The Effects of Blur and Eccentric Viewing on Adult Acuity for Pediatric Tests: Implications for Amblyopia Detection

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PURPOSE. The detection of amblyopia in children relies on an accurate assessment of visual acuity. Visual deficits in anisometropic and strabismic amblyopia are different, but the influence of chart design, in particular position, and type of crowding features on visual acuity in the two types of amblyopia, is not clear. Certain aspects of amblyopic spatial vision are mimicked in healthy individuals by imposing increasing levels of blur and retinal eccentricity. We measured the effects of these conditions on visual acuity in healthy adults, with crowded and uncrowded vision tests.

METHODS. Visual acuity was measured under conditions of blur (0–4 D) and eccentric viewing (0–5 degrees) using high-contrast optotypes derived from common children’s acuity charts. Optotypes were presented in isolation, in commercially available crowded configurations, and in configurations with closer target-flanker separations than those currently available.

RESULTS. Dioptric blur had similar degenerative effects on crowded and isolated visual acuity (P > 0.05), whereas eccentric viewing resulted in a larger deterioration of visual acuity for crowded tests (E2 of 0.86–1.06) than for isolated optotypes (E2 of 1.57–1.72) (P < 0.05). Maximum crowding effects occurred for closer target-flanker separations than those currently used commercially.

CONCLUSIONS. In so far as blur and eccentric viewing mimic spatial acuity deficits in amblyopia, the results suggest that crowded tests might be of limited value in the detection of anisometropic amblyopia, but should be valuable in the detection of strabismic amblyopia. Crowding effects would be greater if flanking features were placed closer to the target than they currently are in commercially available charts.

Keywords: crowding, children’s visual acuity charts, amblyopia, dioptric blur, eccentric viewing

Visual acuity measured with optotypes that are surrounded by nearby objects may be worse than when an isolated target is used. This phenomenon is referred to as contour interaction when describing the effect of adjacent contours, such as bars and crowding, when other more complex objects, such as letters, are used. Contour interaction is a component of crowding and both contour interaction and crowding have been observed in adults and children, and in normal foveal, peripheral, and amblyopic vision.

Flom et al. reported that in a Landolt C visual acuity task, performance was similarly affected by flanking bars for adult observers with normal vision and those with reduced vision due to amblyopia. However, some studies have found that the effects of contour interaction and crowding on visual acuity are more pronounced in amblyopia than in normal vision. Furthermore, it has also been suggested that differences in crowding exist between strabismic and anisometropic amblyopia with a larger and more extensive crowding effect seen in strabismic than in anisometropic amblyopes.

The measurement of visual acuity is important in children’s vision screening programs, which aim to identify amblyopia at an early age to ensure the best possible visual outcome of treatment. In a review of the literature, Simons recommended that children’s visual acuity in screening programs and clinical settings should be measured using a single optotype with contour interaction provided by bars. More recently, the Pediatric Eye Disease Investigator Group developed a protocol for the measurement of visual acuity in children in the Amblyopia Treatment Study, also using a single letter optotype surrounded by bars, placed at a distance of 0.5-optotype width away to provide contour interaction. The UK National Screening Committee recommends the use of a line chart rather than single letters. However, in clinical practice, a number of children’s acuity charts are still available to the practitioner. These commercially available charts differ in the optotypes that are presented, the presence and location of flanking features, and the type of flanking features used.

In children with normal vision, visual acuity measured with commercially available crowded charts (i.e., charts in which flanking features are present) is often poorer than that measured with single, isolated optotypes, but the magnitude of the effect, that is, crowding, is affected by the child’s age and by the design of the chart. Younger children show a greater magnitude of crowding than older children and charts in which flankers are placed closer to the target have a larger effect on acuity than when flankers are farther away.

