Foveal crowding differs in children and adults

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We used custom-designed acuity tests to compare the magnitude and extent of crowded letter recognition in children and adults. Visual acuity (logMAR) was measured monocularly in children and adults using five custom-designed letter tests with varying degrees of crowding: single letter, single letter surrounded by four flanking bars, single letter surrounded by four flanking letters, line of five letters surrounded by flanking bars, and line of five letters surrounded by flanking letters. The tests were constructed using Sloan letters and presented on an iPad (Apple Incorporated, Cupertino, CA) at 4 m using a standardized endpoint and instructions. Crowded logMAR was normalized to unflanked logMAR and results were analyzed in three groups: younger children aged 4–6 (n = 32), older children, aged 7–9 (n = 30), and adults (n = 27). Both groups of children showed a greater extent of crowding than the adults. The adult participants showed no difference in performance between single or linear presentation and letter or bar flankers. Letter flankers and linear presentation individually resulted in poorer performance in the younger children $p < 0.001$ and $p = 0.003$, respectively (mean normalized logMAR 0.17 in each case) and together had an additive effect (mean 0.24), $p < 0.001$. Crowding in the older children was adult-like except in the linear presentation with letter flankers, $p < 0.001$. These results indicate that both target-flanker similarity and linear presentation contribute more to foveal crowding in young children than in adults.

Introduction

Measuring visual acuity accurately in children is important in screening for amblyopia, refractive error, and other ocular abnormalities. The use of crowded acuity tests for children increases the sensitivity of amblyopia detection (Hilton & Stanley, 1972; Song, Levi, & Pelli, 2014; Youngson, 1975), but commercially available crowded tests use different interoptotype spacing, flanker type (line, box, or letter), and optotype arrangement (single or linear), which affect the amount of crowding present (Huurneman, Boonstra, Cox, Cillessen, & Van Rens, 2012; Norgett & Siderov, 2011).

In a clinical sense, crowding is the reduction in visual acuity in the presence of nearby flanking bars or optotypes. Crowding is sometimes used interchangeably with contour interaction, which is the more specific reduction in visual acuity caused by the proximity of nearby contours (Flom, Weymouth, & Kahneman, 1963b). Here we consider crowding in the aggregate to include contour interaction, imprecise gaze control (Kothe & Regan, 1990), and attentional influences (Flom, 1991; Leat, Li, & Epp, 1999).

Recent theories of crowding argue for a two-stage process in object identification, where features are first detected, independent of each other and then integrated to allow object recognition to occur (Levi, 2008; Pelli, Palomares, & Majaj, 2004). Flanking contours or optotypes present within the zone of integration may be inappropriately integrated with the target features (substituted or pooled), causing a misperception of the object. Although such theories have been developed to account for crowding in the periphery, they may also apply to foveal crowding in children. Alternative theories based on antagonistic receptive field interactions that occur in early stages of visual processing (Bedell et al., 2013; Latham & Whitaker, 1996), or mechanisms based on a form of overlap masking have also been proposed to account for foveal crowding (Song, Levi, & Pelli, 2014).

Although visual acuity develops rapidly in the first 6 months of life, it does not mature until between about 4 and 6 years of age, (for reviews, see Braddick & Atkinson, 2011; Fern & Manny, 1986; Leat, Yadav, &

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Irving, 2009). As the optical quality of the eyes of such children is at least as good as adults (Carkeet, Leo, Khoo, & Eong, 2003), limitations to children's visual acuity probably reflect retinal or cortical immaturity. However, the developmental course of crowded visual acuity appears slower than that of uncrowded letter acuity (Drover et al., 2008; Langaas; Morad, Werker, & Nemet, 1999; Norgett & Siderov, 2011; Pan et al., 2009; Sonksen, Wade, Proffitt, Heavens, & Salt, 2008), (although others have proposed parallel developmental courses [Kothe & Regan, 1990]). The maximum distance from optotype to flanker where recognition of the optotype is impaired, is referred to as the "critical spacing." For foveal crowding, the critical spacing appears to be up to twice as large in young children than in adults, reaching adult levels between 9 and 12 years of age or older (Bondarko & Semenov, 2005; Jeon, Hamid, Maurer, & Lewis, 2010; Semenov, Chernova, & Bondarko, 2000).

