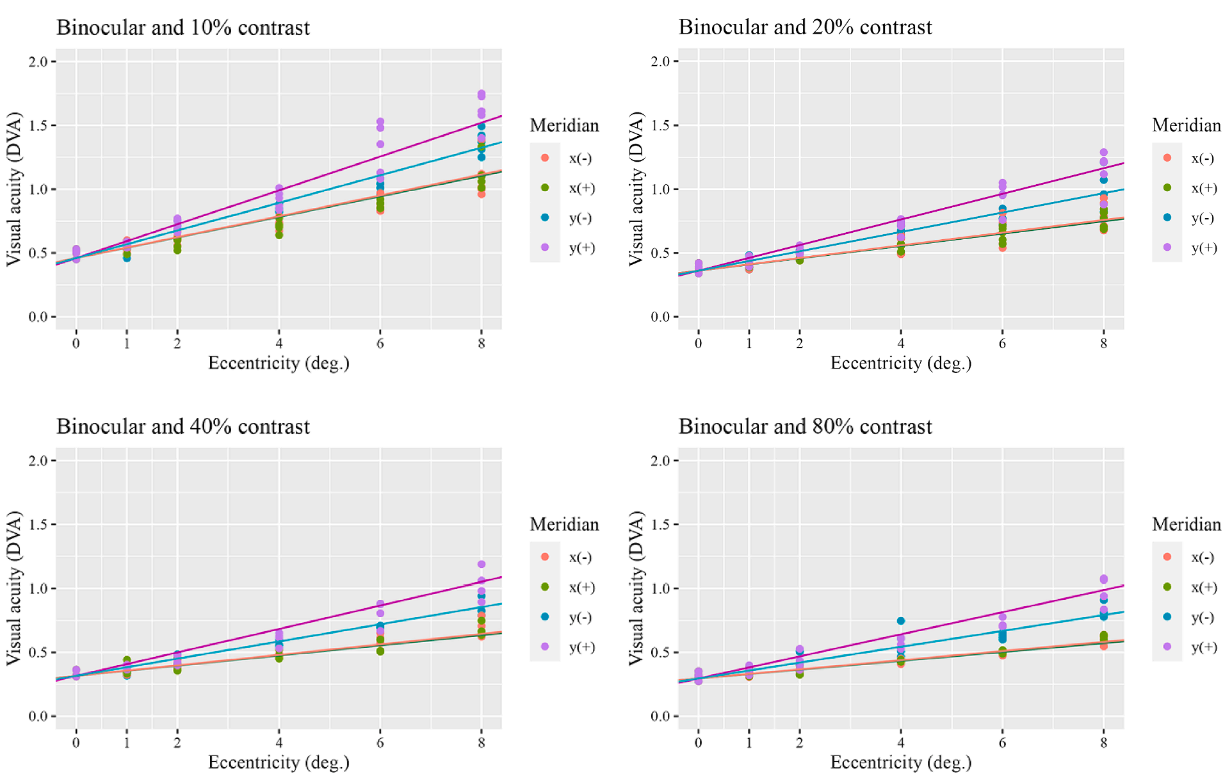

Fig. 4. Fitted VWF visual acuity for binocular condition in 4 contrast levels.