If the commercially available crowded charts are to be more sensitive in detecting amblyopia than isolated letters, the reduction in acuity resulting from the crowded presentation...
has to be greater in children with amblyopia than in children with normal vision. Some evidence for this is available. The problem of recording good levels of visual acuity in strabismic amblyopes when using the isolated letters of the Sheridan-Gardiner test was highlighted by Hilton and Stanley 28 and Youngson.29 The crowded logMAR test, in which flanking features are placed at a distance of 0.5 optotype away, has been found to be more sensitive in detecting amblyopia than isolated letter acuity measures when interocular visual acuity differences were considered.26,30

Some comparisons of children’s visual acuities obtained from different charts are available,4,26,31,32 but it is not clear whether the effects of different chart design and in particular of crowding, are different for anisometropic and strabismic observers, whereas it has been established that the spatial vision deficits in anisometropic and strabismic amblyopia are fundamentally different.35–37 Certain aspects of spatial vision in amblyopia can be mimicked in healthy individuals by imposing increasing levels of dioptric blur and increasing levels of eccentric viewing.35,38–41 To investigate the potential sensitivity of a range of charts to detecting amblyopia, we measured the effects of increasing blur and retinal eccentricity on visual acuity in adults with commercially available children’s vision charts (Experiment 1). In Experiment 2, we used chart designs that incorporate features at different distances away from the target, including those closer than are currently available commercially. The use of adults in this study allowed us to measure acuities across a range of vision tests and under degraded visual conditions (i.e., blur and eccentric viewing). Candy et al.32 showed that in adult patients, relationships between visual acuities obtained with different vision tests are similar to those that are reported in studies of children’s vision.

**EXPERIMENT 1**

**Methods**

**Apparatus and Stimuli.** High-contrast optotypes (black optotypes of 0.6 cd/m² on a white background of 102.0 cd/m² resulting in a contrast of 99.4%) derived from common children’s acuity charts were presented on a Sony Trinitron monitor (Model F520, 120 Hz, resolution of 769 × 1024; Weybridge, UK) in isolation, that is, Sheridan-Gardiner letters (Keeler Ltd., Windsor, UK) and Kay pictures (Kay Pictures Ltd., Tring, UK), and in configurations of commercially available crowded charts, that is, logMAR Crowded Test (Keeler Ltd.), Cambridge Crowding Cards (Clement Clarke International Ltd., Harlow, UK), Sonksen logMAR Test (Novomed Ltd., Maidstone, UK), and Kay Picture Test (Kay Pictures Ltd., Maidstone, UK). These charts differ in the optotypes and crowding features used and in the separations between them (see Table 1). The optotypes were scanned and converted to matrices, which were then scaled for the required size to be displayed on the monitor. Prior to commencement of the experiments, each matrix was manually checked for any single pixel errors that might have occurred during scaling and corrected if needed. A program written in Matlab (MathWorks, Cambridge, UK) controlled the experimental routine and a Cambridge Research System graphics card (VSG 2/5; Rochester, UK).

**Experimental Protocol.** Data were collected using the method of constant stimuli. Each experimental run consisted of 105 trials, in which optotypes across a range of seven sizes separated by approximately 0.1 logMAR were presented pseudo-randomly to ensure that each size was being tested on 15 trials. The step size was not always 0.1 logMAR due to the limitations imposed by the pixilated nature of displays, that is, the physical size of the stimuli (in mm) being restricted to multiples of pixel size rather than the exact desired size. However in any calculations, actual rather than desired sizes were used (e.g., logMAR of 0.098 rather than 0.1). For each condition, a range of sizes was chosen so that a full psychometric function could be generated. The responses were given verbally, entered using a keyboard by the examiner, and no feedback was provided. The display time was unlimited and once a response was given, the display extinguished and was replaced by a mean luminance screen for a minimum of 500 ms, to avoid any sudden changes in local luminance cues being used as an aid in identifying the optotype.