Differences in the depth of crowding between children and adults are less certain and results are conflicting (Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988; Manny, Fern, & Loshin, 1987; Zhang, Zhang, Xue, Liu, & Yu, 2009). Variation in targets and flankers may play an important part in contributing to the different results noted, as differently sized and shaped targets may not be processed by the same cortical receptive fields (Danilova & Bondarko, 2006) or may reflect differences in the attentional demands required (Desimone & Duncan, 1995).

In the adult periphery, there is more crowding when the flankers and target are similar rather than dissimilar (Bernard & Chung, 2011; Freeman, Chakravarthi, & Pelli, 2012; Leat et al., 1999; Nazir, 1992), but such dependence does not appear for adult foveal crowding (Leat et al., 1999; Song et al., 2014). On the other hand, the similarity of target and flankers may increase foveal crowding in children because of a greater attention demand needed to separate the target from the flanking elements (Atkinson, 1991).

Immature development of eye movement control may also contribute to foveal crowding in children (Kothe & Regan, 1990), a notion supported from direct measurement of children's fixational eye movements that show an increase in the variability of fixational eye movements in young children (Aring, Grönlund, Hellström, & Ygge, 2007; Kowler & Martins, 1982). However, it is not clear whether such fixational instability is sufficient to interfere with visual acuity (Flom, 1991).

In summary, foveal crowding in children displays a larger critical spacing than in adults, which becomes adult-like possibly as late as the early teen years (Jeon et al., 2010; Semenov et al., 2000), target-flanker similarity may have an effect on foveal crowding in children that is not present in adult foveal viewing (Atkinson, 1991), and linear presentation of optotypes requiring multiple fixations may produce poorer visual acuity in young children than single, similarly crowded optotypes due to an increase in fixational instability, or relatively poorer saccadic accuracy (Aring et al., 2007). Therefore, the aim of the current study was to determine the effects of foveal crowding on visual acuity in normally sighted children at various ages as a function of target-flanker separation, single versus linear presentation of optotypes and target-flanker similarity.

Methods

Participants

Seventy-five children were recruited from a local elementary (primary) school in Cambridge, UK, and a control group of 27 adults was recruited from the local community. Written, informed consent was obtained from the children's parents or guardians and from the adult participants and verbal assent from the children, after all the procedures were explained to them. Ethical approval for the study was obtained from the University Research Ethics Panel and the study followed the tenets of the Declaration of Helsinki. All participants were screened and excluded from the study if any one of the following criteria were met: visual acuity worse than 6/9 (20/30) on the Snellen chart; significant hyperopia, defined as visual acuity of 6/12 (20/40) or better when viewing through a +2.00D lens; presence of strabismus on cover test or no stereopsis measured on the Lang II Stereotest (Lang-Stereotest, Küsnacht, Switzerland), and an inability to cooperate with the experimental protocol. Four children who failed the screening were referred to an optometrist for a full eye examination and four other children did not complete all of the tests. None of these children were included in the study. A further five children were not available on the test days.

For analysis, participants were grouped into three age bands, 4–6 years (32 participants, mean age 5 years, 9 months), 7–9 years (30 participants, mean age 8 years, 7 months) and adults over 18 years (27 participants, mean age 25 years, 0 months). The number of participants in each group was sufficient to obtain a power of 80% at the 5% level (two-tailed) for an effect size of 0.1 logMAR.

