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ORIGINAL ARTICLE

# Factors Affecting Crowded Acuity: Eccentricity and Contrast

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## ABSTRACT

***Purpose.*** Acuity measurement is a fundamental method to assess visual performance in the clinic. Little is known about how acuity measured in the presence of neighboring letters, as in the case of letter charts, changes with contrast and with nonfoveal viewing. This information is crucial for acuity measurement using low-contrast charts and when patients cannot use their fovea. In this study, we evaluated how optotype acuity, with and without flankers, is affected by contrast and eccentricity.

***Methods.*** Five young adults with normal vision identified the orientation of a Tumbling-E presented alone or in the presence of four flanking Tumbling-Es. Edge-to-edge letter spacing ranged from 1 to 20 bar widths. Stimuli were presented on a white background for 150 ms with Weber contrast ranging from −2.5% to −99%. Flankers had the same size and contrast as the target. Testings were performed at the fovea, 3°, 5°, and 10° in the inferior visual field.

***Results.*** When plotted as a function of letter spacing, acuity remains unaffected by the presence of flankers until the flankers are within the critical spacing, which averages an edge-to-edge spacing of 4.4 bar widths at the fovea and approximately 16 bar widths at all three eccentricities. Critical spacing decreases with a reduction in contrast. When plotted as a function of contrast, acuity only worsens when the contrast falls below approximately 24% at the fovea and 17% in the periphery, for flanked and unflanked conditions alike.

***Conclusions.*** The letter spacing on conventional letter charts exceeds the critical spacing for acuity measurement at the fovea, at all contrast levels. Thus, these charts are appropriate for assessing foveal acuity. In the periphery, the critical spacing is larger than the letter spacing on conventional charts. Consequently, these charts may underestimate the acuity measured in the periphery because of the effects of crowding.
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Key Words: acuity, contrast, eccentricity, crowding, periphery, critical spacing, critical contrast

Visual acuity measurement is one of the most fundamental methods to assess visual performance in the clinic, and the most common instrument for assessing acuity is the printed letter chart.[1] Letter charts are used in a wide variety of situations, so it is important to understand the factors that affect acuity measurements under differing stimulus and observer conditions. The current best letter chart design is likely to be the Bailey-Lovie chart,[2] or variants of it (e.g., the Early Treatment of Diabetic Retinopathy study [ETDRS] chart[3] or the Lea symbol chart[4]). A characteristic of these charts is that there are five optotypes on each line, and the spacing between adjacent optotypes (1 optotype width) is designed to minimize the effect of contour interaction. Contour interaction refers to the degrading effect on acuity caused by the presence of nearby contours. Although acuity in the presence of this effect can be informative, for example, to help detect amblyopia,[4,5] the usual desire of clinicians is to avoid the deleterious influence that may introduce undesirable variability to measurements of acuity.[2] The adoption of a spacing of 1 full optotype width between adjacent optotypes on letter charts comes from the findings of Flom et al.[6,7] Flom et al. measured the accuracy for identifying the orientation of small, high-contrast Landolt-C optotypes in the presence of flanking bars at a range of target-flanker spacings. When expressed in terms of multiples of the size of the gap of the Landolt-C, they found that flanking bars beyond 5 gap widths (equivalently "5 bar widths," which equals 1 full letter width) had little detrimental effect on the identification of the direction of the gap in the Landolt-C. However, these results, and the design of the Bailey-Lovie chart, assume foveal viewing and are based on high-contrast targets.

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In the clinic, it is not uncommon to encounter patients who are unable to view a letter chart foveally, as in cases of people with central vision loss or even for patients with mild macular edema. It is necessary to understand how the measured acuity of these patients might be affected by contour interaction, or "crowding." (Although Flom[8] made a distinction between these two terms, we use them interchangeably.[9]) Previous studies have shown that the deleterious effect of crowding on acuity extends over 5 bar widths in the periphery,[10,11] but the maximum spatial extent of the interference, in terms of bar widths at resolution threshold, has not been quantified.[8] There has been extensive study of the angular spatial extent of crowding in the periphery,[12–14] and it is well known that isolated letter acuity changes with eccentricity.[10,15] However, because the nominal critical spacing (the letter separation in terms of bar or letter widths necessary to overcome crowding) is dependent on both of these two variables, how it changes with eccentricity at resolution threshold remains an open question. An overview of the nontrivial issue of nominal versus angular critical spacing is discussed further in Appendix 1 (available at http://links.lww.com/OPX/A127). The first goal of this study is to identify the nominal critical spacing in the periphery.

In addition to high-contrast acuity, low-contrast acuity is routinely assessed for some groups of patients in the clinic (e.g., low-vision patients or patients with cataracts or corneal problems) because low-contrast acuity may be more sensitive than traditional high-contrast acuity in detecting certain abnormal ocular conditions.[16–21] Although it is now established that acuity measurements from low-contrast charts viewed foveally will be less affected by crowding than their high-contrast counterparts,[22–27] it is unclear if this same reduction in the influence of crowding occurs peripherally. The second goal of this study is to determine the effect of contrast on the critical spacing in the periphery.

