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Developmental changes during childhood in single-letter acuity and its crowding by surrounding contours

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ABSTRACT

Crowding refers to impaired target recognition caused by surrounding contours. We investigated the development of crowding in central vision by comparing single-letter and crowding thresholds in groups of 5-year-olds, 8-year-olds, 11-year-olds, and adults. The task was to discriminate the orientation of a Sloan letter E. Single-letter thresholds, defined as the stroke width forming the smallest discriminable E, were worse than those of adults (0.83 arcmin) at 5 years of age (1.05 arcmin) but not at older ages (8-year-olds: 0.81 arcmin; 11-year-olds: 0.78 arcmin). The maximum distances over which crowding occurred, as measured in multiples of threshold stroke width, were smaller in adults (2.83) than in the three groups of children, who did not differ from each other (5-year-olds: 7.03; 8-year-olds: 7.84; 11-year-olds: 7.13). Thus, even 11-year-olds are more affected than adults by surrounding contours despite having single-letter acuity that has been mature for several years. The stronger influence of crowding in children may be caused by immaturities in the brain areas beyond the primary visual cortex (V1) where early visual inputs are combined and may contribute to their slower reading speed.

Introduction

The accuracy with which we can identify the finest details of an object depends on our visual acuity. In practice, the visual acuity of humans has been measured by asking participants to perform a discrimination task with symbols, usually letters, such as reading a Snellen acuity chart. The Snellen chart displays high-contrast letters arranged into rows of letters that become successively smaller.

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Charts for preliterate children are constructed similarly with symbols (e.g., apple, bird). Typically, an observer views the chart from a fixed distance and attempts to name the letter or symbol or to point to the corresponding letter on a matching card with a number of choices. When letters are presented in isolation, sensitivity is mature at around 6 years of age (Simons, 1983). However, it is rare in everyday perception that we look at single-letters or details of objects without them being surrounded by other letters or details. With such surrounding elements, acuity is much poorer, a phenomenon commonly known as crowding (Stuart & Burian, 1962).

Since the early 1930s (Ehlers, 1936), the phenomenon has been given many names, including crowding (Stuart & Burian, 1962), lateral masking (Loomis, 1978; Wolford & Chambers, 1983), and contour interaction (Flom, Weymouth, & Kahneman, 1963). As its many names suggest, the effects of crowding are found in numerous visual tasks, including letter identification (Ehrt & Hess, 2005; Flom et al., 1963; Pelli, Palomares, & Majaj, 2004; Strasburger, Harvey, & Rentschler, 1991), orientation discrimination (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001), and even face recognition (Farzin, Rivera, & Whitney, 2009; Martelli, Majaj, & Pelli, 2005).

Recently, crowding has been linked to processes involved in object recognition. For example, Pelli and colleagues (Pelli et al., 2004; Pelli & Tillman, 2008) argued that crowding is the consequence of the excessive integration of features by our visual system. From this perspective, the features of a target and those of surrounding objects are first detected independently at low levels of the visual system. Crowding takes place when these features of a target and those of nearby objects fall within the same "integration zone" (Levi, 2008; Pelli et al., 2004), a hypothetical region in higher visual areas where the low-level features are processed further to form the percept of an object. A recent review on crowding (Levi, 2008) noted an emerging consensus that crowding arises during the second stage of a two-stage process of object recognition, namely feature detection followed by integration of the features to form the perception of an object.

The interference of surrounding contours with target identification in crowding has naturally led scientists to study its relationship to reading and dyslexia (Falkenberg, Rubin, & Bex, 2007; Kwon, Legge, & Dubbels, 2007; Levi, Song, & Pelli, 2007; Pelli et al., 2007). Recent findings from adults (Levi et al., 2007; Pelli et al., 2007) suggest that the reading rate is not determined by text size but rather is determined by the distance over which crowding occurs for that letter size. The reading rate increases rapidly with increased spacing up to a critical value, called the critical spacing, after which it reaches a plateau until the spacing becomes so large that the rate decreases again.

Despite the many studies of crowding in adults and its relationship to reading, few studies have investigated the development of crowding and their results are not in agreement. Part of this disagreement may stem from different ways to characterize crowding. One measure, which was used by early researchers, is "crowding acuity," where the distracter spacing is set at some predetermined multiple of target size and the target size is varied over trials. For example, Atkinson, Anker, Evans, Hall, and Pimm-Smith (1988) measured crowding in visually normal 3- and 4-year-olds, 5- to 7-year-olds, and adults by comparing single-letter acuity thresholds to crowded acuity measured with the target letter surrounded by four other letters that were never target letters. With a viewing distance of 6 m, the edge-to-edge separation between the target letter and the surrounding letters was kept constant at 0.5 letter width while the size of the stimulus composite was varied. The results suggested that crowding impeded detection of the single-letter more in 3- and 4-year-olds than in 5- to 7-year-olds, who did not differ from adults. The performance of 3- and 4-year-olds did not improve when they were tested at a closer distance of 3 m. Note that with this method, the size of the target and the size of the flanker distance are not varied independently; hence, the results of Atkinson and colleagues' study do not indicate the distance over which crowding occurs for different target sizes. This confound also limited the smallest spacing with which adults could be tested and, hence, may have led to an underestimate of the differences between adults and children.

Alternatively, crowding can be quantified by measuring the "critical spacing," defined as the distance over which the surrounding flankers degrade the identification of a target of a fixed size. If the target is set near its detection limit, this method is advantageous because in adults foveal crowding occurs only near the resolution limit (Flom et al., 1963; Leat, Li, & Epp, 1999; Toet & Levi, 1992). Only two studies have used this approach to study the developmental trajectory of crowding (Bondarko & Semenov, 2005; Semenov, Chernova, & Bondarko, 2000). One of the two studies by

Semenov and colleagues measured crowding thresholds in 3- to 9-year-olds by first measuring single-letter acuity (defined as the minimum letter size that could be identified with 75% accuracy) and then measuring the distance over which crowding occurred for that threshold target size (Semenov et al., 2000). The spatial extent of crowding declined steadily with age, reaching adult levels at 9 years.

In the second study on the development of crowding (Bondarko & Semenov, 2005), 8-, 11.5-, 12.5-, 15-, and 17-year-olds were tested using a broader range of stimuli—not only a Landolt C flanked by single bars but also a Snellen letter E flanked by other Es and a rectangular grating flanked by other gratings. The authors reported that the distance over which crowding occurred declined with age, but they could not estimate the age of maturity because no adults were tested and the data from the oldest children were discarded because of a procedural error. The results differed among the three types of targets, with a significant improvement between 8 and 11.5 years of age for the letters C and E but a more gradual improvement from 8 to 15 years of age for the gratings. However, these values come from group curves because each individual was tested with each flanker distance on only four trials, so that individual thresholds could not be estimated. Moreover, there were no criterion trials verifying that the children understood the task. Reductions in crowding thresholds with age might have been attributable, at least in part, to a better understanding of the task requirements in older children than in younger children.