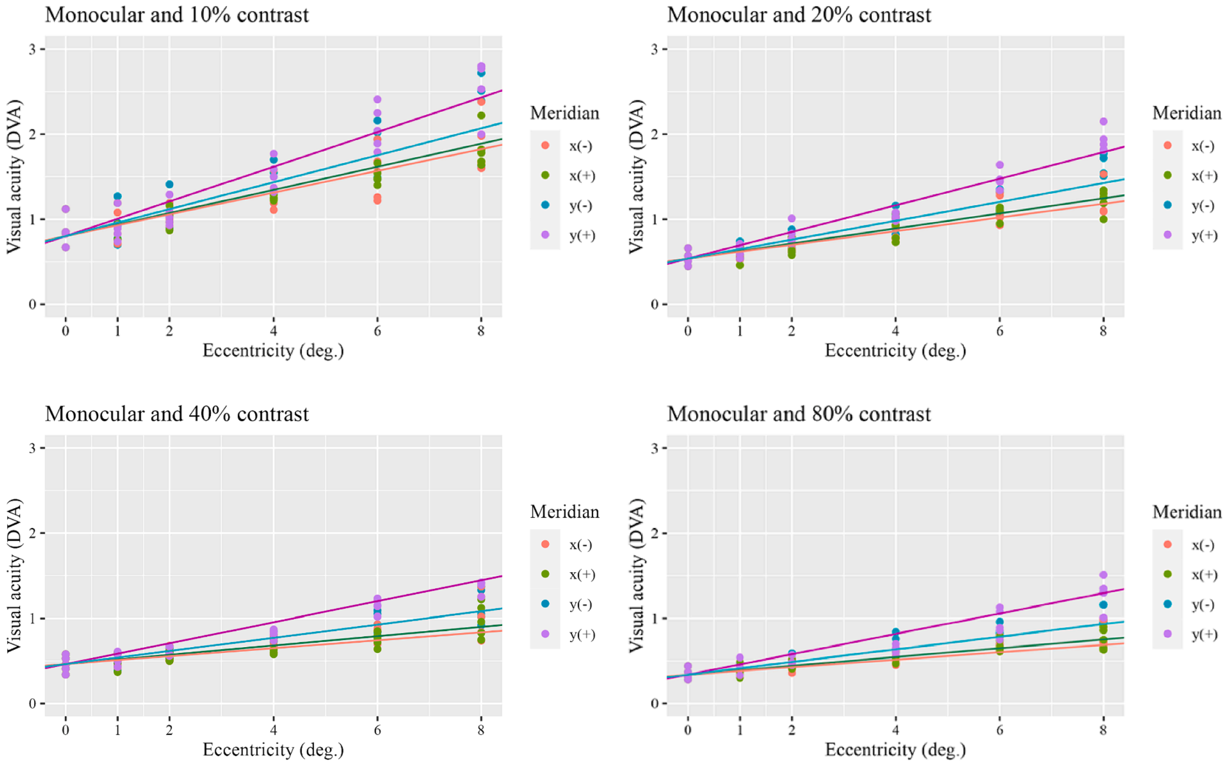

Fig. 5. Fitted VWF visual acuity for monocular condition in 4 contrast levels.

vertical meridian asymmetry (Baldwin et al., 2012, Carrasco et al., 2001, Karim & Kojima, 2010, Previc, 1990, Rubin et al., 1996). Performance asymmetry occurs on the vertical meridian, i.e., the upper versus lower meridian, but not on the horizontal meridian, i.e., the temporal meridian versus nasal meridian (Edgar & Smith, 1990, Liu, Heeger & Carrasco, 2006, Previc, 1990).

Directly measuring *M* in humans is complex, as another common and psychophysically based scaling factor, E_2, is usually employed to characterize the relationship between visual performance and its connection to the spacing of anatomical units (Beard et al., 1997, Levi et al., 1985, Levi et al., 1984). E_2 represents the eccentricity (E) at which a stimulus diameter has to be doubled in order to maintain similar foveal performance in the periphery (Beard et al., 1997).

We also found that the E_2 values, i.e., the scaling of the cortical magnification factor, were smaller in the upper visual field than in the lower one. Our psychophysical results were consistent with previous neural evidence for the topography of ganglion cell densities, which are higher in the superior retina (Curcio & Allen, 1990), and for the representation of the visual field in the primary visual cortex (Horton & Hoyt, 1991). While most studies suggest significant differences in E_2 along the horizontal meridian, our data showed that E_2 values were somewhat smaller for the temporal meridian (mean E_2 values across 4 contrasts = 6.8) than for the nasal meridian (mean $E_2 = 7.7$), which corresponds to the nasal–temporal difference in ganglion cell density (Curcio & Allen, 1990). In addition, E_2 values along the left meridian (mean $E_2 = 7.2$) were slightly smaller than those along the right meridian (mean $E_2 =$ 7.4) across the 4 contrast levels.