When using low-contrast letter charts, how the contrast of the optotype affects the measured acuity, particularly in the presence of flanking letters in the periphery, is also an open question. For single-letter testing, it has been shown that, at the fovea, above some critical contrast (the minimum contrast that still yields the maximal acuity) in the range of 20% to 40% Weber contrast, there is little change in letter or grating acuity with contrast.[28–30] In the periphery, Thibos et al.[31] found a critical contrast of approximately 20% for the resolution of gratings located at 30° in the nasal visual field. The critical contrast for reading has also been identified, with values ranging from 2% to 5%,[32] 10%,[33] to 20%.[34] It is unknown exactly how the measurement of acuity in the presence of adjacent letters, as in the case of a letter chart, affects the critical contrast, and how the critical contrast for acuity measurement changes from foveal to peripheral viewing of a chart. If the critical contrast for a given condition (e.g., peripheral viewing of a chart) is below the contrast of the printed letters on a low-contrast acuity chart, the usefulness and the effectiveness of this chart as a diagnostic aid may be affected.

Given all these considerations, the general goal of this article is to examine the interplay of letter contrast, viewing eccentricity and letter spacing on acuity measurement. Specifically, the goals are (1) to quantify the *nominal critical spacing* for high-contrast optotypes in the periphery, (2) to evaluate how the nominal critical spacing changes with contrast in the periphery, and (3) to determine the *critical contrast* for acuity measurement in the fovea and periphery in the presence of crowding.

## METHODS

### Stimulus Characteristics

Acuity was measured using Tumbling E optotypes adhering to the recommended Sloan dimensions.[35,36] The limbs (bars) and gaps of each character were one-fifth of the overall optotype size, which had equal width and height. For testing flanked acuity, four additional Tumbling Es appeared, located above, below, and to the left and right of the target letter. The orientation of the target and each of the four Tumbling E flankers (when present) was completely random, with the limbs of each letter pointing to the left, right, up, or down. The separation (in blank space) between the target and each of the flankers was specified as a multiple of the size of one limb of the "E," occupying 1, 2, 4, 5, 10, or 20 bar widths. Eight different levels of contrast were evaluated: −2.5%, −3.4%, −6.7%, −12.5%, −22%, −44%, −70%, and −99% Weber contrast. Weber contrast is defined as $(L - L_b) / L_b$, where $L$ indicates the luminance of the foreground optotypes and $L_b$ denotes the luminance of the background. The contrast of the flankers was always the same as that of the target. The stimuli appeared in the fovea or one of three eccentricities in the lower visual field: 3°, 5°, or 10°. The stimuli were presented for 150 ms, a duration short enough to avoid voluntary saccadic eye movements to the stimulus once subjects fixated on the fixation target. As soon as the subjects responded, the next stimulus appeared.

### Testing Conditions

Testing occurred in a dim room with less than 1 cd/m$^2$ of ambient light. A 19″ NEC Accusync 120 CRT monitor (NEC, Tokyo, Japan) at a resolution of 1280 × 1024 pixels was used. The luminance of the white background displayed on the monitor was 75 cd/m$^2$. Luminance measurements were performed using a Minolta LS100 photometer (Minolta, Tokyo, Japan). Subjects viewed the stimuli binocularly with their habitual distance correction. Distance from the monitor depended on the retinal eccentricity being tested. For the foveal condition, subjects were seated 2.4 m from the monitor; for the 3° condition, at 1.8 m; and for the remaining conditions (5° and 10°), 40 cm from the monitor. At the farthest viewing distance (2.4 m), one pixel on the monitor subtended 0.43 min of arc. For the eccentric conditions, a cross (which was present throughout a trial) served as the fixation target, and the target E (flanked or unflanked) appeared at the appropriate eccentricity below the cross. The size of the fixation cross was 3.1 mm, so the angular subtense of the cross varied with viewing distance, having a size of approximately 27′ at 40 cm and 6′ at 1.8 m. To avoid masking effects, no fixation cross appeared for the foveal targets. Stimuli were rendered and displayed with custom software written in the Python programming language using the PsychoPy psychophysics library.[37]

### Subjects

Five subjects participated in this study. Table 1 lists the demographic information of the subjects. Written informed consent