The goal of the current study was to chart the developmental trajectory of crowding, defined as the distance at which single-letter acuity decreases when the target letter is surrounded by other contours. Unlike Atkinson and colleagues (1988), we tested crowding distance for a fixed size of target just above the threshold for single-letter acuity and used much finer steps. We tested four different age groups, including an adult group, and unlike all previous studies (Atkinson et al., 1988; Bondarko & Semenov, 2005; Semenov et al., 2000), we restricted the age range in each group to no more than 6 months. Rather than a Landolt C (Bondarko & Semenov, 2005; Semenov et al., 2000), we used a Sloan letter E surrounded by flanking bars that varied in orientation within and across trials so as to minimize the possibility that observers would pick up regional differences in luminance associated with specific combinations of the letter and flankers. In addition, we screened the participants for normal vision and included criterion trials and a practice session to verify that all participants understood the task.

In this study, we normalized the crowding distances against single-letter acuity and found that the ratio is much higher throughout middle childhood than it is in adults. The protracted development may impact children's reading speed and make crowding especially vulnerable to the adverse effects of abnormal visual input.

Method

Participants

The final sample consisted of 19 5-year-olds (mean age = 5.60 years, range = 5.34–5.75, 14 boys and 5 girls), 20 8-year-olds (mean age = 8.44 years, range = 8.25–8.72, 9 boys and 11 girls), 20 11-year-olds (mean age = 11.54 years, range = 11.26–11.75, 12 boys and 8 girls), and 19 adults (mean age = 19.38 - years, range = 17.7–23.1, 8 men and 11 women). All participants in the final sample had passed a visual screening exam (see "procedure" section), and all had a single-letter acuity that did not deviate from the group mean by more than ±2.5 standard deviations. This latter criterion ensured that we did not introduce variance in the crowding thresholds from atypical sizes of the central target. An additional 15 individuals were excluded from the final sample for not meeting one of these requirements: because they failed to meet our criteria on the visual screening exam (2 5-year-olds, 3 8-year-olds, 2 11-year-olds, and 3 adults), because their single-letter acuities deviated more than ±2.5 standard deviations from the group mean (1 5-year-old and 1 8-year-old), or because, on the crowding measure, their staircases did not converge during the last six reversals (2 5-year-olds and 1 adult) (see crowding threshold results).

The children were recruited from a database of children whose parents volunteered to participate at the times of their children's births. Children received a toy and certificate for participation. Adults were student volunteers or McMaster University undergraduate psychology students participating for course credit. Prior to any testing, we obtained informed consent from participants or their parents. We also obtained assent from the children 8 years of age or older.

Apparatus and stimuli

The experiment was controlled by an Apple iBook G4 computer running MATLAB version R14 with the Psychtoolbox extension (Brainard, 1997). The stimuli were presented on a Dell P1130 monitor, 39.5 cm (5.32° from the viewing distance of 424 cm) wide by 29.5 cm (3.98°) high, surrounded by a gray cardboard cutout screen to block nearby surrounding objects. The monitor had a pixel resolution of 1600 × 1200 and a refresh rate of 60 Hz. A pixel subtended a visual angle of 0.20 arcmin at the testing distance of 424 cm.

The stimuli consisted of a target presented alone or the target surrounded by crowding bars. The target was a single black Sloan letter E rotated either clockwise ("down") or counterclockwise ("up") by 90° from its upright position and presented against a homogeneous gray background to achieve a Michelson contrast of 80%. Sloan letters are characterized by an equal height and width, with the height equal to five times the stroke width. The Sloan E ranged in size from 0.118 × 0.118 cm (0.016 × 0.016° when viewed from 424 cm) to a maximum of 30.89 × 30.89 cm (4.167 × 4.167°). The minimum and maximum stroke widths for the E were 0.0032 and 0.833°, respectively. Measurements of the stimulus (mean luminance = 1.24 cd/m^2) and uniform gray background (mean luminance = 22.99 cd/m^2) were performed with a Minolta LS-100 photometer. The mean background luminance was measured as 20 to 25 cd/m^2 (*SD* = 0.334) during the course of the experiment.

The crowding stimuli consisted of an E flanked by four sets of three black bars. Each flanking bar had the same stroke width as the stems of the E (see Fig. 1). The spatial extent of the set of three flanking bars was the same as that of the E. The orientation of the flanking bars varied randomly within and across trials to minimize spurious cues that the older participants might otherwise have learned to use to solve the task (e.g., consistently lower/higher contrast near the opening of the E, consistently matched alignment of the bars near the opening).

Procedure

Visual screening

All participants in the final sample passed a visual screening exam (with optical correction if needed), with the criterion set to that expected at each age. The visual screening exam included tests

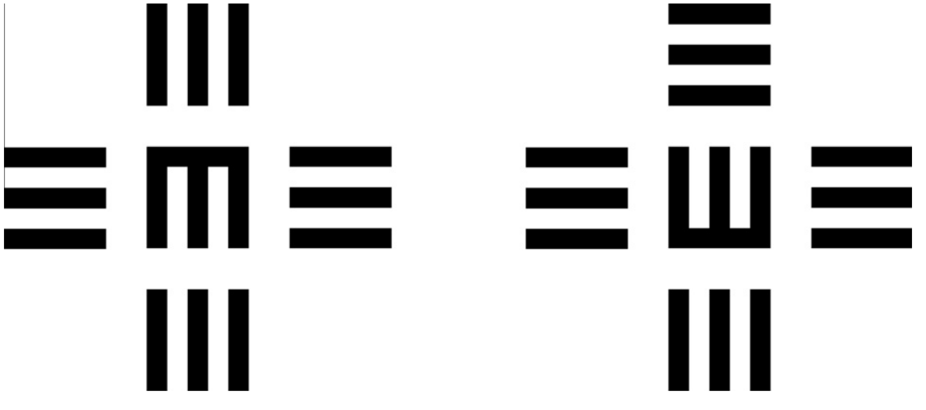

Fig. 1. Examples of the crowding stimuli. The target letter is the Sloan alphabet E, randomly rotated either clockwise or counterclockwise across trials. The orientations of the flanking bars around the target were also randomized across and within trials.

of linear letter acuity, binocular fusion, and stereo acuity. Adults, 11-year-olds, and 8-year-olds were required to have a minimum linear letter acuity of at least 20/20 in each eye when tested monocularly with the Lighthouse Distance Visual Acuity Test chart. The 5-year-olds had a minimum linear letter acuity of at least 20/25 when tested with the Goodlite Crowding cards. Participants were required to have worse acuity with an added +3.00 dioptre lens to rule out the possibility of hypermetropia (farsightedness) of more than 3 dioptres. Binocular fusion was assessed using the Worth 4-Dot Test, and stereoacuity was assessed with the Titmus Fly Stereotest. Participants were required to show evidence of binocular fusion and stereoacuity of at least 100 arcsec for the 5-year-olds and 40 arcsec for the older participants.

Single-letter acuity

The experiment consisted of two parts: measuring single-letter acuity and measuring the crowding distance for a letter slightly larger than the single-letter threshold. For each part, the participants viewed the monitor binocularly in a dark room from a distance of 424 cm. A chin rest was used to keep each participant's head at the required distance and oriented toward the monitor. Before taking threshold measurements, participants were given demonstration, criterion, and practice sessions to ensure that they understood the task.