For each test, performance was assessed at the fovea with four levels of dioptric blur of 0, 0.5 diopter (D), 1 D, and 2 D, and without blur at four retinal eccentricities of 0 (fovea), 1.25 degrees, 2.5 degrees, and 5 degrees in the lower visual field. These levels of blur and eccentric viewing were chosen as they degrade normal visual acuity to a similar range as that observed in most amblyopic patients.43 Testing was monocular with the subject’s dominant eye, selected using the “hole in the hand”
sighting alignment test, while the other eye was covered with a black patch. Different levels of blur and eccentric viewing, and different acuity tests were run in a counterbalanced manner to minimize the effects of fatigue and practice. Testing without blur and with foveal viewing, and with low levels of blur and eccentricity was performed at 9.5 m, whereas for other conditions, the distance was appropriately reduced (in 0.1 log steps) to allow the presentation of the desired set of sizes on the screen. To achieve eccentric viewing, subjects were asked to look at a fixation target placed above the center of the visual display unit to achieve the desired eccentricity. The accuracy of fixation was not monitored, but any deviation in fixation would have been evident in the pattern of results. Adequate training was given to familiarize observers with the optotypes and task.

Data Analysis. Each condition was repeated twice and averaged data were fit with a Weibull function, using IgorPro (WaveMetrics, Portland, OR), to derive the threshold for letter identification (visual acuity) and slope value. The Weibull function is expressed by the following formula:

\[
P_{\text{correct}}(s) = 1 - (1 - g) \times \exp \left[ -10^b(s - th) \right]
\]

where \(g\) is the guess rate (ranging from 12.5% to 20.0% for the different tests, using 8 to 5 optotypes), \(b\) is the slope of the psychometric function, \(s\) is a target size in logMAR and \(th\) is the estimated resolution threshold corresponding to the logMAR at which the optotype was identified correctly 67.8% to 70.6% of the time (determined by the guess rate appropriate to the test).

To quantify the effect of increasing retinal eccentricity on visual acuity we measured with each test, \(E\) values (i.e., the eccentricity at which the resolution threshold is twice that of the fovea39) were calculated by fitting data expressed as MAR versus eccentricity with the following equation:

\[
T = T_f \times \left(1 + \frac{E}{E_f}\right)
\]

where \(T\) is the threshold at a given eccentricity \(E\) and \(T_f\) is the threshold at the fovea.

Data were analyzed statistically using repeated measures ANOVA with Greenhouse-Geisser correction for violation of sphericity. When appropriate, post hoc analyses with Tukey HSD correction were also performed. Statistical analyses were carried out using Statistica (StatSoft, Ltd., Bedford, UK).

Subjects

Five adult observers (four females and one male; three Caucasian and two Asian; mean age 31.0 ± 5.3 years; age range 19–47 years), with a spherical refractive error between +1.00 and −5.00 D (and <2 D with-the-rule astigmatism), participated in Experiment 1. All participants had normal or corrected-to-normal vision (6/5 or better) and normal binocular vision with stereoscopic acuity of 30 arcsec as measured with the Dutch Organization for Applied Scientific Research stereo test (Lameris Ootech, Ede, The Netherlands) to ensure that any degenerative effects were due only to experimental manipulation.

The conduct of this research was approved by The Anglia Ruskin University Research Ethics Committee, which complied with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all observers before the start of the experiment.

Results

Blur. Thresholds for letter identification (visual acuities as logMAR) averaged across all subjects are shown in Figure 1a. There was a significant difference in the visual acuities measured with the different tests (\(F_{2,90.37} = 9.127, P = 0.008\)). Post hoc analysis was used to compare visual acuities obtained with isolated and crowded optotypes. The visual acuity obtained with the crowded Kay picture test was not significantly different from that in the single Kay picture presentation (\(P = 0.584\)) and visual acuity obtained with the isolated optotypes of the Sheridan-Gardiner test was not significantly different from any of those with the crowded optotypes (\(P > 0.05\) for all). The tests used, therefore, did not produce any crowding effects in our adult subjects. The effect of blur on visual acuity was significant (\(F_{1.18,4.75} = 112.516, P < 0.001\)) but similar for all tests (no interaction between blur and test, \(F_{2,73.91} = 3.25, P = 0.067\)). Vision measured with Kay pictures was better than with letter targets (Fig. 1), and this
difference was significant for the crowded configuration, that is, the crowded Kay picture test and crowded logMAR test (both of which present a line of targets separated by a distance of 0.5 optotype width, surrounded by a box) (post hoc; \( P < 0.001 \)) but not for isolated optotypes (post hoc; \( P = 0.140 \)). On average, single and boxed Kay acuities were 0.077 ± 0.07 logMAR and 0.035 ± 0.06 logMAR, whereas single and boxed Sheridan Gardiner acuities were 0.15 ± 0.06 and 0.17 ± 0.07.