**TABLE 1.**
Subject demographics

| Subject | Gender | Age | Best corrected visual acuity | Refractive errors |
|---|---|---|---|---|
| S1 | M | 20 | OD: 20/20<br>OS: 20/20 | OD: −5.57<br>OS: −4.75 |
| S2 (co-author) | M | 27 | OD: 20/16<br>OS: 20/16 | OD: −11.25 −0.50 × 003<br>OS: −11.75 −0.25 × 124 |
| S3 | F | 22 | OD: 20/20<br>OS: 20/16 | OD: −4.00 −0.75 × 165<br>OS: −3.75 −0.75 × 170 |
| S4 | F | 19 | OS: 20/12.6<br>OS: 20/12.6 | OD: −2.00<br>OS: −2.00 |
| S5 | F | 20 | OD: 20/20<br>OS: 20/20 | OD: −2.50 −0.50 × 176<br>OS: −3.00 −0.50 × 013 |

was obtained from each subject after the procedures of the experiment were explained and before the commencement of data collection. The experimental protocol was approved by the institutional review board at the University of California, Berkeley, and conformed to the Declaration of Helsinki.

## Psychophysical Procedure

Threshold letter size (specified as the minimum angle of resolution [MAR] in units of minutes of arc) for each condition was determined using an adaptive three-down, one-up staircase procedure, which identified the threshold for 79% correct performance. For each staircase run, the target Tumbling E, with or without its four flankers, initially appeared at a size significantly above threshold for the selected testing eccentricity: 2° letters at the fovea, 2.5° letters at 3° eccentricity, 3° letters at 5° eccentricity, and 4° letters at 10° eccentricity. The stimulus size was reduced after three consecutive correct trials, and increased after a single incorrect trial. The amount by which the stimulus size changed after each of these reversals became progressively smaller, using the following sequence: three reversals of one log unit, four reversals of 0.2 log units, and five reversals of 0.1 log units. A single staircase ended when all 12 reversals were completed and took, on average, 78 trials, with 95% of the staircases taking between 50 and 200 trials. There was no systematic effect of retinal eccentricity, stimulus contrast, or letter spacing on the number of trials it took to estimate a threshold. The threshold was determined as the average of the sizes at which the reversals occurred, with the exclusion of the first two reversals, which were not used in the threshold calculation.

## Testing Sequence

Every condition (eccentricity, contrast, and spacing) was tested at least twice, with the order of execution determined as follows. For each subject, a random order of eccentricities was constructed from the set of eight eccentricities (four eccentricities, each appearing twice). To test an eccentricity, a random ordering of contrasts was generated. For each contrast, the order of flanker spacings (including unflanked) was randomized. For each of these conditions (eccentricity, contrast, and spacing), the software first displayed the parameters (eccentricity, contrast, and spacing) about to be tested, then commenced the staircase procedure defined in "Psychophysical Procedure" to determine the threshold. Testing all conditions for one eccentricity (all contrasts and all spacings) took an hour to an hour and a half. This randomization of the sequence of trials was performed to minimize the effects of fatigue and practice.

## Data Analysis: Fitting Individual Acuity Versus Letter Spacing

To evaluate how acuity is affected by the spacing between adjacent letters and to derive the critical spacing for the different contrasts and eccentricities, thresholds are first analyzed as a function of letter spacing. The primary method of modeling the data is to adopt the formulation used by previous studies.[38–41] This method has been used to model crowded acuity in the fovea and periphery of normal subjects, amblyopes, and people with age-related macular degeneration. In this model, data for a given condition are fit using a two-line function, with acuity plotted as threshold size against nominal spacing, on logarithmic axes. Fig. 1 shows an example of this model with subject data collected at 3° eccentricity in the lower visual field and with high-contrast stimuli. When flankers are far from the target (or absent), acuity is unaffected by the spacing of the flankers, and the ordinate is a horizontal line. When the flankers are in close proximity to the target, acuity is affected by spacing. These data are well described by a line with a slope of negative one, which implies a complete trade-off between acuity and spacing. This complete trade-off between acuity and spacing is a direct consequence of the fixed angular size of the crowding zone at any given eccentricity.[14] The intersection of the two lines is the critical spacing, by definition. The basis of this formulation is described in further detail in Appendix 2 (available at http://links.lww.com/OPX/A128). Although the fit is performed as described above, in this article, results are presented with the units of edge-to-edge letter spacing (in bar widths) on the abscissa and MAR (in minutes) on the ordinate to better relate our findings to clinical practice. The effectiveness of this model in fitting the present data is demonstrated in the Results section. Although more complex formulations have been used to fit data like ours, such as the rectangular parabola,[42] the simplicity of the two-line fit, and the clear interpretation of its parameters, justify its