The properties of task and visual stimuli that affect the cortical magnification factor are well documented (Strasburger et al., 2011). Strasburger, et al. (2011) compared E_2 values of assorted acuity measures in the literature and showed that letter acuity and grating acuity have higher E_2 values (around 2.6 to 3.3) than do Landolt-C acuity (around 1 to 2.6) and vernier acuity (around 0.6 to 0.8). Kao and Chen (2012) used a text detection task and four types of visual word form stimuli to examine the effects of size and eccentricity on contrast threshold along the horizontal meridian and found that E_2, on average, was 0.82 degrees of visual angle. In our study, the E_2 values were apparently larger than those in previous studies, with average E_2 values of 6.8 to 7.7 along the horizontal meridian and 3.5 to 5.1 along the vertical meridian. The average E_2 (3.5 for monocular and binocular) in the upper visual field was closer to those found for letter acuity or grating acuity in previous studies. Although we chose simple characters with which our participants were familiar before the formal experiment, the results showed that Chinese character identification had larger E_2 values, indicating that a larger peripheral receptive field would be needed to identify the visual stimuli. A possible reason may be that character identification involves not only the retinal and the early visual cortex but also higher-level mechanisms in the visual system (McCandliss, Cohen & Dehaene, 2003).

However, our study had limitations in study design. Each participant performed all runs binocularly on one day and then completed the other runs monocularly on another days. The order of presentation is confounded potential order effects. Our rationale for this design was primarily driven by the practical consideration that starting with binocular testing facilitated observer acclimatization to the experiment. Subsequently, the transition to monocular testing was expected to yield more reliable results. We did not explicitly consider the potential sequential effect when deciding to perform the experiments binocularly first and then monocularly.

To conclude, we investigated the effects of contrast and eccentricity on the character size threshold in the monocular and binocular conditions. For monocular and binocular viewing, we found no apparent differences between them in terms of E_2, but obvious differences in the values of ω_{T0}, which is the size threshold in the center of the fovea. Therefore, monocular or binocular viewing does not influence the magnification factor. While E_2 values mainly depended on the meridian effect, the low contrast condition (contrast of 10 %) was also shown to affect E_2 values.

(A)
(B)
(C)