During the demonstration phase for single-letter acuity, participants were shown examples of the stimuli with the following verbal instructions:

> Today we will play hide-and-seek with a letter E. First you will see a picture in the middle of the screen like this [show fixation stimulus]. We want you to be alert when you see these pictures since our letter E will be hiding behind the picture. Here comes our letter E! [show E on first demonstration trial]. But here the letter tries to trick you by turning himself up or down. You can tag (or catch) this E by telling me which way it is pointing. Can you tell me which way it is pointing? This E is pointing down [point three fingers downward showing the stem direction]. [Show E on second demonstration trial.] This E is pointing up this time [point three fingers upward showing the stem direction]. When you get it right, you are going to see a smiley face and a "ta-da" sound [show positive feedback stimulus], but if you get it wrong, then you will hear an annoying buzzer sound with a funny face [show negative feedback stimulus]. When you tag (or catch) the E a few times in a row, the letter will get smaller and smaller to make the game difficult. But if you tag the E wrong, then it will get bigger and bigger. Get it? Any questions? Are you ready for practice? Good!

Participants were then required to pass a criterion by correctly judging the orientation of a suprathreshold target letter on 4 consecutive trials of 12 trials. All participants met this criterion, usually after the first 4 trials. Participants then completed a practice staircase that was identical to the experimental staircase to follow with the single-letter E.

We used a two-alternative forced-choice (2AFC) procedure to measure single-letter thresholds for the letter E. The task on each trial was to verbally identify whether the stems of the E were pointing up or down. At the start of each trial, a fixation stimulus ($0.7 \times 0.7°$) was presented in the middle of the screen, namely one of 178 preloaded black-and-white cartoon images (an example is shown at the top of the single-letter sequence in Fig. 2). When the experimenter judged that the participant was fixating centrally, the target letter E was presented for 500 ms with an initial stroke width of 10 arcmin. The experimenter entered the participant's up/down verbal responses into a keyboard. After each response, visual and auditory feedback was provided to indicate whether or not the response was correct.

A sample stimulus sequence is depicted in the left stream of picture frames in Fig. 2. The stroke width of the letter varied across trials according to a three-up/one-down staircase procedure (Levitt, 1971). The stroke width of the letter decreased after three consecutive correct responses and increased after one incorrect response. The initial step size was 1 octave, where an octave is a doubling or halving of a value. The step size decreased to one-half octave after the first three reversals and decreased further to one-quarter octave after six reversals. The staircase was terminated after 10 reversals, and the threshold stroke width of the letter E was calculated from the geometric mean of the last six reversals. With the three-up/one-down staircase, this threshold corresponds to the stroke width of the letter E for which target orientation was judged accurately 79.1% of the time (Levitt, 1971).

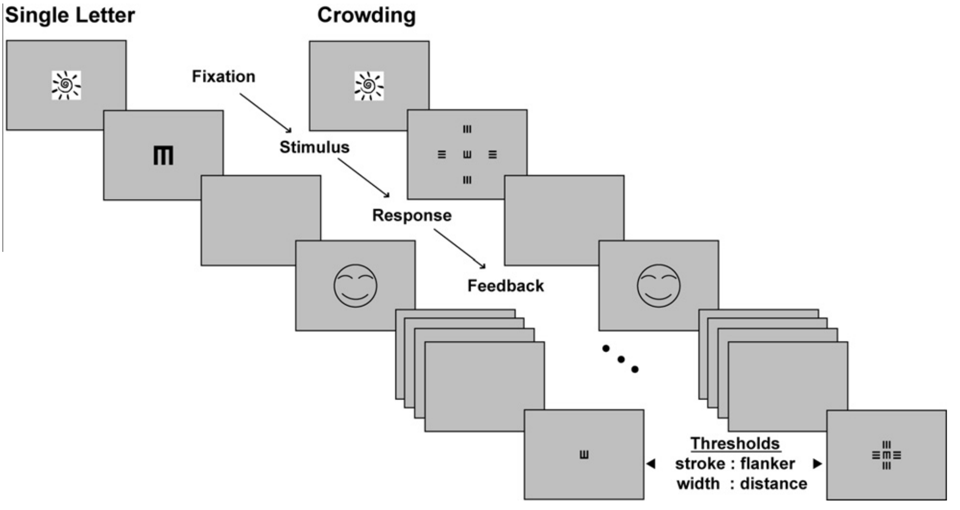

Fig. 2. Representative trial sequences for the measurements of single-letter acuity (left) and crowding (right). For both, a trial began with a fixation picture. When the participant was ready, the experimental stimulus was presented for 500 ms. Auditory and visual feedback was provided to signal whether or not the participant's response was correct.

Crowding threshold

After completing the single-letter acuity test, participants were tested with the target E surrounded by flanking bars. To ensure that the negative effect of flankers on target discrimination is caused mainly by crowding and not by the difficulty of seeing the single-letter at threshold, the target E was presented at either the minimum of a 1-pixel increase from the threshold or 1.2 times the participant's single-letter threshold, whichever was bigger.

Testing began with demonstration trials of the types of stimuli that would be encountered and the following instructions:

> Now we will be playing a different game with the letter E. Here we are going to put our letter E into jail. First you will see a picture in the middle of the screen as before [show fixation stimulus]. Again we want you to be alert when you see these pictures since our letter E will appear right after the picture. Here what you are going to do is the same as before. But this time when you tag (or catch) the E with right answers, the bars around the E will get closer to E to catch the letter in jail. So the goal is to move the bars as close as you can get to the E. Again when you get it right, you are going to see this smiley face and the "ta-da" sound [show positive feedback stimulus]. If you get it wrong, then you will be hearing an annoying buzzer sound with a funny face again [show negative feedback stimulus].

Participants then received criterion trials and a full practice staircase as they had received for single-letter acuity. The separation of the flanking bars from the target varied over trials according to the same three-up/one-down staircase procedure. We defined the crowding threshold by the geometric mean of the last six reversals, which corresponds to the minimum separation between the nearest edges of the flankers and the target for which the orientation of the target E was judged accurately 79.1% of the time. A sample stimulus sequence is depicted in the right stream of picture frames in Fig. 2. All other procedural details were identical to those described for single-letter acuity.

Results

Single-letter acuity

For each age group, we calculated the mean and standard deviation of single-letter acuity. Any individual whose acuity deviated from the mean of his or her age group by more than ±2.5 standard deviations was replaced with a new participant from the same age group so as to avoid introducing variance into the crowding thresholds from atypical sizes of the central target.

The statistics were computed on the logarithms (base 10) of the estimated values of thresholds, as is conventional for measures of visual sensitivity because effects are typically multiplicative rather than linear (Ellemberg, Lewis, Liu, & Maurer, 1999). Fig. 3 shows the mean single-letter acuity at each age. The gray letter Es in the middle of the graph represent the relative size of the single-letter acuity at threshold for each age group normalized against each other. The Levene's statistic for the test of homogeneity of variances confirmed that the variances among the four age groups were not significantly different, $F_{\text{Levene}}(3, 74) = .197$, $p > .80$. A one-way analysis of variance (ANOVA) showed a significant main effect of age, $F(3, 74) = 10.611$, $p < .001$. Post hoc comparisons between the age groups using a Tukey's HSD (honestly significant difference) test showed that the single-letter thresholds for 5-year-olds differed significantly from those for 8-year-olds, 11-year-olds, and adults. However, there were no significant differences among the older age groups. Thus, single-letter acuity is adult-like at 8 years of age but not at 5 years of age.

