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ORIGINAL ARTICLE

Development of Central and Peripheral Vision and Visual Field Asymmetries from Preschoolers to Adults

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ABSTRACT

This study explored how meridian, eccentricity, contrast, and age influence the development of central and peripheral visual acuity (VA) in 37 children (aged 4–12)—divided into three groups—and eight adults. Psychophysical methods were used to measure VA using Lea symbols at contrast levels of 40% and 80%, measured at the fovea and at eccentricities of 2°, 4°, 6°, and 8° along the superior, inferior, right, and left meridians. The results showed that children aged 6 to <8 years had already achieved adult-like VA performance at both central and peripheral locations across contrast levels. At 40% contrast, younger children (4 to <6 years) showed significantly lower VA, especially at the fovea and across eccentricities. The analyses revealed better VA along the horizontal meridian relative to the vertical meridian, and superior meridian performance relative to the inferior meridian, with these asymmetries becoming more pronounced with age. Although the results indicated significant differences between the right and left meridians, post-hoc analyses identified such differences only in a few conditions. Overall, the findings demonstrate that the development of VA is influenced by the interaction of meridional orientation, eccentricity, contrast, and age, highlighting an age-related increase in visual field asymmetry.

1 | Introduction

The macula, a cone-rich retinal region responsible for high-acuity vision and color perception, covers the central visual field (VF) within 10°–18° degrees of visual angle (DVAs). Within the macula, cone cells are densely packed in the fovea, which subserves the central VF for approximately 5° DVAs. The development of the macula follows a structured sequence, progressing from the center outward. Cone differentiation begins centrally and extends peripherally, with foveal cones maturing last to attain adult morphology [1, 2]. Optical coherence tomography studies in children indicate that most morphological development in the human macula—including increased cone density, retinal thickness, and volume—occurs within the first 5 years of life [3, 1]. However, the peripapillary retinal nerve fiber layer thickness does not develop in parallel with these macular changes [3].

These structural changes are associated with functional improvements in visual acuity (VA) and contrast sensitivity (CS), both crucial for pattern recognition [4]. VA refers to the ability to resolve fine spatial details under high-contrast conditions, whereas CS determines the capacity to perceive subtle luminance differences, particularly under low-contrast or dim lighting conditions, making it essential for daily visual tasks. Studies suggest that adult-like VA and CS development in children depends on age and assessment methods [5–7]. While foveal VA approaches adult levels between ages 5 and 8, foveal CS matures later, between ages 7 and 12 [5–7].

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1.1 | Central and Peripheral Vision

VA and CS are not uniformly distributed across the macular VF in either children or adults [8–12]. This nonuniformity is attributed to the cortical magnification factor (M), which describes the number of neurons in the visual cortex responsible for processing a stimulus of a given size as a function of its location in the VF [13]. In the fovea, a small central retinal region, a disproportionately high number of primary visual cortex (V1) neurons are dedicated to visual processing, corresponding to the highest VA and CS in the central VF. Conversely, in the peripheral VF, fewer neurons are allocated per unit area, leading to reduced processing capacity, lower spatial resolution, and increased optical aberrations [14–16].

1.2 | Visual Perceptual Asymmetry

Beyond eccentricity, visual performance—especially in peripheral vision—depends on the VF quadrant in which a stimulus is presented [17]. Adult studies show that, at the same eccentricity, performance is better along the horizontal meridian (HM) than the vertical meridian (VM), a phenomenon termed horizontal–vertical anisotropy (HVA). Additionally, performance is superior on the lower VM compared with the upper VM, a pattern known as VM asymmetry (VMA) [11, 18–21]. These asymmetries vary by task type, being pronounced in spatial resolution and CS tasks [18, 22], but less evident in orientation discrimination tasks [23].

More research on visual asymmetry has focused on adults, with limited studies in children. Some evidence suggests that children exhibit similar visual half-field and polar angle asymmetries [24–27], though these patterns differ from those observed in adults. Specifically, HVA is less pronounced in children, and VMA is often absent [27]. Visual performance related to eccentricity and VF asymmetry is influenced by task demands, polar angle, and age-related neural development extending from the retina to the visual cortex [27, 28]. However, data remain insufficient regarding when foveal and peripheral VA in children reach adult-like levels and how contrast influences these measures.

1.3 | The Current Study

To date, only one study has explored the development of perceptual asymmetry between HM and VM from preschool age to adulthood [24]. However, the developmental trajectory of these asymmetries across both central and peripheral VFs remains unclear. The present study builds upon previous research using the Lea symbol optotype to assess foveal and peripheral VA along the HM and VM in children. Specifically, we aim to determine the age at which adult-like VA is reached at different eccentricities and whether polar angle asymmetries, such as HVA and VMA, are present in children. Additionally, we examine how contrast levels influence these asymmetries. Unlike prior studies, our research considers the combined effects of eccentricity and contrast on visual asymmetries. These findings provide novel insights into the development of VA across the macular field at different contrast levels and the evolution of perceptual asymmetries from childhood to adulthood.

2 | Methods

2.1 | Participants

Participants aged 4–30 years were recruited and categorized into four groups: 4–5 years (4 years, 0 months–5 years, 11 months), 6–7 years (6 years, 0 months–7 years, 11 months), 8–11 years (8 years, 0 months–11 years, 11 months), and adults. Participants were screened for ocular health, and exclusion criteria included ocular diseases affecting visual performance, uncorrected or corrected VA worse than 20/25, developmental delays (children), neurological conditions (adults), and color vision deficiencies.