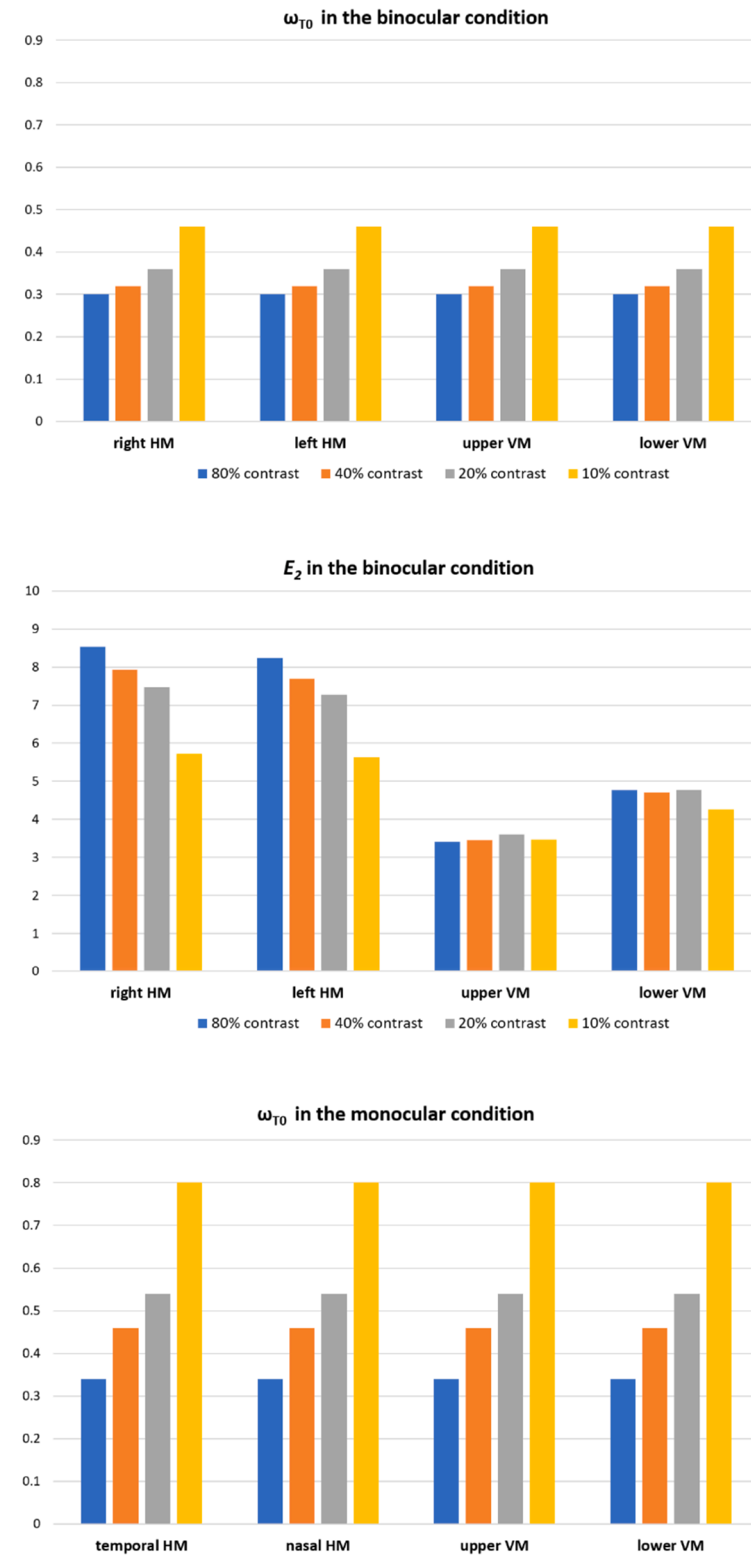

Fig. 6. Parameters (ω_{T0} and E_2) in the binocular and monocular conditions.

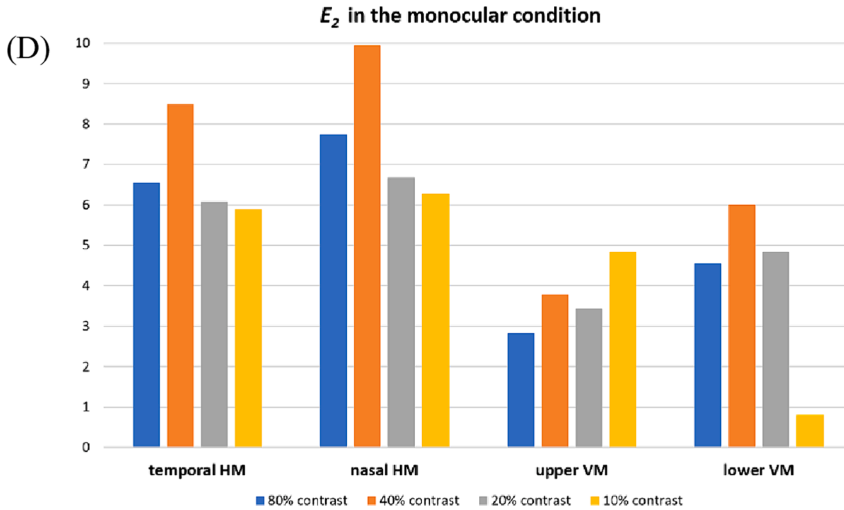

Fig. 6. (*continued*).

