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Development of foveal crowding in typically developing children and children with developmental dyslexia

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ABSTRACT

Foveal crowding refers to the impaired recognition of a foveal stimulus due to the presence of adjacent flankers. Previous research has produced inconsistent results regarding the maturation of foveal crowding, either at ages 5–7 or remaining elevated from ages 5 to at least 11. We investigated this developmental trajectory using a specialized set of digit stimuli (Pelli fonts) tailored for measuring foveal crowding. We measured foveal crowding in preschoolers, school-age typically developing children, and school-age children with developmental dyslexia, as well as in a group of adults. The results show that foveal crowding decreases with age, reaching adult-like levels around 8 years among preschoolers and typically developing children. Furthermore, dyslexic children exhibited heightened foveal crowding compared to their typical peers by approximately the same amount, regardless of age and reading level. Notably, preschoolers exhibited the most pronounced foveal crowding effects with considerable individual variability: some displayed crowding similar to that of older typical children and adults, while others exhibited similar or even higher levels of crowding compared to dyslexic children. This large variability suggests that foveal crowding may have the potential to serve as an early indicator for identifying developmental dyslexia, a possibility that warrants further longitudinal investigation.

1. Introduction

Visual crowding, defined as the impaired recognition of a target stimulus in the presence of adjacent flankers, is particularly significant in contexts that require rapid visual processing, such as reading, where individuals must efficiently recognize closely spaced letters and words (Pelli et al., 2007; Strasburger, 2020). Given that effective reading relies heavily on foveal vision, understanding how foveal crowding evolves with age is essential for investigating its impact on literacy development. Nevertheless, the developmental trajectory of foveal crowding among young children who are still acquiring reading skills remains unsolved.

Research has generally indicated that the strength of the foveal crowding effect reduces as visual and cognitive systems mature (e.g., Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988; Semenov, Chernova, & Bondarko, 2000; Bondarko & Semenov, 2005; Jeon, Hamid, Maurer, & Lewis, 2010; Norgett & Siderov, 2014; Doron, Spierer, & Polat, 2015; Lalor, Formankiewicz, & Waugh, 2018; Waugh & Formankiewicz, 2020). However, the specific age at which foveal crowding reaches adult-like levels is a matter of debate. For example, Atkinson et al. (1988) tested foveal crowding using letter stimuli, in which the target letter was surrounded by four other letters. They found that crowding decreased generally over preschool ages and reached adult levels at ages 5 to 7. In contrast, Jeon et al. (2010) found that significant and constant differences in crowding between children and adults persisted until at least age 11 when using a tumbling E target surrounded by 3-bar flankers (same as Es without the vertical bar). They attributed this discrepancy compared to Atkinson et al. (1988) to methodological differences, including finer measurement techniques.

However, the crowding stimuli used in Jeon et al. (2010) may create conditions that are difficult for children due to excessive feature

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similarity, which could lead to pronounced feature confusion and stronger crowding effects than those encountered in typical reading conditions. On the other hand, when regular letters are used as stimuli, often foveal crowding is still absent when adjacent letters are already abutting (Strasburger, Rentschler, & Juttner, 2011), making reliable assessment of this effect challenging. To address these limitations, we used a set of digit stimuli with a 1:5 aspect ratio designed by Pelli et al. (2016) in this study. These elongated stimuli remain visible and non-overlapping at small sizes and inter-letter spacings, enabling a more nuanced examination of the intricacies of foveal crowding.

We also studied the changes in foveal crowding as a function of age in school-age children with developmental dyslexia. Developmental dyslexia is characterized by difficulties with accurate and fluent word recognition, spelling, and decoding (Lyon, Shaywitz, & Shaywitz, 2003). Many studies have documented abnormal crowding effects in the visual periphery in dyslexic children (Bouma & Legein, 1977; Spinelli, De Luca, Judica, & Zoccolotti, 2002; Bertoni, Franceschini, Ronconi, Gori, & Facoetti, 2019). In contrast, foveal crowding in dyslexia has been rarely studied, probably because early research by Bouma and Legein (1977) only discovered weak foveal crowding in some, but not all, dyslexic children. However, a recent study of ours (Liu, Yu, Hao, Wang, & Wang, 2024) revisited this topic using Pelli fonts tailored for measuring foveal crowding (Pelli et al., 2016) (see Fig. 1). The results revealed significantly heightened foveal crowding in dyslexic children compared to the typically developing children. Moreover, the severity of foveal crowding in the dyslexic group was correlated with their maximum reading speed and reading acuity measured with Chinese Reading Acuity Charts (C-READ) (Han, Cong, Yu, & Liu, 2017), which established a link between foveal crowding and reading abilities. We studied the change in foveal crowding with age in school-age dyslexic children compared to their typically developing peers. Moreover, as dyslexic children are typically identified in the early years of elementary school, we explored whether foveal crowding could potentially serve as an early indicator of developmental dyslexia.