To better visualize the change in visual acuity with blur for each test, we plot normalized logMAR in Figure 1b, where normalized logMAR is the difference between visual acuity obtained with and without blur for that test. To assess the effect of blur for each test, we fit line functions to the normalized logMAR versus blur data. The rate of change was not significantly different for the different tests (\( F(2,30,9.20) = 0.368; \ P = 0.729 \)), again confirming that the detrimental effect of blur was the same for all tests, at 0.37 ± 0.06 logMAR/D.

**Eccentricity.** Recognition thresholds (i.e., visual acuity) expressed in logMAR as a function of eccentricity for the different tests are shown in Figure 2a and normalized results (i.e., logMAR \( = \) logMAR [fovea]) are shown in Figure 2b. Increasing retinal eccentricity had a detrimental effect on visual acuity (\( F(1,25,5.00) = 477.73; \ P < 0.001 \)) and more importantly, this effect was greater on visual acuity measured with the tests that contain crowding features than with isolated optotypes, confirmed by a statistically significant interaction between test and eccentricity (\( F(2,23,8.93) = 8.51; \ P = 0.008 \)).

The effect of increasing retinal eccentricity on visual acuity can be quantified by an \( E_2 \) value.\(^{39} \) \( E_2 \) values were calculated for each test used in this study (see Methods) and are shown in Table 2. \( E_2 \)'s were larger for isolated optotypes (1.72 ± 0.28 for letters and 1.72 ± 0.23 for Kay pictures) than for tests that contain crowding features (0.87 ± 0.06 to 1.04 ± 0.11), indicating a faster decline in acuity with increasing eccentricity when measured with crowded tests than isolated optotypes. The effect of test type on \( E_2 \) was statistically significant (\( F(1,21,4.82) = 10.29; \ P = 0.05 \)). Post hoc analysis revealed statistically significant differences between the \( E_2 \)'s for the Sheridan-Gardiner test and all crowded tests, and between the single and crowded Kay pictures (\( P < 0.05 \) for all), whereas the \( E_2 \) values obtained for all crowded tests were not significantly different from each other.

**EXPERIMENT 2**

**Methods**

In Experiment 1, we used commercially available test configurations. The minimum separation between the optotype and the flanking features in those charts is 0.5 optotype width, but this separation was too large to result in any crowding in foveal viewing using healthy adult observers (Fig. 1). Therefore, to allow an investigation of the effects of blur on crowding in Experiment 2, crowded tests with separations between the optotypes and flankers (described below) of 0 (where the flankers abut or touch the target optotype), 0.25, 0.5, and 1 optotype width were designed. The letters from the Cambridge crowding cards were used as targets (i.e., H, T, O, V, X) and presented in the Cambridge crowded configuration (i.e., a letter surrounded by other letters, and in a configuration that resembles the other crowded tests used in Experiment 1, with four letters surrounded by a box, to eliminate any differences in the measured visual acuity that might exist due to letter or picture choice on commercially available charts. The maximum level of blur was increased to +4 D to increase the range of acuities that could be investigated, because it appeared that differences between crowded and isolated tests may have been emerging at the highest level of blur used in Experiment 1 (Fig. 1b). Four different adult participants took part in Experiment 2 (two females and two males; two Caucasian and two Asian; mean age 26.0 ± 1.9 years; age range 21–29 years), with a spherical refractive error between +5.00 D and −5.00 D (and <2 D with-the-rule astigmatism). All had normal or corrected-to-normal vision (6/5 or better) and normal binocular vision with stereoaucuity of 30 arcsec or