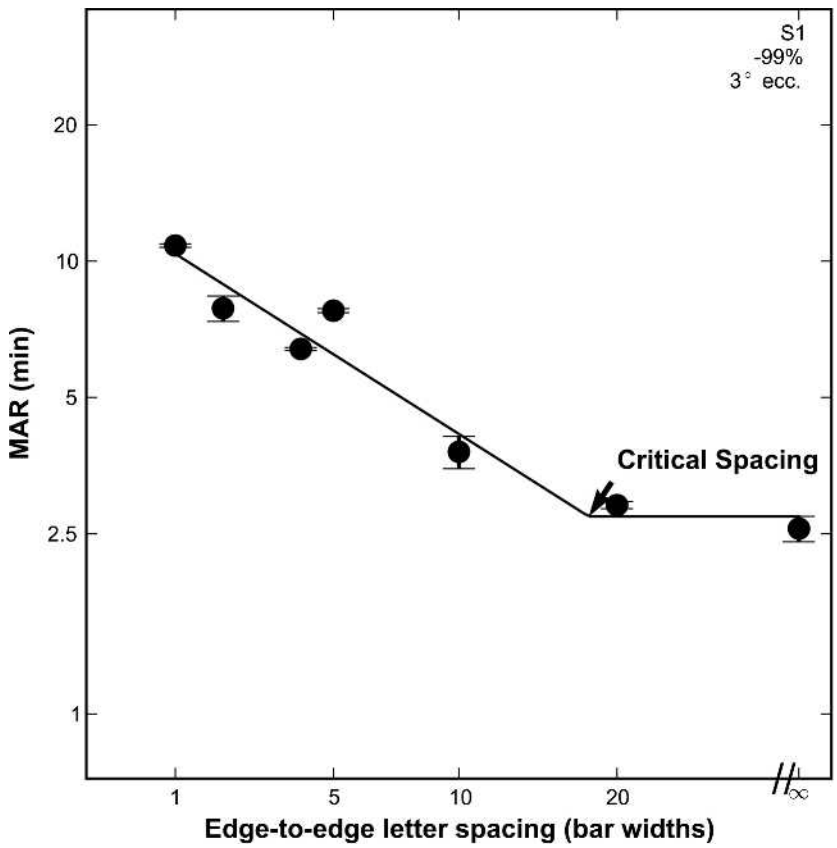


**FIGURE 1.**
Subject S1's data with high-contrast stimuli at 3° in the lower visual field demonstrating the two-line fit of acuity versus letter spacing. The datum plotted at a letter spacing marked with "∞" represents unflanked acuity. The critical spacing is where the two lines intersect. Error bars indicate the standard deviation between the thresholds from the subject's two separate staircase runs. To the right of the critical spacing acuity is flat, implying that it is unaffected by crowding. To the left of the critical spacing, adjacent characters are within the "crowding zone," and thus, crowding is evident. The slope in this portion is constrained to −1.

use. With this fit, the dependent variable increases monotonically as flankers approach the target. Some researchers have identified a facilitation effect, whereby flankers very near the target may actually aid its identification,[6,27,43,44] although with percent correct as the dependent variable. It is not clear that the same effect would be apparent when acuity is measured nor has there been evidence of this effect in the periphery.

## Data Analysis: Fitting Individual Acuity Versus Contrast Data

To evaluate how acuity is affected by stimulus contrast, the critical contrast for acuity measurements for the different eccentricities and letter spacings is derived. To do so, threshold is plotted as a function of contrast on log-log axes, for each eccentricity and letter spacing. The acuity versus contrast function can also be described by a two-line fit, but unlike the acuity versus spacing fit, the slope of the decreasing portion of the curve is allowed to vary. The critical contrast is defined as the contrast at which threshold begins to worsen from its optimal value, which is achieved at full contrast. This critical contrast is the value on the abscissa where the two lines intersect. A similar fit has been used previously by O'Brien et al.[32] and Chung and Tjan,[33] but with reading speed as the ordinate.

## Curve Fitting

Curve fitting was accomplished using the scipy.opt optimization library in Python. Summed square error was minimized using the L-BFGS algorithm, an iterative fitting procedure capable of nonlinear fitting. When the dependent variable was an acuity measurement, errors were minimized on a log axis, as suggested by Westheimer.[45]

# RESULTS

## Acuity Versus Letter Spacing

First, threshold size is analyzed as a function of nominal letter spacing. Fig. 2 shows the individual subject data (S1–S5, separate rows) for all four eccentricities (different curves in each panel) at each stimulus contrast (each contrast in a column). As expected, acuity worsens as eccentricity increases, with the lowest curve (smallest threshold) representing data obtained at the fovea, and each curve above corresponding to data obtained at the more eccentric target locations. Acuity also worsens as contrast decreases (an upward shift in the family of four curves with the columns going from left to right). The unflanked foveal acuity measured at the highest contrast corresponds to a threshold of approximately 1 min of arc for four of the subjects (1.08, 1.09, 1.0, and 0.92 min, respectively, for S1–S4), with much poorer acuity for S5 (3.19 min), who had higher overall variability. We suspect that location uncertainty for the foveal targets and short stimulation duration (150 ms) made the task difficult for our observers,[46] which could account for why the high-contrast unflanked foveal acuity was not better.