5. Conclusions

In conclusion, the results of this study suggest the existence of different meridian effects on the cortical magnification factors between the vertical and horizontal meridians and different contrast effects on the foveal magnification between monocular and binocular viewing. This latter finding suggests that a nonlinear binocular contrast summation process is involved in this effect.

Author contributions:

Li-Ting Tsai: Conceptualization, Material preparation, Methodology, Data collection, Analysis, Writing – original draft, review and editing.

Kuo-Meng Liao: Resources, Analysis, Writing – original draft, review & editing.

Chiun-Ho Hou: Methodology, Writing – review & editing.

Yuh Jang: Resources, Writing – review & editing.

Chien-Chung Chen: Conceptualization, Methodology, Writing – review & editing, Supervision.

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CRediT authorship contribution statement

Li-Ting Tsai: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kuo-Meng Liao:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis. **Chiun-Ho Hou:** Writing – review & editing, Methodology. **Yuh Jang:** Writing – review & editing, Funding acquisition. **Chien-Chung Chen:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Appendix

Table A1
Characters, and their configurations of visual stimuli.

Group	Configuration	Character
I	single	大 da 太 tai 天 tian
II	left–right	仕 shi 仟 qian 任 ren
III	top-down	吉 ji 古 gu 占 zhan
IV	surrounding	目 mu 旦 dan 貝 bei
V	left–right	汙 wu 江jiang 汪wang

Total 5 configuration groups and 15 Traditional Chinese characters with similar legibility were used as visual stimuli to investigate the asymmetry across the visual field and the effect of quarter visual field polar angle.

Table A2
Visual acuity threshold at different contrast, eccentricity, and binocular and monocular conditions.