The study was approved by the Institutional Review Board and adhered to the Declaration of Helsinki. Written informed consent was obtained from all participants or, in the case of children, from their parents or caregivers. Children provided verbal assent before participation.

2.2 | Apparatus and Visual Stimuli

Visual stimuli were displayed on a ViewSonic G90fB 19-in. monitor (1280 × 1024 resolution, 85-Hz refresh rate), controlled by a MacBook Pro equipped with an Intel HD Graphics 3000 display card. Stimuli were generated using Psykinematix software with the Mono 10.8-bit bit-stealing method for 10-bit resolution [29]. Gamma correction was performed using Psykinematix and Eye-One Display 2 [29].

Four Lea symbols, commonly used for VA assessment in preschool children (Group, 2010), were employed as visual stimuli. The display (Figure 1) featured a circular aperture window with a 12° radius and 90-cd/m^2 luminance, set against a background with 73-cd/m^2 luminance. A black fixation cross (0.2° × 0.2°; <1 cd/m^2) was centrally positioned.

During testing, a symbol was randomly presented at 17 locations, including the fovea and 2°, 4°, 6°, and 8° eccentricities along the upper, lower, left, and right meridians. Initial symbol sizes varied by location: 0.6° DVA at the fovea and 0.9°, 1.2°, 1.5°, and 1.8° DVA at 2°, 4°, 6°, and 8° eccentricities, respectively. Participants viewed the stimuli from 50 cm, with their heads stabilized by a chin rest.

2.3 | Procedure

Participants were initially screened by ophthalmologists to confirm ocular and visual health and assess refractive errors. Monocular and binocular VA, along with binocular crowded VA, were measured using the Freiburg VA Test [30]. The color perception was evaluated with the Hardy–Rand–Rittler pseudoisochromatic test [31]. The dominant eye was determined using the Miles test [32], while hand dominance was assessed with the Edinburgh Handedness Inventory [33].

Before the experiment, participants were given time to familiarize themselves with the Lea symbols. For preschool children, this process included practicing symbol matching and using their

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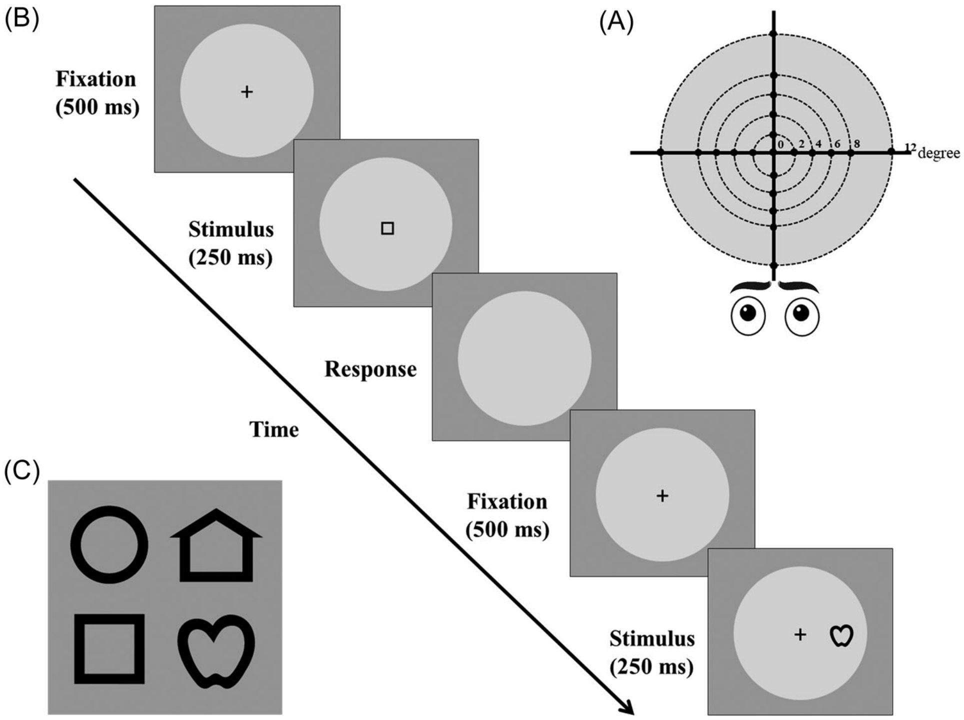

FIGURE 1 | Trial sequence. Participants performed a Lea symbol recognition task. Each trial began with the presentation of a central fixation cross to help maintain focus. Once the symbol appeared at the fixation point, the cross disappeared. A total of 17 possible locations were used along either the vertical meridian (VM) or horizontal meridian (HM), including the fovea and eccentricities of 2°, 4°, 6°, and 8° of visual angle. In each trial, only one location contained a circle, square, apple, or house. Participants responded by either pressing a key on the keyboard or verbally reporting the symbol.

names for the symbols. The experiment commenced only after verifying that the children could accurately identify all symbols. Participants then practiced maintaining fixation on a central cross while recognizing symbols presented in peripheral locations. Because peripheral vision performance is significantly influenced by practice [14], participants received extensive training and completed abbreviated practice staircases before formal testing. Stabilization was confirmed when DVA increased gradually from the fovea to the periphery, and the eccentricity profile reached a smooth asymptote. The four symbols were assigned to keys on a numeric keypad, and participants capable of independent responses familiarized themselves with the key positions before the formal experiment began.