To model the data, we use the constrained two-line fit as described above. $R^2$ statistics for the fit to the peripheral data averaged 0.85 (±0.17) across all subjects and contrasts, implying that the two-line fit provides an excellent description of the peripheral data. However, in the fovea, the $R^2$ values for the fit are typically low positive numbers, yielding an average of 0.33 (±0.3) across subjects and contrasts. This is due to the fact that the foveal crowding functions are relatively unaffected by the flankers for the range of spacings and contrasts tested, which is evident in Fig. 2 by the flatness of the foveal curves. The two-line fit yields very small nominal critical spacings, meaning that a straight line would

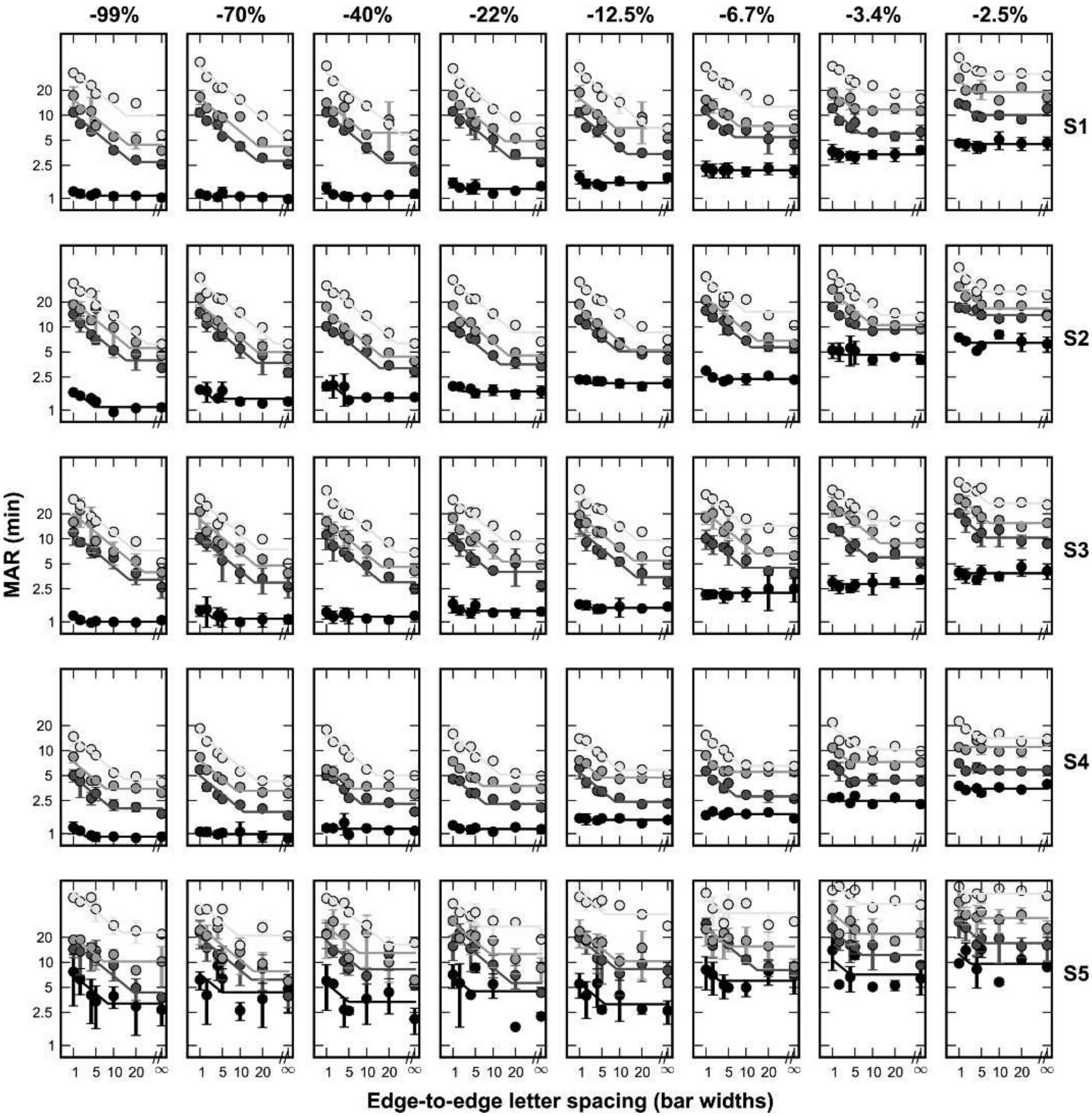


**FIGURE 2.**

Individual subject data showing acuity versus letter spacing at the four eccentricities tested (different shaded curves in each panel), at all stimulus contrasts. Each column is a given contrast, and each row is a particular subject. Error bars indicate the standard deviation between the thresholds from the subject's two separate staircase runs, and the lines show two-line fits. In each plot, the lowest curve comprises the foveal condition, with each successive eccentricity (3°, 5°, and 10°, respectively), stacked above.

fit the data almost as well as the model, resulting in a low $R^2$ despite a small sum of squared error. Regardless, it is parsimonious to have a single model that can describe the data accurately across all conditions.