Resampling analyses of single-letter acuity

In addition to the threshold for single-letter acuity, we estimated the slope of the psychometric function relating performance to changes in stimulus size. To approximate and compare the underlying distribution of psychometric functions for each age group, we applied a bootstrap resampling technique (Efron, 1979; Efron & Gong, 1983) that can be used when the number of samples is relatively small. In essence, the bootstrap method generates a large number of simulated repetitions of the original experiment. Specifically, for each age group, we first pooled the frequency of correct responses ($k_{1,2,...,i}$) across trials and participants with respect to the stroke widths ($s_{1,2,...,i}$) tested. Next, we generated 1000 synthetic data sets using the aggregated data as the generating binomial probability $p_{1,2,...,i}$ ($=k_i/n_i$) of seeing the specific stroke widths $s_{1,2,...,i}$ using MATLAB's binomial random number generator. A Weibull function (Eq. (1)) was fitted using the maximum likelihood procedure (Eq. (2)) for each synthetic data set. Eq. (1) is defined by

$$p_i(c) = \gamma + (1 - \gamma - \lambda)(1 - e^{(\frac{s_i}{\tau})^\beta}), \quad (1)$$

where γ is the correction for guessing (set to .50 in the case of a 2AFC procedure), λ is an estimate of the observer's lapse rate or errors made no matter how intense a stimulus, s is the stimulus strength expressed in stroke widths, τ is the location parameter that determines the location of the curve along the dimension of stroke width, and β is the slope of the psychometric function (the rate of change in

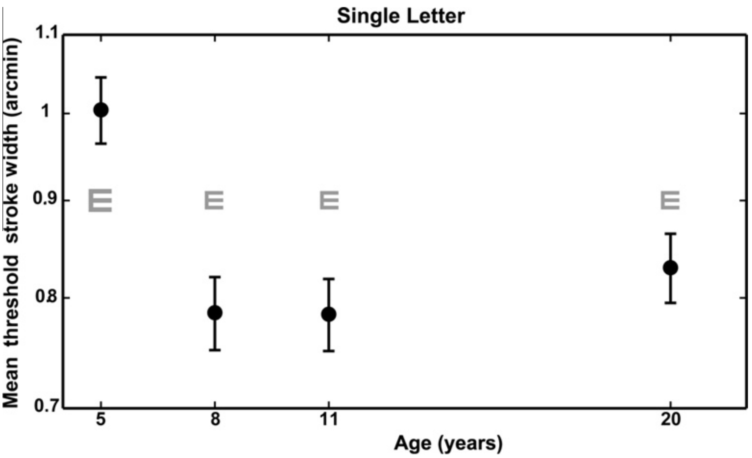

Fig. 3. Mean single-letter acuity as a function of age expressed as the threshold stroke width. Grayed-out letters in the middle of the graph represent the relative size of the single-letter acuity at threshold for each age group normalized against each other.

response probability in relation to the change in stimulus strength). The likelihood function that was applied was defined as

$$\text{likelihood} = \prod_i \frac{n_i!}{k_i(n_i - k_i)!} p_i^{k_i}(1 - p_i)^{n_i - k}, \quad (2)$$

where n_i is the total number of trials, k_i is the number of correct trials, and i is the probability of correct responses for each letter stroke width. $\prod_i$ represents the product of binomial probabilities across all letter stroke widths tested for an age group.

Fig. 4 shows the results of the resampling and respective fitting for each age group. The families of curves are the fits obtained for the 1000 resamplings. The abscissa represents the stroke widths in log arcmin. The ordinate represents the probability of correct responses. Black dots represent the accuracy p_i calculated from the original pooled experimental data. Different dot sizes represent relative frequencies of corresponding stroke widths shown during the experiment. This unequal number of aggregated trials for different stimulus sizes was caused by the fact that we used a staircase; thus, each size was not presented a fixed number of times. The width of the gray vertical band represents the 95% confidence interval of the threshold at .791 probability of a correct response (the value obtained from the original three-up/one-down staircase) computed using the bootstrap percentile method. (The 95% confidence intervals for the age groups are $CI_5^{95th} = 0.2537$, $CI_8^{95th} = 0.1233$, $CI_{11}^{95th} = 0.0973$, and $CI_{adult}^{95th} = 0.1168$.) The white dotted line in the middle of the band represents the mean threshold at that performance level. (The mean thresholds of the resampled data $[\mu(\hat{\tau})]$ are as follows: $\mu(\hat{\tau}_5) = 0.9465$, $\mu(\hat{\tau}_8) = 0.7987$, $\mu(\hat{\tau}_{11}) = 0.7760$, and $\mu(\hat{\tau}_{adult}) = 0.8345$, $\hat{F}(3, 3996) = 3403.29$, $\hat{p} < .0001$.)

As shown in Fig. 4, there is a horizontal shift to the left in the location of the mean from 5-year-olds to older age groups, as found in the original analyses. The variance of the thresholds from the 5-year-old group seems higher than that from the remaining age groups. However, the variance actually results from the significantly shallower slopes ($\hat{\beta}$) of the psychometric functions in the 5-year-olds compared with those in the remaining age groups [$\mu(\hat{\beta}_5) = 0.8601$, $\mu(\hat{\beta}_8) = 0.3893$, $\mu(\hat{\beta}_{11}) = 0.3485$, and $\mu(\hat{\beta}_{adult}) = 0.3656$], $\hat{F}(3, 3996) = 6939.34$, $\hat{p} < .0001$. This is illustrated in the graph for 5-year-olds by the band of psychometric functions that change slowly with increasing stroke width. Interestingly, the resampled lapse rate $\hat{\lambda}$ (the rate at which observers respond incorrectly even for intense stimuli) is very low in 5-year-olds (only $\sim$ 2%). Nonetheless, this value is significantly higher than the values of the three older age groups, who rarely lapse [$\mu(\hat{\lambda}_5) = 0.0201$, $\mu(\hat{\lambda}_8) = 4.0058\text{e-}006$, $\mu(\hat{\lambda}_{11}) = 1.0062\text{e-}016$, and $\mu(\hat{\lambda}_{adult}) = 4.8589\text{e-}015$], $\hat{F}(3, 3996) = 3970.97$, $\hat{p} < .0001$; Tukey's HSD posttests: 5-year-olds against each older age group, $p < .0001$, all other comparisons, *ns*. Together, the results from the bootstrapping technique indicate that the immaturity of single-letter acuity in 5-year-olds is most likely to result from either (a) lower absolute resolving power at the resolution limit than in older age groups or (b) less sensitivity to a small change in stroke width for a letter of any size, that is, coarser ability to discriminate changes in details.