Tests

A series of letter tests was produced comprising single letters and lines of letters, with bar and letter

Test	Letter target	Flanker type	Flanker spacing	Example display
S_0	single	no flanks		H
$SB_{0.25}$	single	bars	0.25	C
$SB_{0.5}$	single	bars	0.5	C
$SB_{1.0}$	single	bars	1.0	C
$SB_{1.5}$	single	bars	1.5	C
$LB_{0.5}$	linear	bars	0.5	CHDNO
$SC_{0.5}$	single	characters	0.5	M AKB J
$LC_{0.5}$	linear	characters	0.5	FQUYA ROHDNSK BWJMT

Table 1. Test chart configurations. Tests used in the study are shown, with an example presentation of each. Letters were presented in single (S) or linear (L) format with bar (B) or character(C) flankers. The edge-to-edge separation measured as a proportion of letter size is denoted by the subscript.

flankers to create a number of conditions where the influence of contour interaction, eye movements and attention could be inferred (Table 1). The tests used the Sloan letter set, constructed in a 5 × 5 format, with the height and the width of each letter five times the stroke width. Individual relative legibility of each Sloan letter differs by no more than 12% from the mean relative legibility of the set (Sloan, Rowland, & Altman, 1952). The tests were produced using Adobe Illustrator CS5 (Adobe Systems Incorporated, San Jose, CA). Non-Sloan letters, except the letter "I," were used as flanking letters and were constructed in the same way using the same software (Pelli et al., 1988).

Tests were displayed, black letters on a white background, on an iPad 2 (Apple Incorporated, Cupertino, CA) with a resolution of 1024 × 768 at 132 pixels per inch, so 1 pixel subtended 0.17′ of arc at a test distance of 4 m. The iPad's auto-brightness function was disabled and the brightness set to maximum. Background luminance of the display was 310 cd/m^2, resulting in a letter Weber contrast of –99%.

The acuity range of the tests was logMAR 0.4 to logMAR –0.4 in steps of 0.05 logMAR and for each level of acuity, five letters were scored on each test. In the single letter presentations, five different letters of the same size were shown consecutively. Each set of five letters was selected to have a similar combined relative legibility of 4.9 (Strong & Woo, 1985). Tests were constructed with edge-to-edge separations between flankers and optotypes ranging from 0.25 to 1.5 letter widths and including an unflanked condition (Table 1). The length of the bar flankers was 0.6 times letter height, or three stroke widths, based on maintaining a constant average length of flanking edge nearest to the target. The line tests were constructed so that letters broadly composed of straight lines (e.g., H, N, V, K, Z) alternated with round-shaped letters (O, D, C, S, R).

Baseline data using test S_0 (unflanked logMAR), were used to normalize subsequent results to minimize any potential confound between letter size and interletter spacing for different acuity sizes (Levi, 2008).

The following between test comparisons were made:

1. $SB_{0.25}$, $SB_{0.5}$, $SB_{1.0}$ and $SB_{1.5}$ to determine the magnitude and extent of contour interaction
2. $SB_{0.5}$ with $LB_{0.5}$ and $SC_{0.5}$ with $LC_{0.5}$, to determine the effect of linear presentation, with controlled contour interaction
3. $SB_{0.5}$ with $SC_{0.5}$ and $LB_{0.5}$ with $LC_{0.5}$ to determine the effect of letter rather than bar flankers (increased attention demand), with controlled contour interaction

In $LB_{0.5}$, the bar flanker between letters was retained so that the next nearest contour to each letter would always be a bar at 0.5 letter widths separation from the target letter, as in $SB_{0.5}$.

Procedure

Children were tested in a school classroom with lighting adequate for visual acuity testing (National Academy of Sciences, National Research Council Committee on Vision, 1980), approximately 100 lux. The experimental tests were viewed by the right eye of eligible participants and spectacles were worn if habitually used. Participants sat 4 m from the iPad, which was mounted on a tripod stand directly in front of them in a position where reflections from the screen were not evident (Black et al., 2013). Participants held a card showing the 10 Sloan letters. Where children were unable to name a letter, they pointed to it on the card. The experimental tests were shown in a random order and participants were allowed unlimited viewing time. Testing began using a letter size 0.1 logMAR larger than the acuity found from initial screening. Smaller letter sizes were presented in steps of 0.05 logMAR until the termination point was reached, at which three or more letters of one size were named incorrectly. If any letters at the starting level were named incorrectly, the next largest size was presented until a size was found where all five responses were correct. When a participant was not sure of a letter, they were encouraged once to guess. For the single-letter test with letter flankers, $SC_{0.5}$, participants were asked to read the middle letter only. For the line test with letter flankers, $LC_{0.5}$, participants were asked to read all the letters on the middle row but only the central five letters were scored. A red line on the left hand side of the two line tests, $LB_{0.5}$ and $LC_{0.5}$, indicated the side where reading should commence. Pointing at the letters by the examiner was not used under any test condition.