The two-line fit summarizes the acuity at each condition with two parameters: the uncrowded acuity (the ordinate corresponding to the horizontal portion of the curve) and the nominal critical spacing (the abscissa corresponding to the intersection of the two lines). Table 2 lists the nominal critical spacings at −99% contrast for each subject as a function of eccentricity. To determine confidence intervals, 1000 individual Monte Carlo simulations based on the subject data were generated, and the model was fit for each simulation.[47] The reported statistics indicate the mean of the fitted parameter values and the 95% confidence interval range. Table 3 shows fits at all contrasts that were tested. The foveal nominal critical spacing (averaged 4.4 bar widths) is generally much smaller than the peripheral values (15–20 bar widths), with the three peripheral values being very similar to each other. The average value of the foveal critical spacing (4.4 bar widths) agrees with previous reports.[6] The novel contribution of this study is the finding that the nominal critical spacing in the periphery, known to be greater than 5 bar widths,[8,10] is 15 to 20 bar widths at the eccentricities tested.

At −99% contrast, a repeated-measures analysis of variance (using the software package R[48]) revealed a significant effect of eccentricity on critical spacing ($F_{3,18} = 7.753$, $p = 0.002$). Post-hoc pairwise comparison using the Tukey honestly significant difference (HSD) test showed that the fovea was different from the nonfoveal eccentricities ($p_{adj} < 0.03$ for the fovea vs. each of the three eccentricities), whereas the nonfoveal eccentricities were not different from each other ($p_{adj} > 0.5$). As shown in Table 3, lower contrasts yielded smaller critical spacings at all eccentricities, with a larger decrease in the periphery. A repeated-measures analysis of variance showed that contrast indeed had an effect on critical spacing ($F_{7,128} = 18.351$, $p < 0.001$), although the interaction between contrast and eccentricity was not significant ($F_{21,128} = 1.326$, $p = 0.171$). Furthermore, post-hoc pairwise comparison using the Tukey HSD test revealed which contrasts were significantly different from each other. Adjusted p values from these comparisons are given in Table 4. In general, at −12.5% contrast and above, none of the corresponding critical spacings were significantly different from each other. Particularly, at the lowest contrast (−2.5%), the nominal critical spacing was markedly reduced from the high-contrast critical spacing, decreasing to less than 5 bar widths.

**TABLE 2.**
Nominal critical spacing at high contrast (−99%), in bar widths

| | Fovea | 3° | 5° | 10° |
|---|---|---|---|---|
| S1 | 2 (0.88–3) | 18 (16–20) | 16 (8.4–26) | 15 (9.5–30) |
| S2 | 4.7 (3.6–6.6) | 15 (8.3–23) | 14 (3.2–38) | 27 (17–46) |
| S3 | 2.2 (0.95–3.1) | 16 (4.3–43) | 21 (7.5–41) | 19 (15–33) |
| S4 | 3 (−0.033–4.6) | 9.5 (3.6–15) | 7.7 (5–9.6) | 14 (9.6–17) |
| S5 | 8.2 (−0.95–35) | 17 (2–39) | 6.9 (3.4–51) | 13 (7.9–20) |
| **AVG** | **4.4 ± 3** | **15 ± 3** | **14 ± 5.3** | **19 ± 5.9** |

Mean of 1000 Monte Carlo simulations, with 95% confidence intervals in parentheses. Last row, in bold, indicates average (AVG) of the five subjects.

**TABLE 3.**
Nominal critical spacing (bar widths) at all contrasts, mean ± standard deviation across subjects

| Contrast, % | Fovea | 3° | 5° | 10° |
|---|---|---|---|---|
| −99.0 | 4.4 ± 3 | 15 ± 3 | 14 ± 5.3 | 19 ± 5.9 |
| −70.0 | 3.6 ± 2.2 | 16 ± 2.7 | 15 ± 3.4 | 22 ± 9.2 |
| −40.0 | 3.2 ± 1.8 | 14 ± 4.5 | 12 ± 3.9 | 22 ± 5.1 |
| −22.0 | 4 ± 3.7 | 13 ± 4 | 12 ± 3.3 | 15 ± 5.7 |
| −12.5 | 2.7 ± 1.7 | 12 ± 3.5 | 11 ± 3.6 | 15 ± 6.4 |
| −6.7 | 2 ± 0.76 | 9.9 ± 2.9 | 8.9 ± 3.6 | 9.6 ± 2.7 |
| −3.4 | 2.8 ± 1.7 | 6.2 ± 1.5 | 7.4 ± 3.1 | 8.4 ± 2.5 |
| −2.5 | 1.9 ± 0.53 | 4.2 ± 1.6 | 4.4 ± 2 | 4.5 ± 1.6 |