**Table 2.** \( E_2 \) Values Averaged Across Observers for the Tests Used in the Study

<table>
<thead>
<tr>
<th>Test</th>
<th>( E_2 ) Average ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheridan-Gardiner test (isolated optotypes)</td>
<td>1.72 ± 0.28</td>
</tr>
<tr>
<td>Single Kay picture test</td>
<td>1.72 ± 0.23</td>
</tr>
<tr>
<td>LogMAR crowded test</td>
<td>0.95 ± 0.09</td>
</tr>
<tr>
<td>Crowded Kay picture test</td>
<td>0.98 ± 0.09</td>
</tr>
<tr>
<td>Cambridge crowding cards</td>
<td>0.87 ± 0.06</td>
</tr>
<tr>
<td>Sonksen acuity test</td>
<td>1.04 ± 0.11</td>
</tr>
</tbody>
</table>
better. All other experimental methods were the same as those described for Experiment 1.

Results

Blur. Visual acuities averaged across observers for the different test configurations are shown as logMAR in Figure 3. There was an overall significant effect of optotype configuration (which takes into account spacing and flanker type) ($F_{2.28,6.84} = 39.65$, $P < 0.001$) and blur ($F_{1.22,5.76} = 101.77$, $P < 0.001$) on visual acuity. There was no interaction between the effects of blur and test configuration ($F_{2.56,7.67} = 1.05$, $P = 0.41$) suggesting that blur reduced acuity in a similar fashion for all test configurations.

Figure 4 shows the magnitude of crowding for each level of imposed blur (i.e., the difference between flanked and unflanked acuity) at each target-flanker separation. The differential effect of separation on the magnitude of crowding is evident in statistical analysis ($F_{2.30,6.90} = 70.96$, $P < 0.001$).

Post hoc tests showed that the difference between flanked and unflanked conditions occurred at a separation of 0 and 0.25 for both flanker types ($P < 0.01$ for all). There was no statistical difference at the separations of commercially available charts used in Experiment 1, that is, 0.5-letter width ($P = 1.00$ and $P = 0.35$ for box and letter configurations, respectively) and 1-letter width ($P = 0.80$ and $P = 1.00$ for box and letter configurations, respectively), confirming an absence of the crowding effect in our adult observers at these target-flanker separations. There was also an overall significant effect of type on the magnitude of crowding ($F_{1.3} = 27.55$, $P = 0.01$) with the letter flankers producing a greater crowding effect than the box configuration. Blur did not have a statistically significant effect on the magnitude of crowding across the range of target-flanker separations used ($F_{2.02,6.05} = 2.47$, $P = 0.16$).

The largest effects of crowding were observed in the unblurred fovea and when the optotypes and flanking features were abutting; these were $0.21 \pm 0.02$ logMAR for the row/
box presentation and $0.23 \pm 0.02 \log MAR$ for the letter flankers (i.e., over two lines on a visual acuity test). The peak magnitude of crowding was lower when blur was imposed and this effect of blur was significant ($F_{2,167.84} = 5.862; P = 0.031$). Post hoc tests indicated that the peak magnitude for 0 D was significantly different from that for blur levels of 1, 2, and 4 D ($P < 0.05$ for all).

**Eccentricity.** Figure 5 shows unflanked and flanked visual acuity as a function of eccentricity. Visual acuity worsened with increasing eccentricity at a rate that is steeper for crowded configurations than isolated optotypes.

There was a significant overall effect of test configuration (which encompasses spacing between optotypes and type of flankers) and eccentricity on visual acuities ($F_{2,69.80} = 21.43; P < 0.001$ and $F_{1,43.29} = 242.11, P < 0.001$). Post hoc comparisons of unflanked and flanked visual acuity indicated a significant difference for separations of 0, 0.25, and 0.5 optotype width for the box configuration and separations of 0, 0.25, 0.5, and 1 for the letter flankers ($P < 0.05$ for all).