All responses were recorded on a spreadsheet by the examiner and letter-by-letter scoring was used. For the line tests, $LB_{0.5}$ and $LC_{0.5}$, if a participant read the incorrect number of letters in a line, without indicating that they were leaving one out, the responses were recorded in the order and position they were read. The procedure for testing the adults was the same as for children except testing was carried out in our laboratory with equivalent illumination. For comparison adult participants also had their visual acuity measured using an internally illuminated Early Treatment Diabetic Retinopathy Study chart (ETDRS chart) (Precision Vision Inc, La Salle, IL; Ferris, Kassoff, Bresnick, & Bailey, 1982).

Data Analysis

Data were analyzed using a repeated-measures ANOVA with a Greenhouse-Geisser correction for violation of sphericity applied, when necessary (Keppel, 1982). Post-hoc analyses with Tukey HSD correction were also performed as required (Statistica StatSoft, Ltd, Tulsa, OK). Letter naming errors were also analyzed in the two line tests, $LB_{0.5}$ and $LC_{0.5}$, to investigate any difference in pattern between the age groups and tests. Errors were defined as either "adjacent" if the response letter was adjacent horizontally to the target letter (either left or right), or "random" if any other letter was named. In the line test with bar flankers, $LB_{0.5}$, errors pertaining to just the central three letters were analyzed, as the end letters only had one possible adjacent option. In the line test with letter flankers, $LC_{0.5}$, errors pertaining to the central five letters were analyzed. Two analyses were

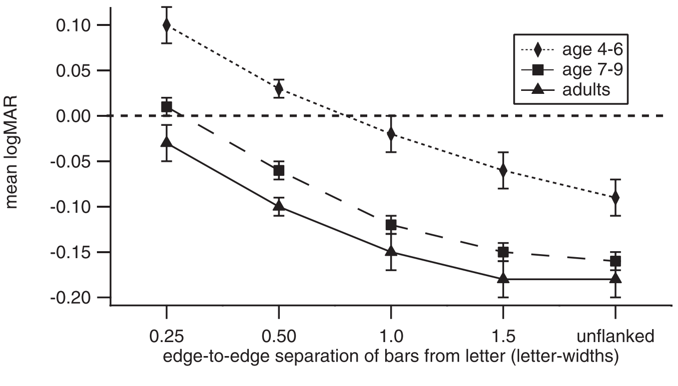

Figure 1. This figure shows logMAR plotted as a function of target and flanker separation for the single letter flanked tests for the three age groups; younger children (4–6 years): diamond symbols, dotted line; older children (7–9 years): square symbols, dashed line and adults: triangle symbols, solid line. The horizontal dotted line shows logMAR 0, or 6/6 (20/20). Error bars represent ±1 *SE*.

carried out. The first one looked for a difference in proportion of adjacent and random errors between the two line tests and the second looked for a difference in the proportion of right and left errors. Chi-square tests were performed to assess statistical significance.

Results

Mean unflanked acuity was better than 6/6 (logMAR 0.0) in all three age groups (Figure 1). There was no significant difference in acuity in the adults between the ETDRS chart and our single-letter test with bars at one letter-width from the target ($SB_{1.0}$) indicating that potential reflections from the iPad did not interfere with the acuity measurements (Black et al., 2013). Mean unflanked logMAR was worse in the younger children (4–6 years) than in the other two groups ($p = 0.048$).