## Acuity Versus Contrast

In addition to the effect of letter spacing at each eccentricity and contrast level, the effect of contrast on acuity for a given condition (eccentricity and letter spacing) was analyzed, using the unconstrained two-line fit described earlier. The main parameter of interest in this analysis is the critical contrast, the contrast value at which acuity begins to worsen with decreasing contrast. Fig. 3 shows a summary of the critical contrasts at each eccentricity for all letter spacings, averaged across subjects, and Table 5 lists all the critical contrasts, averaged across subjects. Critical contrasts were, on average, lower in the periphery (14.5% [flanked] to 18% [unflanked]) than at the fovea (22% [flanked] to 26% [unflanked]), with similar values at the three nonfoveal eccentricities. Repeated-measures analysis of variance with both eccentricity and spacing as factors revealed a significant effect of eccentricity on critical contrast ($F_{3,112} = 9.635$, $p < 0.001$), a nearly significant effect of spacing ($F_{6,112} = 2.128$, $p = 0.056$), and no interaction ($F_{18,112} = 0.472$, $p = 0.97$). Post-hoc pairwise comparison using the Tukey HSD test showed that the fovea was different from the nonfoveal eccentricities ($p_{adj} < 0.01$ for the fovea versus each of the three eccentricities), whereas the peripheral eccentricities were not different from each other ($p_{adj} > 0.24$).

## DISCUSSION

In his classic 1991 review of contour interaction and crowding, Flom[8] noted that the critical spacing value of "5 gap widths" in the fovea had not yet been extended to the retinal periphery. This extent has now been quantified as approximately 15 to 20 bar widths between 3° and 10° eccentricity, as shown by the black points in Fig. 4. The critical spacing is relatively invariant to changes in retinal location over this range of eccentricities. For comparison, the horizontal dotted line in Fig. 4 indicates the character spacing on a modern chart designed with the principles to avoid foveal crowding.[2] Note that the characters on such a chart are outside the critical spacing at the fovea (the dotted line is above the critical spacing we measured), meaning that acuity is unaffected by crowding for this letter spacing. Outside the fovea, however, because the critical spacing is much larger, adjacent characters on such a chart are within the critical spacing. Thus, nonfoveal acuity measurements using a traditional letter chart may not be optimal because they are limited by crowding.

**TABLE 4.**

Pairwise significance testing of critical spacing as a function of stimulus contrast values from Table 3

| | −2.5% | −3.4% | −6.7% | −12.5% | −22.0% | −40.0% | −70.0% | −99.0% |
|---|---|---|---|---|---|---|---|---|
| −2.5% | | n.s. | **0.002** | **h.s.** | **h.s.** | **h.s.** | **h.s** | **h.s.** |
| −3.4% | | | n.s. | **0.04** | **0.003** | **h.s.** | **h.s.** | **h.s.** |
| −6.7% | | | | n.s. | n.s. | **0.01** | **0.002** | **h.s.** |
| −12.5% | | | | | n.s. | n.s. | n.s. | n.s. |
| −22.0% | | | | | | n.s. | n.s. | n.s. |
| −40.0% | | | | | | | n.s. | n.s. |
| −70.0% | | | | | | | | n.s. |

Adjusted p values are from Tukey HSD test. Those in bold are significant at 0.05 level.
h.s., highly significant (adjusted $p < 0.001$); n.s., not significant at 0.05 level.

Fig. 5 illustrates how a traditional letter chart (left side) could be modified to yield optimal acuity for peripheral viewing up to approximately 10° (right side). Alternately, optotypes may be presented in isolation, if isolated letter cards are available. However, a clinician may be interested in assessing additional information with a letter chart, such as the search ability of patients. This is especially important for patients with central vision loss who often lose their place during reading of text or when viewing letters on an acuity chart. Even if isolated letters are used, it is important to know how much white space is necessary to surround a single letter because any edges in the visual environment may cause lateral interference. Finally, if there is no alternative to using a traditional letter chart to assess peripheral acuity, in Appendix 2 (available at http://links.lww.com/OPX/A128), we describe a simple way to predict the optimal (isolated letter) acuity based on the crowded acuity. This is possible for two reasons: (1) the crowded thresholds fall on the line with a slope of −1 as described earlier, and (2) the nominal critical spacing is roughly invariant to retinal location within 3° to 10° eccentricity.