2. Methods

2.1. Participants

One hundred sixty-four preschool and elementary-school Chinese children and 13 adults (6 males, mean age = 21.46 ± 0.71 (*SE*) years) participated in this study. The children were divided into three groups: a preschooler group ($N = 32$, 11 boys, 5.72 ± 0.14 years old, range = 4 to 6 years), a developmental dyslexia (DD) group ($N = 94$, 58 boys, 9.23 ± 0.15 years old, range = 7 to 14 years), and a typically developing (TD) group ($N = 68$, 37 boys, 9.73 ± 0.21 years old, range = 7 to 13 years). Age was calculated as years + months/12 based on the date of birth. Individual data plots use these continuous age values, while group averages were binned with a 1-year bin width. Those in the DD group were defined as having scores 1.5 standard deviations below the mean for their grade level on a Chinese character recognition test (Liu et al., 2017), and those in the TD group had their recognition scores above one standard deviation below the mean. As part of an ongoing study, data from our previous paper (Liu et al., 2024) were combined with newly collected data for analysis from a developmental perspective. The data in Liu et al. (2024) included 64 children with dyslexia and 43 typically developing children aged 7 or older. Additional data were newly collected, including 32 in the preschooler group, 13 in the adult group, and an additional 30 in the DD group and 25 in the TD group.

The dyslexic children were recruited from Peking University Sixth Hospital, while preschoolers and typical children were recruited from local kindergartens and elementary schools. All participants were native Mandarin speakers with normal hearing and vision (or corrected vision), without intellectual disabilities (i.e., normal Raven IQ scores), other developmental or mental disorders, or any history of head injury or neurological conditions. Informed consent was obtained from all participants or their parents before data collection. The study was approved by the Ethics Committee of the Peking University Sixth Hospital and the Peking University Institution Review Board and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Apparatus and stimuli

The stimuli were generated with MATLAB-based Psychtoolbox-3 (Pelli, 1997) and presented on a 13.9-inch laptop monitor with a display resolution of 1920 × 1080 pixels and a frame rate of 60 Hz. The pixel size was 0.161 arcmin in both width and height at the current viewing distance of 210 cm. The mean luminance was 50 cd/m^2. Observers viewed the displays binocularly, with head movements minimized using a head and chin rest.

The stimuli consisted of five digits (1, 2, 3, 5, & 7, Fig. 1A) from a set of specially designed digits with an aspect ratio of 1:5 and strokes half the digit width (Pelli et al., 2016). Four other digits (4, 6, 8, 9) in the stimulus set were excluded because they contained large ink areas that could facilitate discrimination from each other and from other digits. Participating children had the opportunity to get familiar with these five digits prior to data collection, and a sheet of printed digits was provided in front of them for reference during the test. In the experiment, a target digit was presented at the fovea, with or without two flanking digits on each side (Fig. 1B). Three digits were randomly selected and always different from each other. The edge-to-edge separation between digits was always one-digit width.

2.3. Procedure

In each trial, a fixation cross was first presented for a random duration of 300 to 500 ms, followed by a 200-ms blank interval, and