Extent of foveal contour interaction

Figure 1 plots logMAR using the single-letter flanked tests ($SB_{0.25–1.5}$) as a function of letter and flanker separation for the younger children (diamonds and dotted line); older children (squares and dashed line) and adults (triangles and solid line). For each of the age groups, maximum contour interaction occurs at the nearest letter-flanker separation (0.25 letter widths). For all groups, and consistent with previous results, (Fern & Manny, 1986; Jeon et al., 2010; Manny et al., 1987; Semenov et al., 2000), logMAR improves as letter-flanker separation increases.

A separate one-way ANOVA (repeated measures) comparing logMAR as a function of letter-flanker separation was performed for each age group and showed a significant effect of separation in each: 4–6 years $F(4, 124) = 84.7$, $p < 0.001$; 7–9 years $F(4, 120) = 96.2$, $p < 0.001$, adults $F(4, 104) = 73.1$, $p < 0.001$. Post-hoc testing (Tukey test) showed that unflanked logMAR was not significantly different to the widest letter-flanker separation of 1.5 in both groups of children: 4–6 years $p = 0.066$, 7–9 year olds $p = 0.668$, indicating no contour interaction at this separation. For all other letter-flanker separations, contour interaction was evident as the logMAR was significantly greater than the unflanked condition (4–6 year olds $p < 0.001$, 7–9 year olds $p = 0.001$). In contrast, the adults' results showed that unflanked logMAR was not significantly different to the flanked conditions for the 1.5 ($p = 1.000$) and 1.0 letter-flanker ($p = 0.096$) conditions, consistent with previous results of the extent of foveal contour interaction in adults (Flom et al., 1963b; Simmers, Gray, McGraw, & Winn, 1999). This shows the extent of contour interaction to be less in adults than in children.

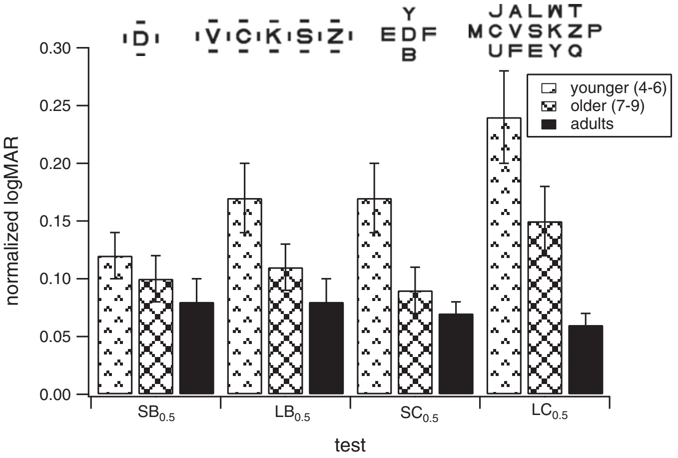

Figure 2. This figure shows mean logMAR for each group, normalized to the unflanked acuity, for the four crowding conditions: single letter with bar or letter flankers and line of letters with line or letter flankers. Dotted bars show younger children (4–6 years), cross-hatched bars show older children (7–9 years), and solid bars show adults. Edge-to-edge target-flanker separation was 0.5 letter-widths. Error bars represent ±1 *SE*.

The data from the single letter tests with bar flankers ($SB_{0.25–1.5}$) were normalized to the uncrowded condition S_0. On average the depth of crowding for the single letter, bar surround condition was significantly greater in the younger children (4–6 years) than in the adults ($p = 0.034$).

Effect of flanker type and single versus linear letter targets on foveal crowding

Figure 2 shows mean logMAR for each group, normalized to the unflanked acuity, for the four crowding conditions: single letter with bar or letter flankers and line of letters with bar or letter flankers. Dotted bars show younger children (4–6 years), cross-hatched bars show older children (7–9 years), and solid bars show adults.