A lack of interaction between the effects of test configuration and eccentricity ($F_{3,51.92} = 3.59, P = 0.08$) suggests the same effect of eccentricity on visual acuity for all test configurations, but the $E_2$ values (Table 3) are significantly different ($F_{1.89,4.76} = 10.92, P = 0.019$). $E_2$ for the isolated targets ($1.57 \pm 0.21$) was larger than for the crowded tests ($0.86 \pm 0.14$–$1.06 \pm 0.11$) indicating a faster decline of visual acuity for the crowded than isolated targets. Post hoc analyses indicated significant differences between $E_2$ values obtained for the isolated and all crowded conditions ($P < 0.05$). $E_2$ values were smaller, and significantly different, for the letter than box configuration ($F_{1,3} = 11.76, P = 0.04$), although for the range of separations tested, the target-flanker separation did not significantly affect the $E_2$ values.

Figure 6 shows the magnitude of crowding at each measured eccentricity (i.e., the difference between flanked and unflanked acuity) at each target-flanker separation. There was a significant effect of separation and eccentricity on the crowding ($F_{2,7.42} = 19.78; P < 0.001$ and $F_{1,9.79} = 61.65; P < 0.001$) but no effect of flanker type ($F_{1,1} = 6.69, P = 0.08$). The maximum effect of crowding was seen when the target and flankers were abutting and reduced as the flankers were moved away (Fig. 6). At most target-flanker separations, the magnitude of crowding increased with each increasing eccentricity and crowding with eccentric viewing of 1.25, 2.5, and 5 degrees was greater than at the fovea ($P < 0.05$ for all). The peak magnitude of crowding was greater when the letters were flanking the target ($0.22 \pm 0.03$ for foveal viewing to $0.42 \pm 0.02$ for 5-degree eccentricity) than when a linear presentation and a flanking box were used ($0.18 \pm 0.03$ for foveal viewing to $0.35 \pm 0.03$ for 5-degree eccentricity), but this difference did not reach statistical difference ($F_{1,3} = 5.948; P = 0.095$).

**Table 3.** $E_2$ Values Averaged Across Observers for the Different Target/Flanker Configurations Used in Experiment 2

<table>
<thead>
<tr>
<th>Target Flanker Separation</th>
<th>Box Average ± SEM</th>
<th>Letters Average ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated</td>
<td>1.57 ± 0.21</td>
<td>0.96 ± 0.11</td>
</tr>
<tr>
<td>0</td>
<td>0.96 ± 0.11</td>
<td>0.99 ± 0.13</td>
</tr>
<tr>
<td>0.25</td>
<td>0.96 ± 0.17</td>
<td>0.90 ± 0.14</td>
</tr>
<tr>
<td>0.5</td>
<td>1.06 ± 0.11</td>
<td>0.89 ± 0.06</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DISCUSSION**

**Effects of Blur on Vision and Crowding**

The reduction in visual acuity with blur up to 2 D (Experiment 1) was linear, with a rate of decrease of $0.37 \pm 0.01 \log MAR/D$ (i.e., approximately four lines on an acuity test for 1 D of blur) but became nonlinear as blur was increased to 4 D (Experiment 2). This pattern is in agreement with the results of previous investigations of the effects of dioptric blur on acuity$^{5,45–49}$ and is similar to that observed when vision is plotted as a function of refractive error.$^{50,51}$

It is possible that blurring of the stimulus could have resulted in the blurred flanker encroaching on the blurred target letter, making it even more difficult to recognize.$^{45}$ However, the rate of reduction of visual acuity with increasing dioptric blur was not statistically different overall for isolated optotypes and crowded configurations used in this study. Other studies reached the same conclusion when investigating the effects of spherical blur of up to 12 D for charts with
interletter spacings of 0.25- and 1-letter width and astigmatic blur with commercially available crowded and uncrowded charts.52

In Experiment 1, there was no significant difference in foveal visual acuities obtained with the commercially available crowded charts and isolated optotypes, indicating that crowding was not evident in our adult subjects at the target-flanker separations used. This result can be attributed to the small angular size of the foveal crowding zone,43 resulting in the extent of crowding being not much more than 0.5 optotype width53,54 and therefore only a small reduction of acuity when flankers are placed at that distance.5

In Experiment 2, foveal visual acuity was reduced by the presence of flanking features, (i.e., the effects of crowding were observed). The maximum amount of crowding was observed when the target and flankers were abutting (i.e., a separation of 0) and was up to two lines on a logMAR chart, similar in magnitude to that reported by others.8,55,56 As the flankers were moved farther away, the amount of crowding reduced and was no longer evident when the bars were 0.5 or 1 optotype width away.