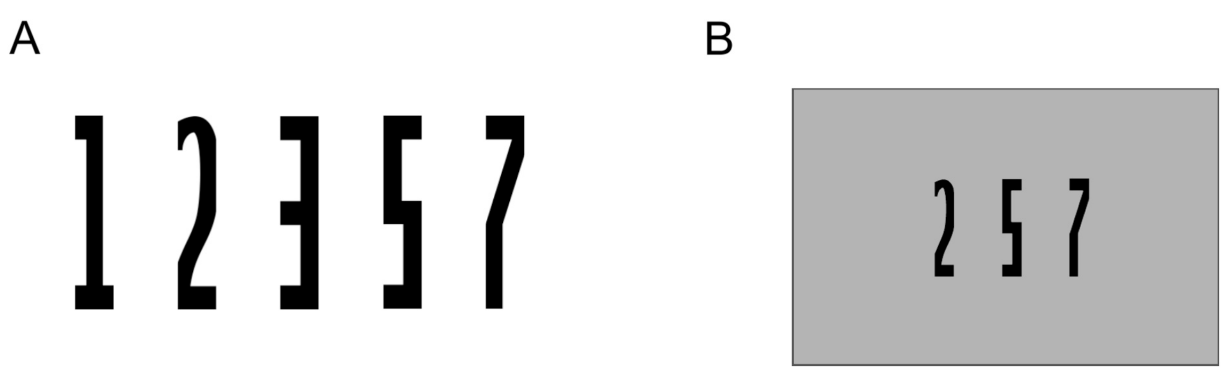

Fig. 1. Stimuli. **A.** Five Pelli font digits used in the experiments. **B.** An example of the stimulus configuration. Participants were required to report the foveal digit stimulus which was presented either alone or with two flanking digits on each side.

then a 200-ms stimulus presentation. Target recognition thresholds were determined using a QUEST adaptive method (Watson & Pelli, 1983), adjusting the digit width to achieve a 70 % accuracy. The resulting thresholds were log-transformed (i.e., logMAR) for all analyses. Each QUEST run involved 30 trials. Children were instructed to verbally report the digit target presented alone or the central digit target when flanked, while their responses were recorded by the experimenter. A correct response was followed by a smiling face as the feedback, while an incorrect response was followed by a sad face and a beep. The Quest staircases with unflanked or flanked stimulus conditions were run in an interleaved sequence. Three Quest staircases were typically performed for each stimulus condition, and the mean threshold was used in data analysis.

2.4. Data and data analysis

Data were analyzed with JASP 0.16.3, which included descriptive statistics, one-way ANOVA, and post hoc comparisons. Curve fitting and parameter estimation were performed using a MATLAB 'lsqnonlin' function.

3. Results

The individual thresholds for unflanked single-digit condition and their year-by-year group-average thresholds are illustrated in Fig. 2A, in the left and right panels, respectively. There was a clear initial decline in recognition thresholds within the preschooler group, which then leveled off around 5 years of age and remained largely unchanged in older children in both this and the school-age typically developing group. To quantify this inflection age, we fitted the data using a two-limb function:

$$Threshold = \begin{cases} k \cdot Age + (b - k \cdot a) \text{ if } Age < a \\ b \text{ if } Age \geq a \end{cases}$$

In this equation, the parameter k represented the slope of the initial linear function up to the inflection or maturation age, the parameter a denoted the maturation age of the threshold, and the parameter b signified the threshold at this maturation age. Data fitting yielded satisfactory results (goodness-of-fit $R^2 = 0.93$), showing a decline in single-digit recognition threshold with age at a slope of -0.182 ± 0.154, which leveled off at 5.562 ± 0.703 years of age. This finding aligns with earlier research indicating that visual acuity reaches adult levels around this age (Mayer & Dobson, 1982).

Furthermore, we used ANCOVA to compare the threshold differences between school-age typical and dyslexic children, using Group (TD vs. DD) as a fixed factor and Age as a covariate. The results revealed no significant main effects for Group ($p = 0.139$, $\eta_p^2 = 0.014$) or Age ($p = 0.255$, $\eta_p^2 = 0.008$). This suggests that, during school ages, single-digit thresholds remained consistent across age and are similar between TD and DD groups, consistent with the general assumption that dyslexic children possess normal visual acuity. Notably, a few typical children displayed higher thresholds compared to other participants across all groups. This discrepancy may be attributed to inadequate vision correction during testing in school settings. However, the statistical conclusions remained unchanged even when excluding these four typical children with the highest thresholds from data analysis (Group: $p = 0.292$, $\eta_p^2 = 0.007$; Age: $p = 0.363$, $\eta_p^2 = 0.005$).