A 3 (age) × 4 (tests) ANOVA (repeated measures) yielded a significant main effect of age, $F(2, 87) = 18$ ($p < 0.001$), a significant main effect of test, $F(2.76, 240.6) = 22.38$ ($p < 0.001$), and a significant interaction between age and test, $F(5.53, 240.6) = 13$, $p < 0.001$. Crowding varied across tests in the two groups of children, but not in the adults, for whom there was no significant difference in logMAR across the tests.

Further analysis of the interaction showed that similar to the adult group, the group of older children (7–9 years) showed no significant difference in logMAR

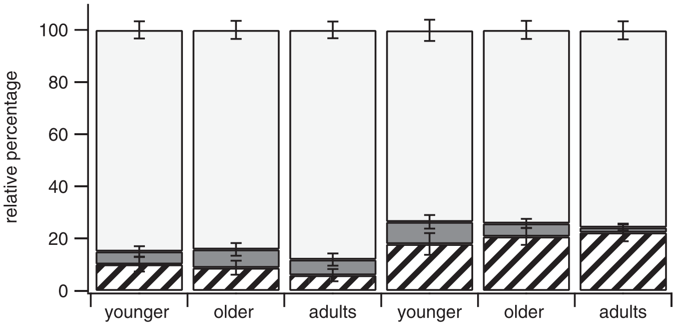

Figure 3. This figure shows the relative percentages of the different error types in the line tests, $LB_{0.5}$ and $LC_{0.5}$ for the three age groups. Light gray shading shows random errors; dark shading shows adjacent left errors and diagonally striped shading shows adjacent right errors. Error bars represent ±1 *SE*.

between the single letter tests with bar or letter flankers, $SB_{0.5}$ or $SC_{0.5}$, or the line of letters with bar flankers, $LB_{0.5}$. However, a significant difference in logMAR was found for the most complex test, the line test with letter flankers, $LC_{0.5}$ ($p < 0.001$), with acuity around 0.05 logMAR poorer in this test than in the other three tests.

The younger children (4–6 years), in the single letter condition, showed more crowding (0.05 logMAR) with letter flankers ($SC_{0.5}$) than bar flankers ($SB_{0.5}$), $p < 0.001$. They also showed more crowding (0.05 logMAR) in the linear test with bar flankers ($LB_{0.5}$) than in the single letter test with bar flankers ($SB_{0.5}$), $p = 0.003$. These results show that using letter rather than bar flankers and using a linear rather than single optotype presentation both present a similar level of increased crowding for the younger children. In addition, for the linear test with letter flankers ($LC_{0.5}$), there is a further increased level of crowding, resulting in a mean worsening of visual acuity of 0.12 logMAR compared to the single letter with bar flankers ($SB_{0.5}$), $p < 0.001$.

Error analysis

Figure 3 shows the relative percentages of the different error types in the line tests, $LB_{0.5}$ and $LC_{0.5}$, for the three age groups. Light gray shading shows random errors, dark shading shows adjacent left errors and diagonally striped shading shows adjacent right errors.

Two error analyses were conducted comparing $LB_{0.5}$ and $LC_{0.5}$. As expected, most of the errors made were random errors. The first analysis compared the proportion of adjacent and random errors between the two line tests. On average, more adjacent errors were made in the test with letter flankers ($LC_{0.5}$), compared to the test with bar flankers ($LB_{0.5}$), ($\chi 2 = 14.0$, $p < 0.001$).

The second analysis examined the frequency of right and left adjacent errors in the line tests. In the line test with bar flankers, $LB_{0.5}$, the numbers of right and left errors were not different ($\chi^2 = 2.22$, $p = 0.329$). However, when letter flankers were used ($LC_{0.5}$), there were more right than left errors in each age group and the proportion of right: left increased with age ($\chi^2 = 46.09$, $p < 0.001$).