Crowding thresholds

Before analyzing the data, the crowding results for two 5-year-olds and one adult were removed because the staircase did not converge during the last six reversals, as evidenced by unusually large standard deviations of the last six reversals (*SD* > 35 stroke widths).[1]

For each age group, we calculated the mean of the threshold flanker separation in visual angle (arcmin) and its standard deviation. The crowding threshold for each participant was calculated by taking the ratio between the threshold flanker–target distance (arcmin) and the stroke width of the central target E (arcmin). Thus, the crowding threshold was expressed in multiples of the stroke width of the target letter (unit-less) to compensate for the difference in single-letter acuity between 5-year-olds and the three older age groups. Normalizing the crowding threshold against the single-letter acuity is important because, as summarized in the Introduction, the extent of foveal crowding in adults varies

[1] We also excluded their single-letter acuities; thus, these three participants were excluded from the final sample (see "participants" section). The inclusion of their results for single-letter acuity would not alter the result that 5-year-olds' acuity is poorer than that of all older age groups.

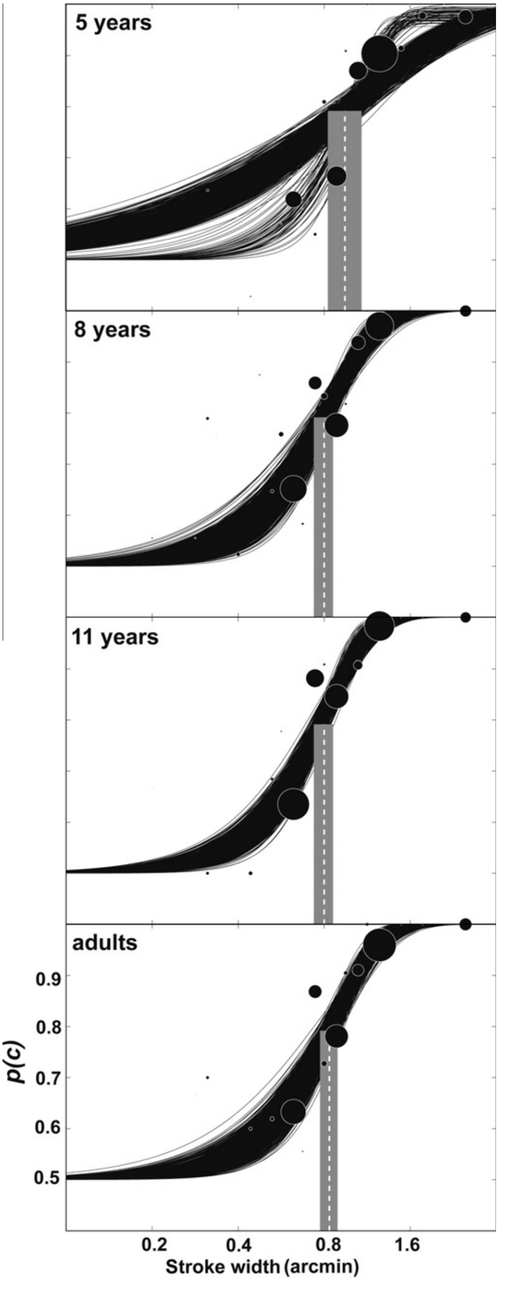

Fig. 4. Results of the bootstrap resampling of single-letter acuity. For each panel, the *x* axis represents the letter size in stroke width and the *y* axis represents the aggregated proportion correct within an age group. The family of curves represents the fits to the 1000 bootstrapped samples, with the vertical gray bands showing the 95% confidence interval of the threshold of 79.1% correct responses. Dots represent the aggregated accuracy in the original data from which 1000 sets of synthetic data were generated. Different sizes of dots result from different numbers of trials tested at the respective letter sizes.

with letter size and is maximal for letter sizes near threshold (Jacobs, 1979; Leat et al., 1999; Loomis, 1978). As was the case in the single-letter acuity data, all sample statistics were computed on the

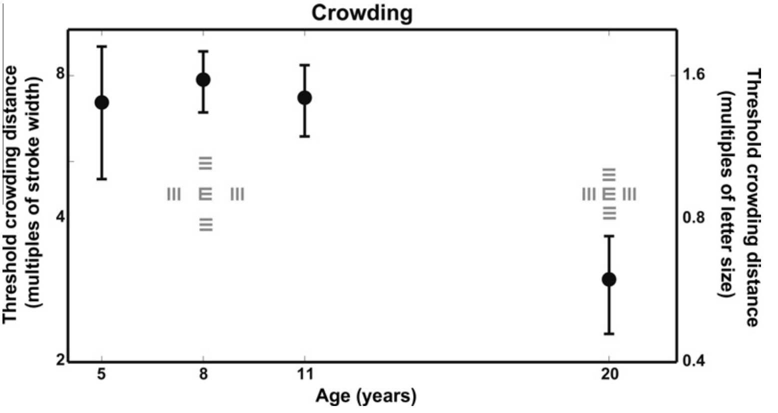

Fig. 5. Mean crowding distance for each age group. The crowding distance threshold is expressed as multiples of threshold stroke width on the left *y* axis and as muliples of threshold letter size on the right *y* axis. Grayed-out stimulus composites show the relative impact of crowding on single-letter acuity for children on the left and for adults on the right.

logarithms (base 10) of the estimated values of thresholds. The Levene's statistic for the test of homogeneity of variances confirmed that the variances among our experimental groups were not significantly different, $F_{Levene}(3, 74) = .403$, $p > .75$. Fig. 5 displays the mean crowding thresholds of the four age groups and suggests that crowding occurs over a larger distance throughout middle childhood than in adults. The gray crowded stimuli in Fig. 5 illustrate the relative impact of crowding on single-letter acuity for children and adults. Given that our target letter size was five times its stroke width, 5-, 8-, and 11-year-olds required the flankers to be spaced approximately 1.5 letter widths away from the target letter to avoid crowding, whereas adults were unaffected when flankers were as close as 0.5 letter width.

A one-way, one-factor ANOVA revealed a main effect of age, $F(3, 74) = 5.856$, $p < .005$. Post hoc comparisons using the Tukey's HSD test showed that the crowding thresholds of all age groups of children were different from those of adults. However, there were no differences among the three groups of children.[2]

Discussion

We found that the single-letter acuity of 5-year-olds was worse than that of 8-year-olds, 11-year-olds, and adults (1.30, 1.35, and 1.27 times worse, respectively), with no significant differences among the older age groups. In contrast, the maximum distance over which crowding occurred, as measured in multiples of threshold stroke width, was similar for 5-year-olds, 8-yeara-olds, and 11-year-olds, all of whom showed effects over significantly larger distances than did adults.

Our finding that single-letter acuity becomes adult-like between 5 and 8 years of age is consistent with Simons (1983), who reviewed seven studies of single-letter acuity and concluded that it matures at around 6 years of age. Nonvisual factors such as differences between adults and 5-year-olds in attention, response criterion, and/or motivation may have contributed to poorer performance in the 5-year-olds but are unlikely to be the whole explanation. The task included criterion trials to verify that the children understood the task and a set of practice trials to familiarize them with the procedure. Moreover, by 5 years of age, children perform as well as adults on some psychophysical tasks that have performance demands like those in the current study, namely tasks that use 2AFC procedures to measure thresholds. For example, studies of sensitivity to the direction of local motion indicate that thresholds of 5-year-olds are nearly adult-like under at least some conditions (Ellemberg

[2] The pattern of results was the same when the data were reanalyzed omitting the results of an adult with an unusually good score (<−2.5 standard deviations from the group mean).

et al., 2003). Similarly, sensitivity to the direction of global motion tested with random dot kinematograms is mature as early as 3 years of age under some conditions (Parrish, Giaschi, Boden, & Dougherty, 2005). However, the slightly higher lapse rate for 5-year-olds compared with the lapse rates for the three older age groups suggests that they may have had difficulty in maintaining attention on the screen from the distance of 424 cm, a much farther distance than that used in the studies where children this young performed as well as adults. Nevertheless, the low absolute lapse rate (missing only 2% of easy trials) indicates that poor attention is unlikely to account for the entire difference in single-letter acuity.