Stimuli were presented at randomized high (80%) or medium (40%) contrast levels. Each contrast condition included three runs, resulting in a total of six runs (3 runs × 2 contrast levels). Each run began with three practice trials to familiarize participants with the procedure and optimize performance. The runs incorporated 17 interleaved staircases covering all test locations. Participants completed the six runs binocularly over multiple days. At the beginning of each session, they adapted to the luminance conditions by sitting in a dimly lit room for 3 min before starting the practice trials. During the experiment, participants were allowed breaks before resuming unfinished runs. For children, each testing session was structured flexibly to accommodate individual needs: at the end of each run, we asked whether they wished to take a break, and breaks were also given whenever reduced attention or fatigue was observed. While adults completed the experiment in a single day or two half-day sessions, children required two to four visits.

The trial sequence is illustrated in Figure 1. Each stimulus was displayed for 250 ms—long enough for symbol recognition while minimizing the effects of saccadic eye movements [34, 35]. Participants fixated on a central cross and either pressed a key or verbally identified the perceived symbol. After each response, the next trial began following a 500-ms interval, during which a fixation point reappeared at the screen's center. Participants were required to maintain fixation throughout the experiment and avoid eye movements during stimulus presentation. Auditory feedback indicated response accuracy. Additionally, if a participant glanced at the keyboard before pressing a key, they were instructed to refocus on the fixation point before proceeding.

VA at the 17 test locations was measured using an interleaved 3-down, 1-up staircase procedure. The character size in DVAs decreased after three consecutive correct responses and increased after a single incorrect response. The decrement rate was 50% before the first reversal and 12.5% afterward, while the size increment rate remained fixed at 25%. Each staircase concluded after six reversals. The VA threshold was determined by averaging the final five reversals for each run, with measurements repeated three times. The final thresholds were calculated as the mean of the three repetitions.

2.4 | Statistical Analysis

Descriptive statistics for continuous variables, including age, VA, refractive errors (S.E.) of diopters sphere (D.S.) and diopters cylinder (D.C.), and spherical equivalent refractive error (SER), are presented as means and standard deviations. Categorical

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variables are expressed as percentages. Baseline differences between age groups were assessed using one-way analysis of variance (ANOVA) with Fisher's least significant difference (LSD) post-hoc tests for continuous variables and chi-square tests for categorical variables.

DVAs for each age group were analyzed across four axes: positive x-axis (x [+]), negative x-axis (x [−]), positive y-axis (y [+]), and negative y-axis (y [−]). Additionally, DVAs were examined for HM and VM at varying eccentricities. HM performance was defined as the average of the positive and negative x-axes, while VM performance was the average of the positive and negative y-axes.

Age was treated as a between-subject variable, whereas eccentricity, contrast, and meridian were treated as within-subject (repeated measures) factors. The relationships between DVAs and independent variables were analyzed using a generalized estimating equation model with a first-order autoregressive (AR1) correlation matrix. Linear regression coefficients (B) with 95% confidence intervals (95% CIs) were reported.

To compare age-group differences in horizontal and vertical DVAs (HM and VM), as well as specific contrasts and eccentricities, two-way repeated measures ANOVAs followed by Fisher's LSD post-hoc tests were conducted. The degree of asymmetry was calculated as the difference between meridians (HM vs. VM), vertical axes (y [+] vs. y [−]), and horizontal axes (x [+] vs. x [−]). Asymmetry was assessed using Student's t-test, and effect sizes were reported using Cohen's d, where d = 0.2 represents a small effect, d = 0.5 a medium effect, and d = 0.8 a large effect. Due to differences in sample size and standard deviation among groups, even if the units and magnitudes of difference are the same, the significance of the same difference in inferential statistics is not entirely the same. In order to observe comparisons across paired groups, it is more reasonable to use the standardized effect size, Cohen's d. Differences in asymmetry across contrast levels, meridians, and eccentricities were visualized using line charts, with significant Cohen's d values in post-hoc comparisons indicated by an asterisk (*).

All statistical analyses were performed using IBM SPSS Statistics Version 25 (IBM Corp., Somers, New York), with statistical significance set at p <0.05 (two-tailed). Graphs and statistical charts were generated in Microsoft Excel (version 16.92).

3 | Results

3.1 | Participants

A total of 47 children participated in this study, of whom 39 met the inclusion criteria. The primary reason for exclusion was substandard VA. Among the 39 eligible children, two—one from the 4- to 5-year age group and another from the 6- to 7-year age group—did not complete all tests. Additionally, eight adults met the criteria and completed the experiment.

Children were categorized into three age groups: 4–5 years (n = 13), 6–7 years (n = 16), and 8–11 years (n = 8). Participants requiring refractive correction wore their prescribed glasses throughout the experiment. Most participants had no prior experience with psychophysical experiments except for three adults.

Participant demographics are summarized in Table 1. No significant differences were observed among the four groups in sex distribution (p = 0.73), eye dominance (p = 0.21), hand dominance (p = 0.86), SER of the left eye (p = 0.11), or monocular VA (OD: p = 0.05; OS: p = 0.08). Although SER of the right eye showed a significant group effect, pairwise comparisons among the children's groups were not significant. Binocular noncrowded and crowded VAs did not differ significantly among the 6–7 years, 8–11 years, and adult groups. The majority of participants were right-eye and right-hand dominant.

3.2 | Association between Recognition VA and Various Factors in the Four Age Groups

Participants underwent repeated DVA assessments at five eccentricities (0°, 2°, 4°, 6°, and 8°), two contrast levels (40% and 80%), and four meridians (x [+], x [−], y [+], and y [−]). DVAs along the x-axis were averaged into HM values, while those along the y-axis were averaged into VM values. Descriptive statistics for DVAs are provided in Table S1.