Discussion

We used a series of custom designed visual acuity tests to infer the relative influence of target-flanker distance, linear versus single presentation and target-flanker similarity on visual acuity (logMAR) in children and adults. Unflanked acuity was on average, better than logMAR 0.0 (6/6) in each of the three groups although a developmental trend was evident. Averaged unflanked acuity was worse in the 4–6 year old group than in the 7–9 year olds and adults, consistent with reports that have showed maturation of unflanked acuity between 4 and 6 years of age (Leat et al., 2009; Simons, 1983). The slightly poorer acuity in the youngest age group may reflect continuing development of the retinal mosaic (Yuodelis & Hendrickson, 1986). In a previous study (Norgett & Siderov, 2011) we reported no change in unflanked acuity in a different sample of children, but over the same age groups, which may reflect a sampling issue in the age bands used, or the greater variance in the 7–9 year olds in our previous study as a result of different inclusion criteria.

Consistent with previous reports (Bondarko & Semenov, 2005; Jeon et al., 2010; Semenov et al., 2000), contour interaction was greater in extent in both groups of children than in the adults. On average, our results suggest that the age at which the critical spacing becomes adult-like is at least beyond 9 years. Although retinal changes are potentially ongoing in the younger children (Simons, 1983; Yuodelis & Hendrickson, 1986), the larger zone of contour interaction we observed in both groups of children probably reflects underlying cortical rather than retinal development, as crowding is known to reflect cortical processes (Flom, Heath, & Takahashi, 1963a; Pelli, 2008). Kozma showed that integration of contours is probably mediated by long-range neuronal connections and that visual spatial integration is still developing between 5 and 14 years of age (Kozma, Kovács, & Benedek, 2001). In addition, Huttenlocher, De Courten, Garey, and Van Der Loos (1982) showed changes in synaptic density in the cortex which continued until around 11 years.

In the normalized single letter bar surround condition ($SB_{0.5-1.5}$), we found the depth of contour interaction, on average, to be larger in the children than the adults. This difference, albeit small, was significant between the youngest children (4–6 years) and the adults.

Effect of attention

Our findings support the view that in young children, crowded visual acuity is determined not only by the resolution potential of the eye and by the distance of nearby objects to the target, but also by the attention demand in disregarding the nearby objects in favor of the target.

Comparing single letters flanked by letters, ($SC_{0.5}$), to single letters flanked by bars, ($SB_{0.5}$), observers were required to preferentially process the target letter while ignoring the flanking letters; the young children (4–6 years) had more difficulty ignoring the letter flankers than bar flankers at the same distance from the target ($SB_{0.5}$), resulting in a logMAR reduction of 0.05, or half a line of letters. The letter flankers were categorically similar to the target, so selecting the target letter and ignoring the flanking letters represents a greater demand on attention than naming a letter with bar flankers. This stronger crowding where there is more similarity of the target and flankers is consistent with the results of Atkinson (1991), and is similar to findings in the adult periphery (Bernard & Chung, 2011; Kooi, Toet, Tripathy, & Levi, 1994; Leat et al., 1999; Nazir, 1992; Zhang et al., 2009), but not in adult foveal viewing (Atkinson, 1991; Leat et al., 1999; Song et al., 2014).

Theories of visual attention propose competition for processing of information in the visual system where there is limited capacity, a "bottom up" mechanism, coupled with a "top-down" selection of the target (Desimone & Duncan, 1995). Studies that explore the development of visual attention show children to be less efficient at allocating attentional resources than adults rendering them less able to ignore task irrelevant stimuli (Enns & Akhtar, 1989; Pastò & Burack, 1997).

A recent study using a tracking paradigm with a target and distractors at varying distances showed that young children were able to process relevant information in the presence of competing stimuli as effectively as adults, until the separation of target and nearby objects became small (Wolf & Pfeiffer, 2014). It was shown that the spatial extent of this "attentional focus" decreased significantly between 7 and 9 years, but was not yet mature at 13 years.