When the digit target was flanked by additional digits, the thresholds for recognizing the central digit target increased, indicating foveal crowding (Fig. 2B). We fitted the flanked thresholds for preschoolers and typical children using the same two-limb function, achieving a goodness-of-fit of $R^2 = 0.96$. Model fitting results indicated that flanked thresholds initially declined with age at a rate (slope) of -0.397 ± 0.340 before leveling off at 5.974 ± 1.088 years old, where the threshold reached 0.542 ± 0.049 logMAR. Furthermore, we compared the flanked thresholds of older typical children (those over 10 years old) to those of adults, which revealed no significant difference ($p = 0.550$, *Cohen's d* = 0.199; independent-sample *t*-test). An ANCOVA that examined flanked thresholds between TD and DD groups revealed significant main effects for Group ($F(1, 158) = 24.65$, $p < 0.001$, $\eta_p^2 = 0.134$) and Age ($F(1, 158) = 9.295$, $p = 0.003$, $\eta_p^2 = 0.055$), but no significant interaction between Group and Age ($p = 0.693$, $\eta_p^2 = 0.002$). The significant main effect of Group suggests that, unlike in the single-digit threshold case, dyslexic children exhibited significantly higher flanked thresholds compared to their typically developing peers. The significant main effect for Age is consistent with the two-limb model fitting that flanked thresholds mature around the early school years. Moreover, the lack of a significant Group and Age interaction suggests that dyslexic children perform worse than their typical peers at the same age.

We employed a foveal crowding index (FCI), calculated as the flanked logMAR − unflanked logMAR (Doron et al., 2015), to summarize our results (Fig. 2C). We fitted the FCI function for preschoolers and typical school-age children using the two-limb function (goodness-of-fit $R^2 = 0.87$). The results showed that foveal crowding first declined with age at a slope of -0.106 ± 0.070, reaching maturity around 8.046 ± 1.620 years, with an FCI of 0.194 ± 0.045 logMAR. The FCIs for older typical children (over 10 years old) did not significantly differ from those of the adults ($p = 0.092$, *Cohen's d* = 0.570; independent-sample *t*-test). An ANCOVA to examine Group (TD vs. DD) and Age effects revealed significant main effects for Group ($F(1, 158) = 52.33$, $p < 0.001$, $\eta_p^2 = 0.773$) and Age ($F(1, 158) = 22.19$, $p < 0.001$, $\eta_p^2 = 0.029$), with no significant interaction between the two factors ($p = 0.34$, $\eta_p^2 = 0.007$). These results further suggest that dyslexic children exhibited higher levels of foveal crowding than typical children across all ages.

Notably, the individual variations within the preschooler group were much larger than those in the other groups, as evidenced by the wide spread of individual data points (Fig. 2C left) and the error bars representing the means (Fig. 2C right). Some preschoolers showed FCIs comparable to those of typical children, while others had higher FCIs that were similar to, or even exceeding, those of dyslexic children. We will revisit this issue in the Discussion.

One common concern in dyslexia research is that the poorer performance of dyslexic children, compared to their typically developing peers of similar age, may be attributed to differences in reading experience. To investigate this issue, we selected two groups of dyslexic and typical children from our pool of participating children whose reading abilities were matched on the basis of scores from the Chinese reading acuity charts (C-READ). This specialized tool measures reading performance, including reading acuity, maximum reading speed, and critical print size, using simplified Chinese characters (Han et al., 2017). Thirteen pairs of dyslexic and typical children were selected. The dyslexic children had a mean age of 10.19 ± 0.41 years, while the typical children had a mean age of 8.51 ± 0.25 years, showing a significant difference ($t = 5.50$, $df = 12$, $p < 0.001$, *Cohen's d* = 1.524). In terms of reading speed, the dyslexia children had a mean score of 112.49 ± 9.90 char/sec, not significantly different from 111.61 ± 9.99 char/sec in the typical children ($p = 0.082$, *Cohen's d* = -0.526; Fig. 3). However, the FCIs differed significantly between the two groups, with dyslexic children showing a FCI of 0.35 ± 0.10 logMAR, while typical children exhibited a FCI of 0.20 ± 0.03 logMAR ($t = 3.71$, $df = 12$, $p = 0.003$, *Cohen's d* = 1.028). These findings suggest that the difference in FCI between dyslexic and typical children is unlikely to be due to differences in reading experience.