Optical differences are also unlikely to explain the poorer acuity of 5-year-olds than of older participants. Between 5 and 18 years of age, pupil diameter and axial length increase, lens power and thickness decrease, and there is no change in corneal curvature (MacLachlan & Howland, 2002; Twelker et al., 2009; Zadnik et al., 2003). It is difficult to compute the net effects of these changes, but modulation transfer functions indicate that the optical quality of the image formed in the eyes of 5- to 7-year-olds is better than that formed in the eyes of adults for comparable pupil sizes (Carkeet, Leo, Khoo, & Eong, 2003). The smaller pupil of a 5-year-olds will lead to better depth of field and fewer abberations interfering with acuity. Although the smaller pupil will also cause greater diffraction, it is are unlikely to be the cause of poorer acuity at 5 years of age because pupil size continues to increase until at least 12 years of age and single-letter acuity is adult-like by 8 years of age.

Retinal immaturities are a more likely explanation of immature acuity at 5 years of age. The retina is still immature at 45 months of age; in the one retina examined, cone packing density was only half that of the adult fovea and the outer segment length of foveal cones was 30 to 50% shorter than that in adults (Yuodelis & Hendrickson, 1986). Acuity is likely to be affected by both of these factors. Reduced cone packing density produces a reduction in spatial sampling and, hence, in acuity. Reduced length of the cone outer segments reduces sensitivity to luminance because it makes the cones less efficient in absorbing light (Pasternak & Merigan, 1981), and adults' acuity diminishes with decreasing luminance (Allen, Bennett, & Banks, 1992; Brown, Dobson, & Mayer, 1987). Wilson (1988, 1993) estimated that the reduction in the photoreceptors' spatial sampling and in the outer segments' quantal catch should result in a 28% reduction in 4-year-olds' acuity compared with that of adults. This estimate corresponds closely to the 20% reduction that we found in single-letter acuity for 5-year-olds in the current study. (There are no anatomical investigations on the retinas of 5-year-olds.)

Limitations beyond the retina might also contribute to immature acuity. Specifically, within the primary visual cortex, there is an increase in synaptic density followed by an approximately 50% decrease that is not complete until 11 years of age (Garey & De Courten, 1983; Huttenlocher, 1984; Huttenlocher, De Courten, Garey, & Van der Loos, 1982). This pruning may be related to the reduction of receptive field size for cortical neurons that, in turn, could contribute to the improvements in acuity that occur during childhood (until pruning reaches the Nyquist limit set by the retina). Thus, it appears that the development of acuity is limited by slow retinal development, with some possible additional limitations beyond the retina. Kiorpes and Movshon (1998) drew similar conclusions based on their psychophysical measurements of additive and nonadditive noise in the visual detection of the infant monkey.

We also found that crowding is greater than that of adults throughout most of chilhood, long after single-letter acuity is mature. The distance over which crowding occurred was approximately 2.5 times greater in 5-year-olds than in adults when calculated as multiples of the stroke width of the single-letter acuity. Moreover, there was no obvious decrease in the extent of the crowding distance through 11 years of age. These results are inconsistent with a previous report indicating that crowding becomes adult-like at 5 to 7 years of age (Atkinson et al., 1988). It also seems inconsistent with previous reports that crowding decreases between 5 and 10 years of age for a Landolt C (Semenov et al., 2000) and between 8 and 11.5 years of age for a Landolt C or letter E (Bondarko & Semenov, 2005). However, as discussed in the Introduction, there are limitations to the conclusions that can be drawn from previous studies. Unlike those studies, we used an E surrounded by flankers of varying orientation, an approach that makes it more difficult to rely on regional differences in luminance. We also used a much finer step size than did Atkinson and colleagues (1988), and unlike Bondarko and Semenov (2005), we included an adult comparison group. Unlike the previous studies, we also included narrow age ranges, included enough trials to obtain individual thresholds, screened the participants for normal vision, and included criterion trials and a practice session to verify that all participants understood the task. The current results are consistent with the studies reviewed by Simons (1983), who concluded that crowded acuity is still immature at 10 years of age, the oldest age tested at that time prior to adulthood, and findings by Bondarko and Semenov (2005) of a significant reduction in crowding between 9 and 15 years of age for a grating surrounded by other gratings.

The immaturities that we observed in crowding are likely to be visual in origin and are unlikely to be caused by motivational or cognitive factors; the 8- and 11-year-olds were just as immature as the 5-year-olds for crowding but were as good as adults for measures of single-letter acuity. At first blush, changes in attention seem to be a more likely explanation for greater crowding; poor attentional control would be expected to have less effect on the single-letter acuity task than on the crowded task that requires processing the central E while ignoring the distracting Es in the periphery. Indeed, tests of visual attention indicate that children are not as good as adults at filtering out irrelevant flanking stimuli (Enns & Girgus, 1985; Goldberg, Maurer, & Lewis, 2001; Ridderinkhof & van der Molen, 1995), with children as old as 10 years being affected more by distractors than adults (Goldberg et al., 2001) and the immaturities for 8- and 10-year-olds (the only ages tested) being larger the closer the flankers (Enns & Girgus, 1985). However, the pattern of results for attentional filtering tasks and for our crowded task do not match; we found greater crowding in 11-year-olds than in adults, with no improvement between 5 and 11 years of age. In contrast, measures of the filtering out of irrelevant flanking distractors indicate improvements between 6 and 8 years of age and between 8 and 11 years of age, at which point performance is as good as that in adults (Ridderinkhof & van der Molen, 1995). Moreover, in adults, overall attentional load affects global efficiency but not the extent of crowding, suggesting distinct neural mechanisms (Dakin, Bex, Cass, & Watt, 2009). Thus, children's greater difficulty in filtering out distractors may have contributed to the greater crowding in children than in adults, but the different shapes of the developmental trajectories between filtering and crowding (improvement in filtering but constant crowding between 5 and 11 years of age) suggest that there are additional factors leading to the greater crowding in children.