Letter strings

Our results show that in the youngest children (4–6 years), recognizing a string of five letters with surrounding bar contours ($LB_{0.5}$) is harder than similarly flanked single letters ($SB_{0.5}$), resulting in a logMAR reduction of 0.05, or half a line of letters. At this age, children are learning to read, but are not sufficiently practiced to have reached their maximum reading speeds (Aghababian & Nazir, 2000; Curtis, 1980), so development of line acuity could be linked to learned patterns of reading. Unpracticed readers could make less accurate saccades, or poor fixation could lead to loss of positional information. Beginning readers have also been shown to make more "regressions" or refixations when reading (Rayner & Duffy, 1986). This behavior could contribute to the younger children losing their place when reading along the line tests in our study. Even in adults, Popple and Levi (2005) showed that compared to widely spaced letters, crowded letters lead not only to recognition errors, but also to loss of position information in the periphery. A similar mechanism may operate to a lesser extent in foveal viewing in children. Furthermore, looking at a line of letters rather than a single, flanked letter represents more information in the respective cortical receptive field, so poorer performance in children may also be as a result of divided visual attention.

In older children (7–9 years), neither linear presentation nor increased letter-flanker similarity alone was sufficient to make mean, normalized logMAR different from adults. However, in the linear test with letter flankers, $LC_{0.5}$, the resulting increased crowding caused logMAR for this test to be significantly poorer than the mean adult logMAR. We suggest that, reading along the line of letters, the letter flankers caused more difficulty than the bar flankers in children because of the requirement for accurate eye movements and the increased attention demand, described above.

It is difficult to separate visual attention and eye movements as they are very closely linked (Flom, 1991; Hoffman & Subramaniam, 1995). Nevertheless, our analysis of errors made when reporting the letters, showed that when bar flankers are used, the resulting naming errors have a similar pattern across the age groups causing a combination of common letter confusions, and random guessing. However, when letter flankers are used, more adjacent errors occurred, suggesting that participants were at times losing their place as they read the line of letters. Furthermore, the way in which participants lost their place in the line changed with age. In adults, the majority of the adjacent errors were "right" errors, caused presumably by omitting a letter on reading from left to right. In the younger children, although there were more "right" than "left" errors, the proportion of right: left errors was lower, suggesting that the younger children were also getting lost on reading the line, but as well as missing letters they also made refixations in the right to left, or backwards direction. We infer that this is evidence in support of an immature control of gaze in the younger children, as previously suggested (Kothe & Regan, 1990). Although the nearest contour to the letter being read was the same in both line tests ($LB_{0.5}$ and $LC_{0.5}$), the center-to-center separation of letters was less in the test with letter flankers ($LC_{0.5}$), putting a greater demand on accurate fixation of the letters near threshold. Of the two differences in the line tests: the interletter separation and the flanker type (letter or bar), we consider the flanker type to be the more significant. The difference in logMAR using letter rather than bar flankers found in the single letter condition (0.05 logMAR) accounts for most of the difference observed between the two linear tests (0.07 logMAR).

An alternative explanation for errors in the line tests could be that the participants became muddled in the stage of rehearsing the letters mentally after visualizing them and before speaking them. We do not consider this explanation to be the primary cause of errors, as participants were given unlimited time to read the lines of letters and there was no requirement to look at all five letters before naming them.

The ability to subitize, or know the number of objects in an array without counting them, increases throughout childhood (Halberda & Feigenson, 2008). This may be linked to a child's ability to accurately read longer strings of letters; a child may struggle to find their place if they are unsure how many letters are in the line they are reading. In the linear test with letter flankers ($LC_{0.5}$), seven letters were read, while in the linear test with bar flankers ($LB_{0.5}$), only five letters were read. This difference gives more opportunity for placement errors in the seven-letter test.

Conclusions

Our results show a greater extent of contour interaction in children than adults, which is still not mature by 9 years of age. Two other factors are also likely to contribute to the overall crowding effect in children younger than 7 years: the greater attention demand of increased letter-flanker similarity and the more precise eye movement control required to read a string of letters. Our data suggest that both attention and eye movement factors mature individually by around 7 years of age, but can have a cumulative effect which extends beyond age 7. Our results have implications for the design and use of vision tests for screening of vision in young children.

Keywords: crowding, children's vision, visual development

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