			Eccentricity					
Eye	Meridian	Contrast	0	1	2	4	6	8
Binocular	x (+)	10 %	0.50 ± 0.03	0.54 ± 0.04	0.58 ± 0.04	0.71 ± 0.05	0.88 ± 0.03	1.12 ± 0.12
		20 %	0.38 ± 0.03	0.41 ± 0.02	0.46 ± 0.02	0.55 ± 0.02	0.65 ± 0.06	0.76 ± 0.07
		40 %	0.34 ± 0.03	0.37 ± 0.05	0.39 ± 0.05	0.48 ± 0.03	0.55 ± 0.05	0.67 ± 0.05
		80 %	0.31 ± 0.03	0.34 ± 0.03	0.35 ± 0.03	0.43 ± 0.01	0.50 ± 0.01	0.62 ± 0.02
	x (−)	10 %	0.50 ± 0.03	0.55 ± 0.04	0.61 ± 0.04	0.73 ± 0.04	0.87 ± 0.06	1.10 ± 0.17
		20 %	0.38 ± 0.03	0.40 ± 0.03	0.46 ± 0.02	0.56 ± 0.07	0.68 ± 0.11	0.80 ± 0.11
		40 %	0.34 ± 0.03	0.35 ± 0.03	0.42 ± 0.03	0.47 ± 0.01	0.62 ± 0.04	0.69 ± 0.07
		80 %	0.31 ± 0.03	0.34 ± 0.03	0.35 ± 0.02	0.43 ± 0.02	0.50 ± 0.02	0.59 ± 0.04
	HM	10 %	0.50 ± 0.03	0.55 ± 0.03	0.60 ± 0.04	0.72 ± 0.04	0.88 ± 0.03	1.11 ± 0.15
		20 %	0.38 ± 0.03	0.41 ± 0.01	0.46 ± 0.01	0.56 ± 0.04	0.66 ± 0.08	0.78 ± 0.08
		40 %	0.34 ± 0.03	0.36 ± 0.04	0.40 ± 0.03	0.47 ± 0.02	0.59 ± 0.03	0.68 ± 0.06
		80 %	0.31 ± 0.03	0.34 ± 0.03	0.35 ± 0.02	0.43 ± 0.01	0.50 ± 0.01	0.61 ± 0.02
	y (+)	10 %	0.50 ± 0.03	0.57 ± 0.02	0.72 ± 0.04	0.92 ± 0.07	1.31 ± 0.20	1.61 ± 0.14
		20 %	0.38 ± 0.03	0.43 ± 0.04	0.52 ± 0.03	0.71 ± 0.05	0.95 ± 0.11	1.14 ± 0.16
		40 %	0.34 ± 0.03	0.38 ± 0.02	0.44 ± 0.04	0.61 ± 0.05	0.81 ± 0.10	1.03 ± 0.12
		80 %	0.31 ± 0.03	0.36 ± 0.03	0.43 ± 0.07	0.58 ± 0.04	0.72 ± 0.04	0.98 ± 0.11
	y (−)	10 %	0.50 ± 0.03	0.53 ± 0.04	0.67 ± 0.06	0.85 ± 0.02	1.04 ± 0.05	1.37 ± 0.09
		20 %	0.38 ± 0.03	0.42 ± 0.05	0.50 ± 0.02	0.65 ± 0.06	0.77 ± 0.05	0.97 ± 0.18
		40 %	0.34 ± 0.03	0.35 ± 0.04	0.42 ± 0.04	0.56 ± 0.03	0.70 ± 0.01	0.85 ± 0.07
		80 %	0.31 ± 0.03	0.34 ± 0.03	0.44 ± 0.08	0.58 ± 0.12	0.63 ± 0.02	0.83 ± 0.06
	VM	10 %	0.50 ± 0.03	0.55 ± 0.03	0.69 ± 0.03	0.88 ± 0.04	1.17 ± 0.11	1.49 ± 0.11
		20 %	0.38 ± 0.03	0.42 ± 0.03	0.51 ± 0.01	0.68 ± 0.03	0.86 ± 0.06	1.06 ± 0.15
		40 %	0.34 ± 0.03	0.37 ± 0.03	0.43 ± 0.03	0.58 ± 0.03	0.75 ± 0.05	0.94 ± 0.06
		80 %	0.31 ± 0.03	0.35 ± 0.03	0.44 ± 0.06	0.58 ± 0.07	0.68 ± 0.01	0.90 ± 0.07