Table 2 summarizes the overall effects of each independent variable on DVAs. Age, eccentricity, and contrast exhibited consistent trends across the three models. The 4–5 years group demonstrated significantly higher DVAs than adults (p < 0.001), while no significant differences were observed among the other age groups. DVAs increased with eccentricity relative to 0° and were lower at 80% contrast than 40%.

However, DVAs varied across meridians. VM DVAs were significantly larger than HM DVAs (Model 1: B = 0.088, p < 0.001). Additionally, DVAs in the negative y-direction (y [−]) and positive x-direction (x [+]) were lower than in the corresponding opposite directions (B = −0.029, p < 0.001; B = 0.022, p = 0.013, respectively).

Figure 2 illustrates estimated DVA values across the eight meridians and four age groups in three models, with eccentricity as the independent variable at both contrast levels. Line charts indicate a relatively uniform HM/VM distribution; however, younger age groups—particularly the 4- to 5-year-olds—exhibited consistently higher DVAs. The VM results for this age group were particularly elevated (Figures 2A,D). In both x-axis and y-axis analyses, DVAs for the 4- to 5-year-olds differed markedly from those of older participants, irrespective of meridian direction. Across all conditions, acuity increased steadily with eccentricity (Figure 2B,C,E,F).

3.3 | Development of the Central and Peripheral Recognition VA

Post-hoc pairwise comparisons among the four age groups across all conditions are provided in Table S2 (p values). For clarity, Table 3 highlights significant differences using asterisks. The findings emphasize key distinctions between the youngest age group (4–5 years) and the other three groups. Table 3 reveals three

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TABLE 1 | Participant demographics.

	Group 1 **4 to <6 years** **(N = 13)**	**Group 2** **6 to <8 years** **(N = 16)**	**Group 3** **8 to <12 years** **(N = 8)**	**Group 4** **adult** **(N = 8)**	***p* value**
Age (years), mean (SD)	5.03 (0.61)	7.08 (0.64)	9.12 (1.04)	25.91 (3.98)	**< 0.001**
Sex, female, *n* (%)	6 (46.2)	7 (43.8)	5 (62.5)	5 (62.5)	0.728
Eye dominance, *n* (%)					0.208
Right eye	9 (69.2)	11 (68.8)	5 (62.5)	7 (87.5)	
Left eye	3 (23.1)	4 (25.0)	3 (37.5)	1 (12.5)	
Inconsistent	1 (7.7)	1 (6.3)	0 (0.0)	0 (0.0)	
Hand dominance, *n* (%)					0.860
Right handed	13 (100)	14 (87.5)	7 (87.5)	8 (100)	
Left handed	0 (0.0)	2 (12.5)	0 (0.0)	0 (0.0)	
Ambidextrous	0 (0.0)	0 (0.0)	1 (12.5)	0 (0.0)	
Mean refractive error					
OD_D.S. (SD)	+0.02 (0.54)	−0.05 (0.40)	−0.31 (0.74)	−1.46 (0.67)	**< 0.001**
OD_D.C. (SD)	−0.29 (0.35)	−0.19 (0.25)	−0.47 (0.31)	−0.31 (0.31)	0.219
OS_D.S. (SD)	+0.08 (0.33)	0.00 (0.27)	0.00 (0.94)	−0.75 (0.61)	0.051
OS_D.C. (SD)	−0.35 (0.42)	−0.31 (0.44)	−0.56 (0.32)	−0.18 (0.38)	0.415
SER (OD, D), mean (SD)	−0.13 (0.49)	−0.14 (0.46)	−0.55 (0.70)	−1.62 (0.80)	**< 0.001**
SER (OS, D), mean (SD)	−0.10 (0.43)	−0.15 (0.40)	−0.28 (0.85)	−0.84 (0.53)	0.109
Visual acuity (OD), mean (SD)	0.06 (0.12)	−0.06 (0.07)	0.04 (0.12)	−0.002 (0.16)	0.051
Visual acuity (OS), mean (SD)	0.05 (0.14)	−0.04 (0.09)	0.05 (0.12)	0.008 (0.10)	0.077
Visual acuity (OU), mean (SD)	−0.02 (0.06)	−0.10 (0.08)	−0.09 (0.08)	−0.12 (0.04)	**0.006**

Note: Boldface entries indicate statistical significance.

Abbreviations: D, diopter; D.C., diopters cylinder; D.S., diopters sphere; OD, right eye; OS, left eye; OU, both eyes; SER, spherical equivalent refractive error.

primary observations: (1) more significant results are observed at 40% contrast than at 80%, with lower contrast distinguishing the 4- to 5-year-olds from the 6- to 7-year-olds; (2) significant differences between the 4- to 5-year-olds and adults persist across both central and peripheral eccentricities; and (3) the magnitude of these differences diminishes as the age gap with adults decreases.

3.4 | Analysis of Asymmetry across Meridians

Figure 3 presents meridional asymmetries (HM/VM, y-axis, and x-axis) at different eccentricities under two contrast levels, quantified by Cohen's d. Significant asymmetries were limited, with minor variations along the y-axis at 80% contrast (Figure 3E) and the x-axis at both contrast levels (Figures 3C,F). However, notable asymmetries emerged along the y-axis at 40% contrast (Figure 3B) at 6° and 8° eccentricities, with significant differences across age groups.