4. Discussion

Our study provides a detailed description of the developmental trajectory of foveal crowding. In preschool and typically developing school-age children, foveal crowding declines with age until leveling off around 8 years. In addition, dyslexic children consistently exhibit heightened foveal crowding effects compared to their typically developing peers independent of age. Notably, preschoolers display substantial variation

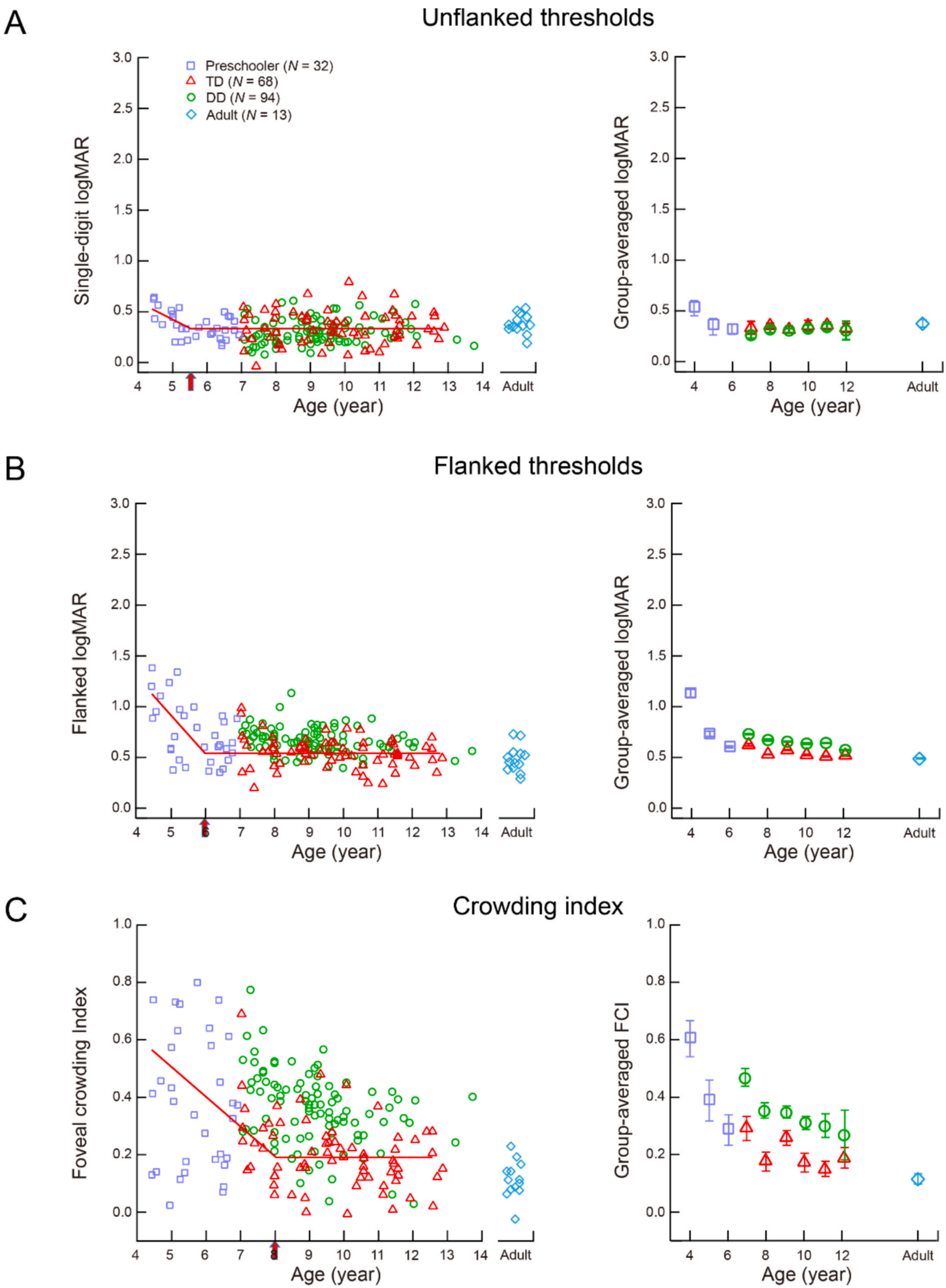

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Fig. 2. The development of foveal crowding. **A**. Unflanked single-digit thresholds. Left: Individual thresholds plotted against age for preschooler, TD, DD, and adult groups. Right: Year-by-year group averages of unflanked single-digit thresholds across the different groups. **B**. Flanked digit recognition thresholds. Left: Individual thresholds plotted against age for preschooler, TD, DD, and adult groups. Right: Year-by-year group averages of flanked digit thresholds across the different groups. **C**. Foveal crowding measured using foveal crowding index (FCI). Left: Individual FCIs plotted against age across preschooler, TD, DD, and adult groups. Right: Year-by-year group averages of FCIs across the different groups. The red lines indicate two-limb fits for the preschooler and TD data. Red arrows indicate the inflection points of the fitted functions. Individual data points show age as years + months/12. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