Monocular	x (+)	10 %	0.83 ± 0.18	0.92 ± 0.18	0.99 ± 0.12	1.25 ± 0.02	1.51 ± 0.10	1.83 ± 0.23
		20 %	0.54 ± 0.08	0.60 ± 0.09	0.68 ± 0.10	0.90 ± 0.15	1.08 ± 0.07	1.22 ± 0.13
		40 %	0.46 ± 0.10	0.50 ± 0.09	0.55 ± 0.05	0.67 ± 0.10	0.76 ± 0.08	0.98 ± 0.20
		80 %	0.35 ± 0.06	0.38 ± 0.07	0.45 ± 0.04	0.56 ± 0.07	0.69 ± 0.07	0.76 ± 0.12
	x (−)	10 %	0.83 ± 0.18	0.86 ± 0.16	1.02 ± 0.10	1.31 ± 0.18	1.53 ± 0.30	1.89 ± 0.31
		20 %	0.54 ± 0.08	0.60 ± 0.07	0.68 ± 0.06	0.90 ± 0.12	1.12 ± 0.17	1.24 ± 0.18
		40 %	0.46 ± 0.10	0.51 ± 0.08	0.58 ± 0.08	0.70 ± 0.08	0.84 ± 0.09	1.04 ± 0.27
		80 %	0.35 ± 0.06	0.37 ± 0.04	0.44 ± 0.07	0.55 ± 0.07	0.69 ± 0.07	0.82 ± 0.16
	HM	10 %	0.83 ± 0.18	0.89 ± 0.17	1.00 ± 0.11	1.28 ± 0.09	1.52 ± 0.20	1.86 ± 0.22
		20 %	0.54 ± 0.08	0.60 ± 0.08	0.68 ± 0.08	0.90 ± 0.13	1.10 ± 0.10	1.23 ± 0.15
		40 %	0.46 ± 0.10	0.51 ± 0.08	0.56 ± 0.07	0.69 ± 0.09	0.80 ± 0.08	1.01 ± 0.23
		80 %	0.35 ± 0.06	0.38 ± 0.05	0.44 ± 0.05	0.55 ± 0.06	0.69 ± 0.07	0.79 ± 0.14
	y (+)	10 %	0.83 ± 0.18	0.92 ± 0.17	1.06 ± 0.14	1.51 ± 0.18	2.08 ± 0.25	2.58 ± 0.34
		20 %	0.54 ± 0.08	0.64 ± 0.07	0.82 ± 0.12	1.03 ± 0.04	1.47 ± 0.11	1.92 ± 0.14
		40 %	0.46 ± 0.10	0.52 ± 0.07	0.61 ± 0.05	0.82 ± 0.05	1.15 ± 0.08	1.38 ± 0.07
		80 %	0.35 ± 0.06	0.42 ± 0.08	0.49 ± 0.05	0.65 ± 0.05	0.94 ± 0.16	1.30 ± 0.18
	y (−)	10 %	0.83 ± 0.18	0.92 ± 0.22	1.12 ± 0.19	1.46 ± 0.19	1.82 ± 0.32	2.21 ± 0.47
		20 %	0.54 ± 0.08	0.61 ± 0.09	0.73 ± 0.09	0.99 ± 0.13	1.19 ± 0.14	1.55 ± 0.23
		40 %	0.46 ± 0.10	0.49 ± 0.09	0.59 ± 0.05	0.76 ± 0.06	0.95 ± 0.12	1.14 ± 0.20
		80 %	0.35 ± 0.06	0.42 ± 0.05	0.50 ± 0.05	0.67 ± 0.13	0.83 ± 0.09	1.01 ± 0.09
	VM	10 %	0.83 ± 0.18	0.92 ± 0.19	1.09 ± 0.15	1.49 ± 0.18	1.95 ± 0.27	2.39 ± 0.40
		20 %	0.54 ± 0.08	0.63 ± 0.08	0.77 ± 0.10	1.01 ± 0.06	1.33 ± 0.12	1.73 ± 0.16
		40 %	0.46 ± 0.10	0.51 ± 0.08	0.60 ± 0.05	0.79 ± 0.04	1.05 ± 0.06	1.26 ± 0.11
		80 %	0.35 ± 0.06	0.42 ± 0.06	0.50 ± 0.05	0.66 ± 0.08	0.89 ± 0.09	1.15 ± 0.10