At 80% contrast, HM/VM asymmetries were observed at 4°–8° eccentricities across all age groups, with Cohen's d values increasing with eccentricity and showing greater asymmetry in older individuals. At 40% contrast, HM/VM asymmetries were even more pronounced, extending from 2° to 8° eccentricities and increasing with both eccentricity and age. Trend lines for Cohen's d showed no overlap, indicating that asymmetry became more pronounced with age.

Overall, HVA was the most prominent asymmetry across all age groups, contrasts, and eccentricities. Vertical meridional asymmetry (VMA: y [+] vs. y [−]) showed moderate significance at 40% contrast at 6°–8° eccentricities, except in the 4- to 5-year age group. No significant differences were observed between x [+] and x [−] in any age group.

4 | Discussion

This study examined the development of central and peripheral recognition VA in children, focusing on eccentricity, age, contrast levels, and meridional asymmetries. The findings provide insights into VA maturation, highlighting developmental trends influenced by contrast and meridional differences. Notably, unlike orientation-based meridional anisotropies described in previous work [36], our results reflect polar-angle asymmetries in recognition VA across isoeccentric meridians.

Children under 6 years exhibited reduced acuity at both the fovea and peripheral locations, with significant declines at greater

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TABLE 2 | Generalized estimating equation (GEE) regression results for the effects of age, eccentricity, contrast, and meridian on Lea symbol recognition acuity (degrees of visual angle).

Variable	B (95% CI)	*p* value
Model 1 HVA		
Age (year)		
Adult	Reference	—
4 to <6	0.176 (0.102, 0.250)	**< 0.001**
6 to <8	0.047 (−0.013, 0.107)	0.125
8 to <12	0.001 (−0.051, 0.053)	0.979
Eccentricity (degree)		
0	Reference	
2	0.079 (0.056, 0.102)	**< 0.001**
4	0.154 (0.130, 0.178)	**< 0.001**
6	0.245 (0.214, 0.277)	**< 0.001**
8	0.329 (0.291, 0.368)	**< 0.001**
Contrast		
40%	Reference	
80%	−0.073 (−0.095, −0.051)	**< 0.001**
Meridians		
HM	Reference	
VM	0.088 (0.074, 0.103)	**< 0.001**
Model 2 VMA		
Age (year)		
Adult	Reference	—
4 to <6	0.184 (0.110, 0.257)	**< 0.001**
6 to <8	0.057 (−0.014, 0.129)	0.117
8 to <12	0.001 (−0.059, 0.062)	0.964
Eccentricity (degree)		
0	Reference	
2	0.076 (0.048, 0.103)	**< 0.001**
4	0.157 (0.126, 0.188)	**< 0.001**
6	0.275 (0.237, 0.314)	**< 0.001**
8	0.436 (0.391, 0.480)	**< 0.001**
Contrast		
40%	Reference	
80%	−0.080 (−0.104, −0.056)	**< 0.001**
Meridians		
y (+)	Reference	
y (−)	−0.029 (−0.043, −0.014)	**< 0.001**
Model 3 HMA		
Age (year)		
Adult	Reference	—
4 to <6	0.169 (0.090, 0.248)	**< 0.001**
6 to <8	0.035 (−0.013, 0.082)	0.154

(Continues)

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TABLE 2 | (Continued)

Model 3 HMA		
8 to <12	0.001 (−0.043, 0.046)	0.959
Eccentricity (degree)		
0	Reference	
2	0.051 (0.025, 0.077)	**< 0.001**
4	0.099 (0.075, 0.123)	**< 0.001**
6	0.159 (0.131, 0.188)	**< 0.001**
8	0.240 (0.198, 0.281)	**< 0.001**
Contrast		
40%	Reference	
80%	−0.067 (−0.091, −0.043)	**< 0.001**
Meridians		
x (+)	Reference	
x (−)	0.022 (0.005, 0.039)	**0.013**

Note: Boldface entries indicate statistical significance.Abbreviations: CI, confidence interval; DVA, degrees of visual angle; HM (horizontal meridian), the average of threshold along the positive *x*-axis and negative *x*-axis at the same eccentric location; HMA, horizontal meridian asymmetry; HVA, horizontal vertical anisotropy; VM (vertical meridian), the average of threshold along the positive *y*-axis and negative *y*-axis at the same eccentric location; VMA, vertical meridian asymmetry; *x* (−), negative direction of the *x*-axis; *x* (+), positive direction of the *x*-axis; *y* (−), negative direction of the *y*-axis; *y* (+), positive direction of the *y*-axis.