What additional factors might underlie the greater crowding in children up to at least 11 years of age? The neural mechanisms underlying crowding in adults are still being debated. The locus must be cortical; crowding occurs even when the flanker and target are presented to separate eyes (Flom et al., 1963), and the primary visual cortex (V1) is the first level of the visual pathway where input from the two eyes converges. Recent evidence indicates that the locus of crowding occurs downstream beyond V1. For example, crowding modulates the functional magnetic resonance imaging (fMRI) BOLD signal in V2/V3 but not in V1 (Arman, Chung, & Tjan, 2006; Bi, Cai, Zhou, & Fang, 2009). Psychophysical evidence points to the involvement of area V4 (reviewed in Levi, 2008). For example, the extent of crowding is similar for chromatic stimuli, which are processed in area V4, and achromatic stimuli, which can be processed at lower levels (Tripathy & Cavanagh, 2002). Moreover, reciprocal crowding occurs between targets defined by luminance and distracters defined by contrast or vice versa (Chung, Li, & Levi, 2007), two visual characteristics that single cell recordings in monkeys indicate activate the same neurons in area V4 but not in lower levels of the visual system (Ferrera, Nealey, & Maunsell, 1994). Similarly, the demonstration that holistic face processing can be affected by crowding (Farzin et al., 2009) suggests that crowding can occcur at higher cortical levels involved in face processing. Thus, the greater crowding in children than in adults may reflect immaturities in the cortical structures beyond V1 that are involved in the integration of local information. Consistent with this notion are findings that other processes involving the integration of local information, such as the ability to integrate contours into a shape (Kovacs, Kozma, Feher, & Benedek, 1999) and to see small differences in the spacing of facial features (Mondloch, Le Grand, & Maurer, 2003), such as crowding, continue to develop after 11 years of age. These relationships are likely to be interactive. For example, small increases in the tuning of visual neurons may lead to greater sensitivity to more closely spaced contours. Greater experience with more closely spaced contours may precipitate further tuning of visual neurons.

Our developmental results on single-letter acuity and crowding have direct implications for the development of reading speed. Reading speed increases continuously throughout the school years and takes a long time to reach adult levels, even though by 6 to 8 years of age visual acuity is mature and there is good knowledge of the alphabet (Carver, 1990; Legge, 2007; Thompson, 2009). For example, Carver (1990) reported that the reading rate increases by 14 words per minute each year from

Grade 2 to college (with words per minute calculated based on a standard length word of six characters of text, including punctuation and spaces). To explain the protracted development of reading speed, researchers have traditionally focused mostly on immature phonological or linguistic skills. Recently, however, the role of improvements in early visual processing in the development of reading skills has been recognized (Kwon et al., 2007; Legge, Mansfield, & Chung, 2001; Levi et al., 2007; Pelli et al., 2007). For example, there is some evidence that reading rate varies with letter size; the critical print size for reading (the smallest print size for which fast, reliable, and accurate reading is attained) decreases with increasing age between 6 and 10 years (O'Brien, Mansfield, & Legge, 2005) but apparently not after 9 years (Kwon et al., 2007). Our results from single-letter acuity suggest that the effect of print size on reading speed before 8 years of age might result, at least in part, from immature single-letter acuity. However, any limitations after 8 years of age must arise from another source. One possibility is that the protracted development of crowding found in the current study may contribute to the slow development of reading rate in addition to other limits. In line with this hypothesis, Pelli and colleagues (2007) demonstrated that the "uncrowded span" in adults—the critical spacing for fast reading—is essentially equal to the distance over which crowding does not occur in a visual crowding task. Our data suggest that the uncrowded span for reading grows gradually until at least early adolescence and suggest that those visual changes may contribute to the gradual change in reading rate.

Our results also have implications for the developmental origins of abnormal crowding in patients with amblyopia. Amblyopia is a developmental condition of the visual system characterized by poor vision in an eye that has no organic or structural damage but that can be traced to an earlier abnormality such as an eye turn or uncorrected misfocus that prevented normal visual input to that eye. It is well documented that the magnitude and extent of crowding in these patients is much greater than normal, although the difference becomes smaller and can be minimized when the extent of crowding is normalized against any deficit in single-letter acuity (Hariharan, Levi, & Klein, 2005; Hess & Jacobs, 1979; Levi, Hariharan, & Klein, 2002). The protracted period over which visually normal children show greater crowding than adults may make crowding especially vulnerable to the adverse effects of abnormal visual experience during childhood (Levi, 2005; Lewis & Maurer, 2005).

In summary, we found that single-letter acuity matures sometime between 5 and 8 years of age, whereas crowded letter acuity is still poorer than that of adults even at 11 years of age. These factors might contribute to improvements in the reading rate with age and emphasize the importance of letter size and letter spacing in designing reading materials for young children.

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References

Allen, D., Bennett, P. J., & Banks, M. S. (1992). The effects of luminance of FPL and VEP acuity in human infants. *Vision Research, 32*, 2005–2012.

Arman, A. C., Chung, S. T. L., & Tjan, B. S. (2006). Neural correlates of letter crowding in the periphery. *Journal of Vision, 6*, 804.

Atkinson, J., Anker, S., Evans, C., Hall, R., & Pimm-Smith, E. (1988). Visual acuity testing of young children with the Cambridge Crowding Cards at 3 and 6 m. *Acta Ophthalmologica, 66*, 505–508.

Bi, T., Cai, P., Zhou, T., & Fang, F. (2009). The effect of crowding on orientation-selective adaptation in human early visual cortex. *Journal of Vision, 9*, 1–10.

Bondarko, V., & Semenov, L. (2005). Visual acuity and the crowding effect in 8- to 17-year-old schoolchildren. *Human Physiology, 31*, 532–538.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

Brown, A. M., Dobson, V., & Mayer, J. (1987). Visual acuity of human infants at scotopic, mesopic, and photopic luminances. *Vision Research, 27*, 1845–1858.

Carkeet, A. L., Leo, S. W., Khoo, B. K., & Eong, K. G. (2003). Modulation transfer functions in children: Pupil size dependence and meridional anisotropy. *Investigative Ophthalmology & Visual Science, 44*, 3248–3256.

Carver, R. P. (1990). *Reading rate: A review of research and theory*. San Diego: Academic Press.

Chung, S. T. L., Li, R. W., & Levi, D. M. (2007). Crowding between first- and second-order letter stimuli in normal foveal and peripheral vision. *Journal of Vision, 7*, 1–13.

Dakin, S. C., Bex, P. J., Cass, J. R., & Watt, R. J. (2009). Dissociable effects of attention and crowding on orientation averaging. *Journal of Vision, 9*, 1–16.

Efron, B. (1979). Bootstrap methods: Another look at the jackknife. *Annals of Statistics, 7*, 1–26.

Efron, B., & Gong, G. (1983). A leisurely look at the bootstrap, the jackknife, and cross-validation. *American Statistician, 37*, 36–48.

Ehlers, H. (1936). V: The movements of the eyes during reading. *Acta Ophthalmologica, 14*, 56–63.

Ehrt, O., & Hess, R. F. (2005). Foveal contour interaction: Detection and discrimination. *Journal of the Optical Society of America A, 22*, 209–216.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research, 39*, 2325–2333.

Ellemberg, D., Lewis, T. L., Meghji, K. S., Maurer, D., Guillemot, J. P., & Lepore, F. (2003). Comparison of sensitivity to first- and second-order local motion in 5-year-olds and adults. *Spatial Vision, 16*, 419–428.

Enns, J. T., & Girgus, J. S. (1985). Developmental changes in selective and integrative visual attention. *Journal of Experimental Child Psychology, 40*, 319–337.