The results are expressed as mean ± standard deviation (SD). The unit is degree of visual angle.
x (+): positive direction of x-axis; x (−): negative direction of x-axis; y (+): positive direction of y-axis; y (−): negative direction of y-axis; HM: horizontal meridian, the average of the same eccentricity angle along the x (+) and x (−); VM: vertical meridian, the average of the same eccentricity angle along the y (+) and y (−).

Table A3
The results of F and *p*-value for two-way repeated measures ANOVA to compare various conditions along the x-axis.

		Main effect						Post-hoc comparisons of x (+/-) (Fisher's LSD)				
		Meridian		Eccentricity		Interaction effect		*P*-value of each paired comparison				
Eye	Contrast	F	*p*	F	*p*	F	*p*	1	2	4	6	8
Binocular	10	0.33	0.595	59.89	<0.001	1.27	0.321	0.476	0.125	0.322	0.855	0.450
	20	0.65	0.464	54.31	<0.001	0.70	0.601	0.530	0.730	0.697	0.453	0.363
	40	1.11	0.370	51.81	<0.001	4.80	0.015	0.329	0.220	0.804	0.158	0.520
	80	1.69	0.284	111.86	<0.001	0.84	0.528	0.490	0.928	0.779	0.095	0.335
Monocular	10	0.30	0.613	130.63	<0.001	0.39	0.812	0.044	0.169	0.458	0.830	0.684
	20	0.11	0.757	50.72	<0.001	0.31	0.870	0.786	0.942	0.876	0.648	0.675
	40	15.95	0.016	20.26	<0.001	2.96	0.052	0.803	0.109	0.179	0.002	0.098
	80	0.05	0.835	41.14	<0.001	2.07	0.132	0.611	0.438	0.730	0.944	0.170

p-value < 0.05 indicates significant difference.
x (+): positive direction of x-axis; x (−): negative direction of x-axis.

Table A4

The results of F and *p*-value for two-way repeated measures ANOVA to compare various conditions along the y-axis.

Eye	Contrast	Main effect: Meridian F	Meridian p	Eccentricity F	Eccentricity p	Interaction effect F	Interaction p	Post-hoc comparisons of y (+/-) (Fisher's LSD), P-value of each paired comparison: 1	2	4	6	8
Binocular	10	18.90	0.012	187.73	<0.001	6.55	0.003	0.143	0.355	0.056	0.036	0.007
	20	13.14	0.022	65.40	<0.001	3.45	0.032	0.601	0.413	0.172	0.036	0.062
	40	5.52	0.100	120.90	<0.001	3.36	0.046	0.063	0.405	0.234	0.132	0.111
	80	140.69	0.001	90.89	<0.001	2.21	0.129	0.018	0.793	0.955	0.037	0.071
Monocular	10	7.85	0.049	74.21	<0.001	8.08	<0.001	0.844	0.445	0.119	0.041	0.026
	20	19.54	0.012	149.67	<0.001	13.63	<0.001	0.169	0.002	0.671	0.002	0.011
	40	9.75	0.035	138.13	<0.001	4.87	0.009	0.058	0.151	0.205	0.049	0.054
	80	4.32	0.106	90.89	<0.001	5.74	0.005	0.577	0.037	0.684	0.261	0.036

p-value < 0.05 indicates significant difference.

y (+): positive direction of y-axis; y (−): negative direction of y-axis.

Table A5

The results of F and *p*-value for two-way repeated measures ANOVA to compare various conditions between HM and VM.

Eye	Contrast	Main effect: Meridian F	Meridian p	Eccentricity F	Eccentricity p	Interaction effect F	Interaction p	Post-hoc comparisons of HM/VM (Fisher's LSD), P-value of each paired comparison: 1	2	4	6	8
Binocular	10	241.84	<0.001	149.78	<0.001	27.80	<0.001	0.635	0.001	<0.001	0.002	<0.001
	20	475.63	<0.001	71.04	<0.001	21.51	<0.001	0.099	0.002	0.001	0.002	0.001
	40	59.33	0.005	187.13	<0.001	12.08	<0.001	0.526	0.093	0.004	0.012	0.021
	80	92.47	0.002	149.30	<0.001	21.25	<0.001	0.151	0.020	0.024	<0.001	0.005
Monocular	10	56.30	0.002	99.57	<0.001	20.58	<0.001	0.140	0.022	0.007	0.001	0.006
	20	152.35	<0.001	103.98	<0.001	56.48	<0.001	0.039	0.007	0.026	<0.001	<0.001
	40	34.63	0.004	64.02	<0.001	10.45	<0.001	1.000	0.045	0.028	<0.001	0.030
	80	89.24	<0.001	108.67	<0.001	13.20	<0.001	0.030	0.013	0.022	0.003	0.006

p-value < 0.05 indicates significant difference.

HM: horizontal meridian, the average of the same eccentricity angle along the x (+) and x (−); VM: vertical meridian, the average of the same eccentricity angle along the y (+) and y (−).

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