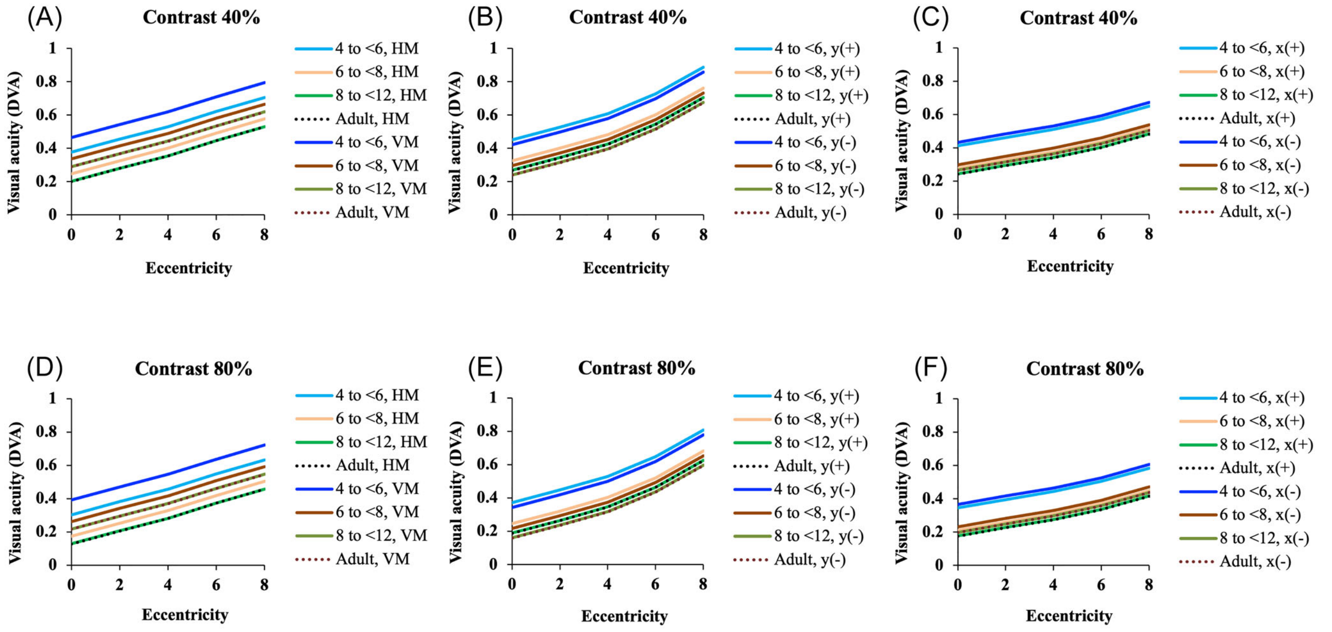

FIGURE 2 | Fitted binocular visual acuity at 40% and 80% contrast levels. This figure shows regression lines fitted to the mean degrees of visual acuity (DVA) scores at each eccentricity for 40% contrast (A-1–A-4) and 80% contrast (B-1–B-4) across the four age groups. Dots represent data points from the Lea symbol recognition task. *x*-axis: eccentricity (°); *y*-axis: estimated visual acuity (degree of visual angle [DVA]). Horizontal meridian (HM): the average DVA along the right meridian (positive *x*-axis direction) and left meridian (negative *x*-axis direction) at the same eccentricity. Vertical meridian (VM): the average DVA along the upper meridian (positive *y*-axis direction) and lower meridian (negative *y*-axis direction) at the same eccentricity. *y* (+): positive direction of *y*-axis; *y* (−): negative direction of *y*-axis.

eccentricities. However, foveal and peripheral acuity improve with age, reaching adult levels by age 6 or older. Visual perceptual asymmetries were observed along the VM, with superior acuity in the lower VF at 6° and 8° eccentricities under low contrast across all age groups, except in the 4- to 5-year-old group. Additionally, VA was consistently better along the HM than the VM, regardless of contrast. Peripheral acuity was lower in the superior and inferior VMs compared with the left and right HMs. No consistent asymmetries were found along the HM.

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TABLE 3 | Comparison of Lea symbol recognition acuity across age groups in degrees of visual angle.

	Contrast 40%						Contrast 80%					
Age groups	**4–5 versus 6–7**	**4–5 versus 8–11**	**4–5 versus adult**	**6–7 versus 8–11**	**6–7 versus adult**	**8–11 versus adult**	**4–5 versus 6–7**	**4–5 versus 8–11**	**4–5 versus adult**	**6–7 versus 8–11**	**6–7 versus adult**	**8–11 versus adult**
Meridian: x												
x (+), d0	*	*	*	—	—	—	—	*	*	—	—	—
x (+), d2	—	*	*	—	—	—	*	*	*	—	—	—
x (+), d4	*	*	*	—	—	—	—	*	*	—	—	—
x (+), d6	—	*	—	—	—	—	—	—	—	—	—	—
x (+), d8	*	*	*	—	—	—	*	*	*	—	—	—
x (−), d0	*	*	*	—	—	—	—	*	*	—	—	—
x (−), d2	*	*	*	—	—	—	—	*	*	—	—	—
x (−), d4	*	*	*	—	—	—	—	—	*	—	—	—
x (−), d6	*	*	*	—	—	—	*	*	*	—	—	—
x (−), d8	*	*	*	—	—	—	*	*	*	—	—	—
Meridian: y												
y (+), d0	*	*	*	—	—	—	—	*	*	—	—	—
y (+), d2	*	*	*	—	—	—	—	*	*	—	—	—
y (+), d4	—	—	*	—	—	—	—	—	—	—	—	—
y (+), d6	*	*	*	—	—	—	—	*	—	—	—	—
y (+), d8	—	—	*	—	—	—	*	*	*	—	—	—
y (−), d0	*	*	*	—	—	—	—	*	*	—	—	—
y (−), d2	*	*	*	—	—	—	—	—	—	—	—	—
y (−), d4	*	*	*	—	—	—	*	*	*	—	—	—
y (−), d6	*	—	*	—	—	—	*	*	*	—	—	—
y (−), d8	*	*	*	—	—	—	*	*	*	—	—	—
Meridian: HM/VM												
HM, d0	*	*	*	—	—	—	—	*	*	—	—	—
HM, d2	*	*	*	—	—	—	*	*	*	—	—	—
HM, d4	*	*	*	—	—	—	*	*	*	—	—	—
HM, d6	*	*	*	—	—	—	—	*	*	—	—	—
HM, d8	*	*	*	—	—	—	*	*	*	—	—	—
VM, d0	*	*	*	—	—	—	—	*	*	—	—	—
VM, d2	*	*	*	—	—	—	—	*	*	—	—	—
VM, d4	*	*	*	—	—	—	—	*	*	—	—	—
VM, d6	*	*	*	—	—	—	*	*	*	—	—	—
VM, d8	*	*	*	—	—	—	*	*	*	—	—	—

Abbreviations: d0, d2, d4, d6, and d8, indicating the location at the fovea and eccentricities of 2, 4, 6, and 8 degrees; HM (horizontal meridian), the average of threshold along the positive *x*-axis and negative *x*-axis at the same eccentric location; VM (vertical meridian), the average of threshold along the positive *y*-axis and negative *y*-axis at the same eccentric location; *x* (−), negative direction of the *x*-axis; *x* (+), positive direction of the *x*-axis; *y* (−), negative direction of the *y*-axis; *y* (+), positive direction of the *y*-axis.