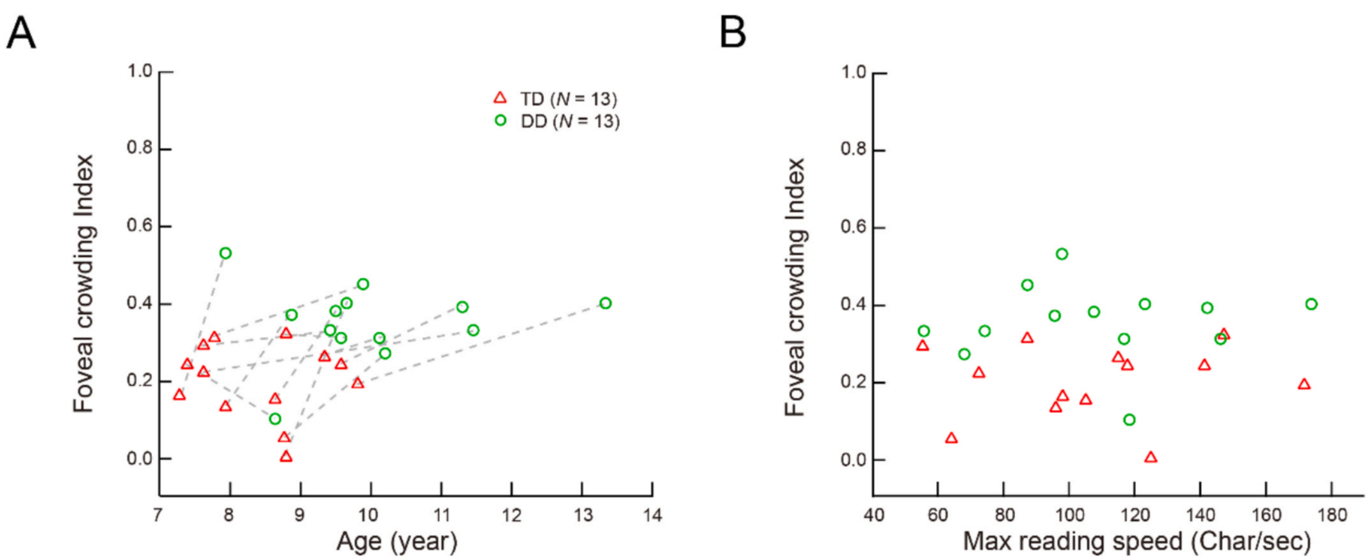

Fig. 3. Foveal crowding index in reading-level matched dyslexic and typical children. **A.** Foveal crowding index as a function of age. **B.** Foveal crowding index as a function of maximum reading speed.

in foveal crowding, which may have potential implications for early identification and intervention strategies, as discussed below.

Our findings are consistent with several previous reports indicating that foveal crowding undergoes significant development during early childhood (e.g., Atkinson et al., 1988; Doron et al., 2015). Whether the developmental change is due to reduced feature mis-integration beyond feature detection (Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004; Greenwood, Bex, & Dakin, 2009), improved attentional resolution (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001), or lessened target mislocation (Huckauf & Heller, 2002; Zhang, Zhang, Liu, & Yu, 2012), all of which have been proposed as mechanisms underlying peripheral crowding, remains to be experimentally clarified. Nevertheless, the sharp decline in foveal crowding effects observed in the preschooler group (ages 4–6) highlights a critical developmental phase in the maturation of this foveal phenomenon.