Falkenberg, H. K., Rubin, G. S., & Bex, P. J. (2007). Acuity, crowding, reading, and fixation stability. *Vision Research, 47*, 126–135.

Farzin, F., Rivera, S. M., & Whitney, D. (2009). Holistic crowding of Mooney faces. *Journal of Vision, 9*, 1–15.

Ferrera, V. P., Nealey, T. A., & Maunsell, J. H. (1994). Responses in macaque visual area V4 following inactivation of the parvocellular and magnocellular LGN pathways. *Journal of Neuroscience, 14*, 2080–2088.

Flom, M. C., Weymouth, F. W., & Kahneman, D. (1963). Visual resolution and contour interaction. *Journal of the Optical Society of America, 53*, 1026–1032.

Garey, L. J., & De Courten, C. (1983). Structural development of the lateral geniculate nucleus and visual cortex in monkey and man. *Behavioural Brain Research, 10*, 3–13.

Goldberg, M., Maurer, D., & Lewis, T. L. (2001). Developmental changes in attention: The effects of endogenous cueing and of distractors. *Developmental Science, 4*, 209–219.

Hariharan, S., Levi, D. M., & Klein, S. A. (2005). "Crowding" in normal and amblyopic vision assessed with Gaussian and Gabor C's. *Vision Research, 45*, 617–633.

Hess, R. F., & Jacobs, R. J. (1979). A preliminary report of acuity and contour interactions across the amblyope's visual field. *Vision Research, 19*, 1403–1408.

Huttenlocher, P. R. (1984). Synapse elimination and plasticity in developing human cerebral cortex. *American Journal of Medical Deficiency, 88*, 488–496.

Huttenlocher, P. R., De Courten, C., Garey, L. J., & Van der Loos, H. (1982). Synaptogenesis in human visual cortex: Evidence for synaptic elimination during normal development. *Neuroscience Letters, 33*, 247–252.

Jacobs, R. J. (1979). Visual resolution and contour interaction in the fovea and periphery. *Vision Research, 19*, 1187–1195.

Kiorpes, L., & Movshon, J. A. (1998). Peripheral and central factors limiting the development of contrast sensitivity in macaque monkeys. *Vision Research, 38*, 61–70.

Kovacs, I., Kozma, P., Feher, A., & Benedek, G. (1999). Late maturation of visual spatial integration in humans. *Proceedings of the National Academy of Sciences of the United States of America, 96*, 12204–12209.

Kwon, M., Legge, G. E., & Dubbels, B. R. (2007). Developmental changes in the visual span for reading. *Vision Research, 47*, 2889–2900.

Leat, S. J., Li, W., & Epp, K. (1999). Crowding in central and eccentric vision: The effects of contour interaction and attention. *Investigative Ophthalmology & Visual Science, 40*, 504–512.

Legge, G. E. (2007). *Psychophysics of reading*. Mahwah, NJ: Lawrence Erlbaum.

Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading: XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research, 41*, 725–743.

Levi, D. M. (2005). Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Developmental Psychobiology, 46*, 222–232.

Levi, D. M. (2008). Crowding: An essential bottleneck for object recognition—A mini-review. *Vision Research, 48*, 635–654.

Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in amblyopic vision. *Vision Research, 42*, 1379–1394.

Levi, D. M., Song, S., & Pelli, D. G. (2007). Amblyopic reading is crowded. *Journal of Vision, 7*, 1–17.

Levitt, H. (1971). Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 467–477.

Lewis, T. L., & Maurer, D. (2005). Multiple sensitive periods in human visual development: Evidence from visually deprived children. *Developmental Psychobiology, 46*, 163–183.

Loomis, J. M. (1978). Lateral masking in foveal and eccentric vision. *Vision Research, 18*, 335–338.

MacLachlan, C., & Howland, H. C. (2002). Normal values and standard deviations for pupil diameter and interpupillary distance in subjects aged 1 month to 19 years. *Ophthalmic and Physiological Optics, 22*, 175–182.

Martelli, M., Majaj, N. J., & Pelli, D. G. (2005). Are faces processed like words? A diagnostic test for recognition by parts. *Journal of Vision, 5*, 58–70.

Mondloch, C. J., Le Grand, R., & Maurer, D. (2003). Early visual experience is necessary for the development of some––but not all––aspects of face processing. In O. Pascalis & A. Slater (Eds.), *The development of face processing in infancy and early childhood: Current perspectives* (pp. 99–117). New York: Nova Science.

O'Brien, B. A., Mansfield, S. J., & Legge, G. E. (2005). The effect of print size on reading speed in dyslexia. *Journal of Research in Reading, 28*, 332–349.

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience, 4*, 739–744.

Parrish, E. E., Giaschi, D. E., Boden, C., & Dougherty, R. (2005). The maturation of form and motion perception in school age children. *Vision Research, 45*, 827–837.

Pasternak, T., & Merigan, W. H. (1981). The luminance dependence of spatial vision in the cat. *Vision Research, 21*, 1333–1339.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision, 4*, 1136–1169.

Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience, 11*, 1129–1135.

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision, 7*, 1–36.
Ridderinkhof, K. R., & van der Molen, M. W. (1995). When global information and local information collide: A brain potential analysis of the locus of interference effects. *Biological Psychology, 41*, 29–53.
Semenov, L., Chernova, N., & Bondarko, V. (2000). Measurement of visual acuity and crowding effect in 3–9-year-old children. *Human Physiology, 26*, 16–20.
Simons, K. (1983). Visual acuity norms in young children. *Survey of Ophthalmology, 28*, 84–92.
Strasburger, H., Harvey, L. O. J., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception and Psychophysics, 49*, 495–508.
Stuart, J., & Burian, H. (1962). A study of separation difficulty: Its relationship to visual acuity in normal and amblyopic patients. *American Journal of Ophthalmology, 53*, 471–477.
Thompson, G. B. (2009). The long learning route to abstract letter units. *Cognitive Neuropsychology, 26*, 50–69.
Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32*, 1349–1357.
Tripathy, S. P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research, 42*, 2357–2369.
Twelker, J. D., Mitchell, G. L., Messer, D. H., Bhakta, R., Jones, L. A., Mutti, D. O., et al (2009). Children's ocular components and age, gender, and ethnicity. *Optometry & Vision Science, 86*, 918–935.
Wilson, H. R. (1988). Development of spatiotemporal mechanisms in infant vision. *Vision Research, 28*, 611–628.
Wilson, H. R. (1993). Theories of infant visual development. In K. Simons (Ed.), *Early visual development: Normal and abnormal, Committee on Vision. Commission on Behavioral and Social Sciences and Education. National Research Council* (pp. 560–572). New York: Oxford University Press.
Wolford, G., & Chambers, L. (1983). Lateral masking as a function of spacing. *Perception and Psychophysics, 33*, 129–138.
Yuodelis, C., & Hendrickson, A. (1986). A qualitative and quantitative analysis of the human fovea during development. *Vision Research, 26*, 847–855.
Zadnik, K., Manny, R. E., Yu, J. A., Mitchell, G. L., Cotter, S. A., Quiralte, J. C., et al (2003). Ocular component data in schoolchildren as a function of age and gender. *Optometry & Vision Science, 80*, 226–236.