* $p < 0.05$ of the corresponding post-hoc paired comparison.

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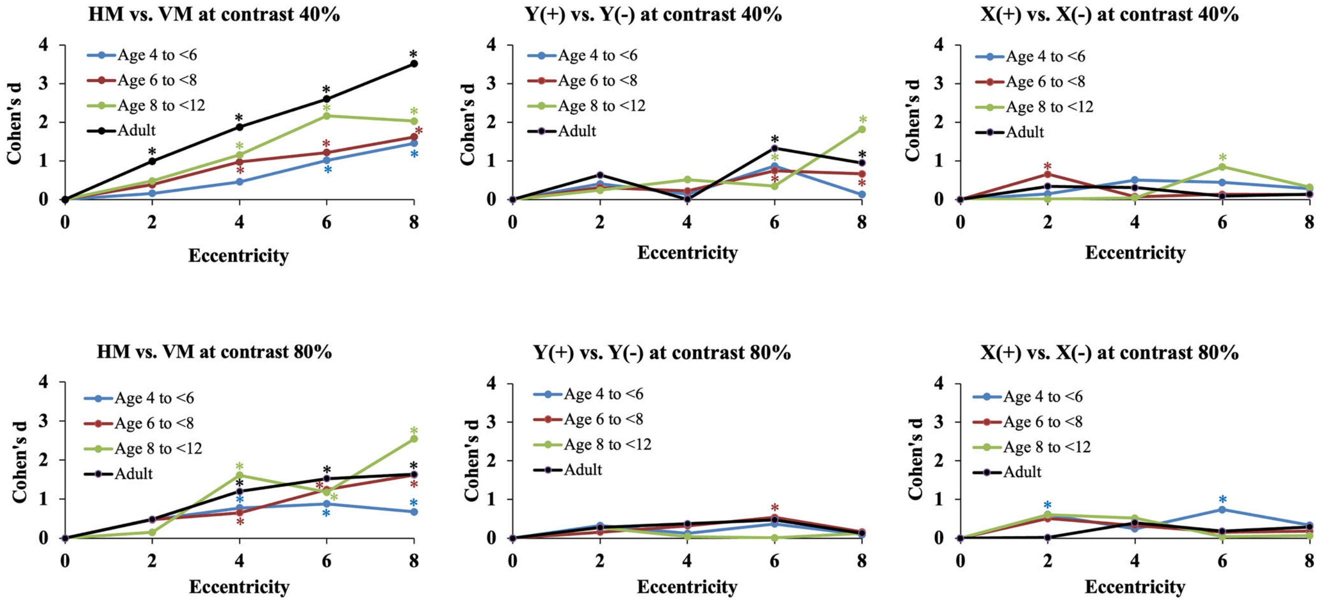

FIGURE 3 | Comparison of meridional asymmetries (HM/VM, *y*-axis, *x*-axis) at different eccentricities under two contrasts. Horizontal meridian (HM): the average degrees of visual angle (DVAs) along the right meridian (positive *x*-axis direction) and left meridian (negative *x*-axis direction) at the same eccentricity. Vertical meridian (VM): the average DVAs along the upper meridian (positive *y*-axis direction) and lower meridian (negative *y*-axis direction) at the same eccentricity. $y\ (+)$: positive direction of *y*-axis; $y\ (-)$: negative direction of *y*-axis. *: indicates significant asymmetry ($p < 0.05$).

4.1 | Development of Central and Peripheral Recognition VA

The Lea symbols are a well-established tool for assessing VA in children over 2.5 years old [36]. Our findings indicate that the youngest group (ages 4–5 years) exhibited the lowest acuity at both foveal and eccentric locations, with gradual improvements observed with age. By ages 8–11, children's VA closely resembled that of adults, highlighting significant maturation of both central and peripheral vision. These results align with previous research suggesting that central visual functions, including VA, continue to develop throughout childhood as visual neural pathways mature. Foveal VA reaches gross maturity by approximately age 5 or later [7, 36, 37].

Age-related differences in peripheral acuity were more pronounced at greater eccentricities, indicating slower development in these regions. Significant VA differences were observed between the 4- to 5-year-old group and older children or adults, particularly at 40% contrast. This suggests that younger children are more affected by lower contrast due to their underdeveloped CS. Lower contrast conditions exacerbated acuity differences, particularly at the fovea and perifovea, underscoring greater visual challenges for younger children in suboptimal viewing conditions.

These findings highlight the importance of using large, high-contrast objects when assessing the VF in young children. This is particularly relevant for children with cerebral visual impairment, who often rely on peripheral vision for visual tasks [38].