In contrast to Jeon et al. (2010), who reported minimal changes in foveal crowding from ages 5 to 11, we found that foveal crowding levels off at around age 8. This discrepancy may partly stem from differences in stimulus materials: Jeon et al. (2010) used a tumbling E target surrounded by 3-bar flankers (i.e., an E with the vertical bar removed) on all four sides. The high similarity of stimulus features between the E target and the 3-bar flankers likely led to greater crowding effects. Notably, the foveal crowding of the 5-year-old group in Jeon et al. (2010) showed error bars at least twice as large as those for the 8- and 11-year-old groups. This suggests that many 5-year-olds exhibited significantly weaker foveal crowding than their older counterparts, a finding that is peculiar and difficult to explain.

Previous research on crowding effects in dyslexic children has primarily focused on parafoveal and peripheral vision, consistently showing stronger crowding in dyslexic children compared to their typical peers (Bouma & Legein, 1977; Geiger & Lettvin, 1987; Spinelli et al., 2002; Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Bertoni et al., 2019). Our previous study (Liu et al., 2024) reveals significantly higher foveal crowding as well, demonstrating a correlation between foveal crowding effects and reading performance in dyslexic children. This finding is consistent with the view that dyslexic individuals require more cognitive and perceptual resources for letter recognition (Spinelli et al., 2002; Bertoni et al., 2019). Although we did not compare peripheral and foveal crowding with the same Pelli fonts, peripheral crowding in general is expected to be much stronger, which is a known fact as foveal crowding was believed to be unmeasurable for a long while. It is not quite clear whether the mechanisms underlying foveal and peripheral crowding are the same. For example, in peripheral crowding experiments, reporting errors often involve misidentifying a flanker as the target (Huckauf & Heller, 2002), or reporting the target at a flanker position when both the flankers and the target need to be reported (Zhang et al., 2012). However, our unpublished data indicate that such positional errors are not evident in foveal crowding, in contrast to Kalpadakis-Smith, Tailor, Dahlmann-Noor, and Greenwood (2022), who reported positional errors in both foveal crowding in typically developing children and peripheral crowding in adults. This difference of observations will be addressed in future work.

The role of crowding in reading difficulties remains debated. While Zorzi et al. (2012) found that increased letter spacing improves reading in dyslexic children, others have reported no such significant impact (Doron et al., 2015; van den Boer & Hakvoort, 2015), or that the benefits are limited to a subset of stimuli causing stronger crowding (Joo, White, Strodtman, & Yeatman, 2018). Our earlier work (Liu et al., 2024) established a significant correlation between foveal crowding and reading performance in dyslexic children, which does not necessarily suggest foveal crowding being a causal factor. Further evidence is needed to clarify whether reducing foveal and peripheral crowding through increased letter spacing can benefit reading in dyslexic children, particularly after a period of practice to mitigate the effects of reduced reading experience.

A noteworthy finding from our study is the substantial individual variability in foveal crowding observed among preschoolers. While some preschoolers demonstrated crowding effects comparable to those of older typically developing peers and adults, others exhibited levels of crowding equal to or even exceeding those seen in children with developmental dyslexia. The excessive foveal crowding in part of these young children may be contributed to attentional lapses, uncorrected optical issues, unfamiliarity with Pelli fonts, and brief presentation durations (200 ms), etc., as prior studies have demonstrated that young children are particularly susceptible to attentional fluctuations and unstable viewing behavior (Manning, Jones, Dekker, & Pellicano, 2018) which may interact with crowding to amplify performance variability (Vickery, Shim, Chakravarthi, Jiang, & Luedeman, 2009; Soo, Chakravarthi, & Andersen, 2018). It is intriguing to hypothesize that the over-strong crowding effects, regardless of their causes, may predict poor reading performance and help identify dyslexia in preschoolers before formal reading instruction. Such a possibility, which we aim to confirm through longitudinal experiments, could be crucial, as addressing visual processing challenges early may improve overall reading outcomes and developmental trajectories for at-risk preschoolers.

CRediT authorship contribution statement

Yan-Ru Chen: Writing – original draft, Methodology, Formal analysis, Data curation. **Xiao-He Yu:** Writing – original draft, Methodology, Investigation, Data curation. **Jun-Yun Zhang:** Writing – review & editing, Supervision, Project administration. **Jiu-Ju Wang:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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.

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Data availability

Data will be made available on request.

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