It has been reported that contour interaction is negligible when dioptric blur is imposed.57 Our results show that crowding is reduced with the addition of dioptric blur but it is still present at the close separations of 0 and 0.25 optotype width. The reduction in the magnitude of crowding at separations other than abutting, when expressed in units of optotype or letter widths, could be attributed to the small and fixed size zone of foveal crowding.5,58,59 As the dioptric blur is increased, the targets need to be larger to allow recognition. Therefore, the same separation in optotype widths with increasing levels of blur corresponds to a larger separation in arcmin, which could mean that the flankers are placed outside the zone of crowding.58,59

### Effects of Eccentric Viewing on Vision and Crowding

The reduction in performance with increasing eccentricity can be characterized by an $E_2$ value (i.e., the eccentricity at which the threshold is twice that at the fovea).58 For the recognition task, we obtained values of 1.57 to 1.72 for isolated targets and smaller values of 0.86 to 1.06 degrees for crowded acuity (Tables 2, 3). These values are in agreement with the $E_2$'s reported for resolution acuity in the literature.60-65 Smaller $E_2$ values indicate a faster fall off in visual acuity with eccentricity for crowded than isolated targets.61,62 reflecting the greater effect of eccentric viewing on crowded than isolated targets. Our results also show that crowding in peripheral vision is greater and more extensive than in foveal viewing.65,66,67

### Effects of Target and Flanker Configuration on Crowding

Commercially available pediatric acuity charts employ different target/flanker configurations as well as different flanking features (Table 1). As crowding is thought to increase as the degree of similarity of the target and flankers increases,65 flanking a letter by other letters could result in a greater magnitude of crowding than using a box as a flanking feature. The effects of flanker type on the crowding function have been observed in some but not all instances8,56 and it has been suggested that tests in which a letter is flanked by other letters would be more sensitive in detection of amblyopia than when a letter is flanked by bars.56 Averaged across all blur and separation conditions, the difference between the acuities obtained with the two configurations used in the current study, was only approximately 1 optotype (or 0.025 logMAR) and therefore not likely to be significant clinically. The fall-off in visual acuity with eccentricity indicated by smaller $E_2$ values, was steeper when the flankers were all letters. However, the two configurations did not produce statistically significant differences in overall or peak crowding effects and are not likely to be clinically significant. In peripheral vision, the increased detrimental effect of similarity of flankers might have been similar to the additional detrimental effects provided by fixational eye movements and attentional aspects,2 as well as positional uncertainty that would have been present when four letters were presented in a line.

Some clinical tests surround the target array of letters, with a box to standardize the crowding effects at each acuity level (see Table 1).22,23 However, grouping of flankers (such as what occurs when four bars are configured so they form a box) can reduce the effects of crowding.57-70 Although foveal crowding in adults is still present when a line of letters (this study) or a single letter is surrounded by a box, the use of bars rather
Implications for the Detection of Amblyopia in Children

If a crowded test is to be more effective in the detection of amblyopia than the use of isolated pictures or letters, the effect of crowding measured with that test needs to be greater in amblyopic than in normal vision. However, if the underlying crowding function in amblyopia measured across flanker separation (in optotype widths) scales directly with acuity,\(^1\) then the placement of crowding features according to optotype size, would not degrade visual with crowded tests any more than when measured with single optotypes.