4.2 | Maturation of Contrast Effects and VA

Comparisons among age groups revealed that children aged 6–7 years performed similarly to adults under most conditions, whereas those aged 4- to 5-year-old exhibited significantly lower VA. This suggests a critical developmental phase between ages 4 and 8 years old, during which VA and CS improve substantially. The stronger effect of contrast on younger children reflects the ongoing maturation of their visual processing systems. These findings align with previous research indicating that CS develops later than spatial resolution, which enables fine-detail perception [7].

Our results contribute to the existing knowledge by demonstrating that CS develops more slowly in peripheral vision. Differences between the 40% and 80% contrast conditions suggest that lower contrast imposes greater demands on the immature visual systems of younger children. This has important implications for clinical assessments, emphasizing the need for age-appropriate visual testing methods.

4.3 | Asymmetry along HM and VM

Our study also examined visual perceptual asymmetries across the VF. Previous research has established that perception is not uniform along the meridians and varies based on stimulus characteristics [20]. Generally, the lower VF provides better support for visual tasks than the upper VF [39, 40]. In recognition-based visual perception, this phenomenon—known as VMA—becomes more pronounced with increasing eccentricity [19]. Studies using

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neuromagnetic recordings suggest that this asymmetry is most evident at eccentricities beyond 5° [11, 41, 42].

Our findings confirm that VMA is particularly pronounced at greater eccentricities (6° and 8°) across all age groups, except in the 4- to 5-year-old group. Even younger children, despite their incomplete VA maturation, demonstrated this asymmetry. Additionally, VA was consistently higher along the HM than the VM across all age groups and contrast levels, reinforcing previous findings that suggest greater sensitivity along the horizontal axis [11]. This asymmetry may stem from the anatomical and functional organization of the VF [24].

While prior studies in adults have shown similar peripheral asymmetries using both simple and complex stimuli [10, 18, 22], research on how these asymmetries affect central and peripheral VA during childhood remains limited [24]. Our results indicate that these asymmetries are present even in younger children who have reached adult-level VA. Moreover, the magnitude of HM and VM asymmetries increased with age, with adults displaying the greatest asymmetry, particularly under low-contrast conditions. This suggests that meridian-specific asymmetries continue to develop beyond early childhood, reflecting improvements in visual processing efficiency as the system matures [24].

Previous studies have discussed the potential underlying factors. Carrasco's research group, in their comprehensive review of polar angle asymmetries, emphasized that genetic and developmental factors contribute to these differences [28]. Consistent with this review, an fMRI study showed that children exhibit a cortical HVA but no cortical VMA, whereas the adult cortical VMA emerges from an increase in the amount of V1 tissue representing the lower vertical meridian [43]. Attention may also play an important role in shaping the development of VF and visual performance around the VF in children [44, 45]. However, in adults, both endogenous and exogenous attention enhance perception uniformly across meridians, but do not abolish HVA or VMA [46]. Beyond attentional influence, prior studies reporting the up/down anisotropies of vertical saccades and differences in the maturation of vertical oculomotor control in healthy children, suggesting that oculomotor factors may also contribute to the observed asymmetries [47, 48].

Notably, our results did not reveal significant asymmetries between the left and right VFs, suggesting a relatively balanced performance along this meridian in symbol recognition tasks. However, prior studies have reported that the left VF excels in linguistic and cognitive processing, potentially due to right hemisphere dominance in spatial attention [49]. This dominance varies depending on spatial frequencies [50].

4.4 | Limitations

This study has several limitations. First, the small sample size, particularly among younger children, may have led to data instability, emphasizing the need for larger samples in future research. Second, the complexity of the task required sustained attention and cooperation, favoring children with higher cognitive abilities. This selective inclusion may have introduced bias, limiting the representation of children with shorter attention spans. Third, we did not employ eye tracking to verify gaze position or fixation on every trial. Although we stabilized the head with a chin rest, used a central fixation point, randomized meridian order, provided practice until performance stabilized, and reminded participants between trials, small fixation errors cannot be ruled out. Fourth, in this study, VA was reported in DVA rather than logMAR. Although logMAR is the conventional unit in clinical and research practice, converting DVA to logMAR could be misleading because the computer-based presentation of Lea symbols was constrained by screen resolution and eccentricity-dependent scaling. Reporting results in DVA, therefore, provides a more accurate reflection of the measurement conditions, but this limits the direct comparability of our findings with studies that use logMAR.

5 | Conclusion

This study provides valuable insights into the development of central and peripheral VA in children and the role of CS in visual maturation. The findings highlight significant age-related and contrast-dependent differences, particularly in younger children, and underscore the importance of considering visual asymmetries in clinical assessments and rehabilitation. Recognizing meridian-specific differences in visual sensitivity can inform the development of more effective vision tests and education or rehabilitation protocols for pediatric populations.

Author Contributions

Conceptualization: L.-T.T. and C.-C.C. Data curation: L.-T.T. Formal analysis: L.-T.T. and C.-H.H. Funding acquisition: L.-T.T. and C.-H.H. Investigation: L.-T.T. Methodology: L.-T.T., C.-C.C., and C.-H.H. Project administration: L.-T.T. Resources: L.-T.T. Software: L.-T.T. Supervision: L.-T.T., C.-C.C., and C.-H.H. Validation: L.-T.T., C.-C.C., and C.-H.H. Visualization: L.-T.T., C.-C.C., and C.-H.H. Writing – original draft: L.-T.T. and C.-H.H. Writing – review and editing: L.-T.T., C.-C.C., and C.-H.H.

Conflicts of Interest

All authors declare no conflict of interest.

Peer Review

For transparency, the peer review documents associated with this article are available at https://doi.org/10.1111/nyas.70240.

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