The result that imposed monocular blur had a similar effect on visual acuity measured with isolated optotypes and with flankers placed at separations of 0 to 1 optotype width, suggests that in uncorrected refractive error and potentially in anisometropic amblyopia, the crowding function (i.e., difference between crowded and isolated acuity at each target-flanker separation) would scale with acuity. Furthermore, dioptric blur actually reduces the peak magnitude of crowding. If imposed monocular blur in normal vision mimics anisometropic amblyopia (and clearly it cannot account for long-term binocular deficits affecting monocular visual acuity), the same or a lower level of degradation in visual acuity with crowded tests than isolated optotypes would be expected. The same would be true for eyes that are blurred due to an uncorrected refractive error.

Eccentric viewing, which can mimick spatial vision in strabismic amblyopia, had a greater effect on the visual acuity measured with crowded tests than with isolated optotypes. Both the magnitude and extent of crowding were greater with eccentric than foveal viewing. Even without potential binocular deficits that might also contribute to a visual acuity loss, this result suggests that in strabismic observers, the crowding function would not scale with visual acuity, but would be more extensive in both extent and peak magnitude. Crowded charts may therefore be more sensitive than isolated letters in detecting strabismic amblyopia. Different crowding effects in strabismic and anisometropic amblyopia have already been suggested\(^{12,13}\) and here we show that this also is true for proposed models of amblyopia in adult observers.

In foveal vision, we found only a relatively low magnitude of crowding (≈0.1 logMAR or one line on an acuity chart for nonabutting flankers). The magnitude increased with eccentric viewing (≈0.3 logMAR or three lines on an acuity chart). The magnitude of crowding is greater for small target-flanker separations both at the fovea and in the periphery, suggesting that flankers in commercially available charts should be placed closer to the target optotype (but farther than the resolution limit of the eye) (e.g., 0.25 optotype width) than the currently used separation of 0.5 or 1 optotype width.

The experiments reported here were performed on adults, using pediatric visual acuity tests (Experiment 1) or modified tests based on commercially available pediatric visual acuity charts (Experiment 2). It would not be possible to conduct such extensive psychophysical studies on children. However, our results point to more select conditions to use in future studies in children. Single-letter visual acuity is thought to reach adult levels by approximately 5 to 6 years of age.\(^{18,21,71}\) Therefore, some of our results are applicable to children who are still in the target group for the detection and treatment of amblyopia (i.e., younger than 7–8 years old).

The effects of crowding are larger\(^{55,71}\) and more extensive in children than in adults,\(^5\) attributable to poorer ocular motor control in children, cognitive and attentional factors, and immaturity of higher cortical areas that may be involved in crowding.\(^4,55,71,72\) It is not clear what role each of these factors plays in determining the extent, magnitude, and peak position of the crowding effect. If children were able to perform the experiments here, crowding might be found for larger target-flanker separations and/or the crowding reported might be greater in magnitude. Further research with a limited selection of conditions, targeting a pediatric amblyopic population, would provide invaluable additional information. At the fovea, crowding is present in adults when a single letter is closely surrounded by a box, as well as other letters or bars, and the magnitude is similar for picture and letter optotypes.\(^{54}\) Atkinson et al.\(^71\) reported that the effect of different flankers is not the same in adults and children, so further experiments could investigate what effect different flanker types (bars, box, and letters) have on crowding in children, and whether crowding is affected by the use of picture versus letter optotypes.

CONCLUSIONS

To the extent that blurred normal foveae mimic spatial vision in anisometropic amblyopia and normal eccentric viewing mimics spatial vision in strabismic amblyopia, our experimental results suggest that optimally designed crowded tests would be particularly helpful in the detection of amblyopia associated with strabismus or in patients who use eccentric viewing loci, but less valuable in the detection of purely anisometropic amblyopia or in uncorrected refractive error.

Crowding in acuity tests could be enhanced by placing flanking features closer to the target letter than in the currently available tests. Our results suggest that a distance of 0.25 optotype width away from the target would be more effective. The magnitude of crowding was only slightly, and not clinically significantly greater when a target letter was surrounded by other letters than when targets were presented as a line surrounded by a box. To reduce confusion of similar targets and flankers, such as letters in a line, or surrounding letters, which may occur for young children, the effect of placing a box (or a combination of bars) at similar distances from a single target letter on contour interaction should be investigated.

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References

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