Since the first groundbreaking studies of Flom et al.,[6,7] there have been many explorations of crowding, but all with different aims from this study. For high-contrast targets in the periphery, critical spacing has primarily been analyzed in terms of absolute *angular* distance.[9,12–14,42,49–51] The now well-established finding that absolute critical spacing changes linearly with eccentricity and is independent of stimulus variables such as size is useful to

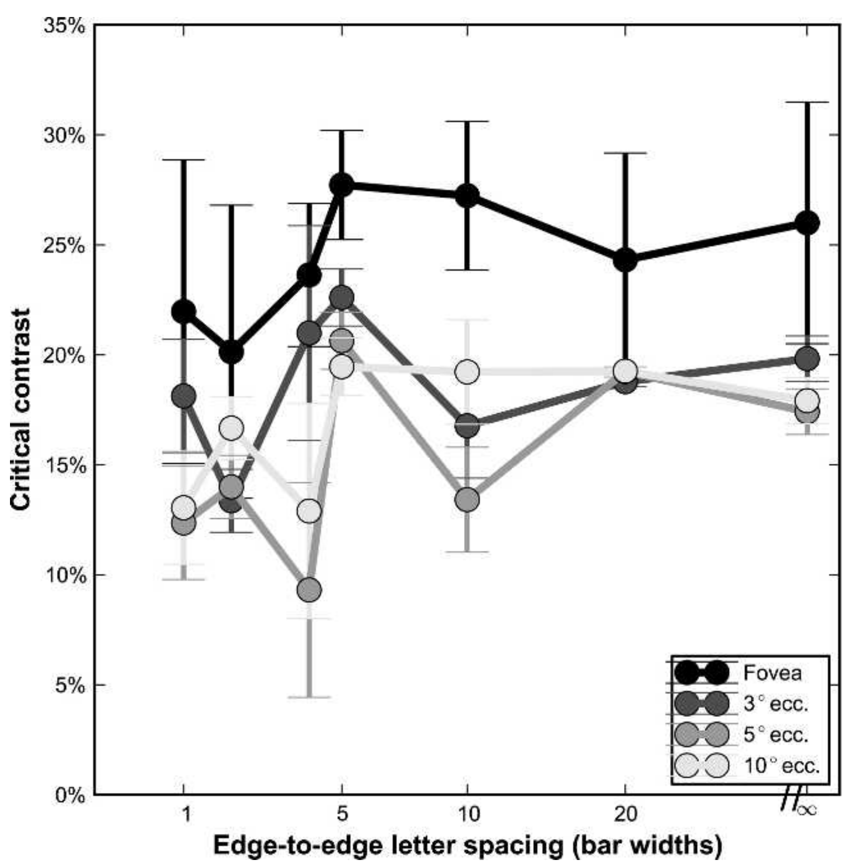


**FIGURE 3.**

Critical contrasts for each eccentricity at the various letter spacings, averaged over all subjects. Error bars represent the standard deviation between the five subjects on the given condition.

**TABLE 5.**
Critical contrast (absolute value %) at all letter spacings, mean ± standard deviation across subjects

| Spacing (bar widths) | Fovea | 3° | 5° | 10° |
|---|---|---|---|---|
| 1 | 22 ± 6.9 | 18 ± 5.3 | 12 ± 9.4 | 13 ± 7.7 |
| 2 | 20 ± 6.7 | 13 ± 10 | 14 ± 8.3 | 17 ± 4.7 |
| 4 | 24 ± 3.3 | 21 ± 7.5 | 9.3 ± 3.8 | 13 ± 9.3 |
| 5 | 28 ± 2.5 | 23 ± 7.6 | 21 ± 9.7 | 19 ± 8.5 |
| 10 | 27 ± 3.4 | 17 ± 6.6 | 13 ± 5.6 | 19 ± 7.8 |
| 20 | 24 ± 4.9 | 19 ± 7 | 19 ± 7.4 | 19 ± 7.3 |
| Unflanked | 26 ± 5.5 | 20 ± 5.2 | 17 ± 6 | 18 ± 5.6 |
| **AVG** | **24 ± 5.6** | **19 ± 7.7** | **15 ± 8.3** | **17 ± 7.9** |

researchers but is of less interest when considering performance on letter charts, for which the character-to-character spacing is fixed physically and the whole chart scales with distance. Furthermore, previous studies have measured thresholds in various ways that introduce confounding factors. First, some studies have measured threshold as a reduction in percent correct with stimuli of fixed size,[12,49,52] which may not directly translate to results in a threshold acuity paradigm where target and flankers are size-scaled together. Others used threshold contrast for identifying fixed-size stimuli,[9,14,50,53–55] which is potentially a confound for crowding in general,[56] and definitely cannot be used if evaluating the effect of contrast on critical spacing. There are several studies that have considered high-contrast, peripheral crowding with flanker spacing measured in terms of bar widths at resolution threshold.[10,11,42,51] Jacobs[10] and Leat et al.[11] did measure threshold acuity and showed that the critical spacing for crowding in the periphery exceeded 5 bar widths and was potentially much greater, but the maximal spatial extent was not identified. Latham and Whitaker[51] and Gurnsey et al.[42] scaled target, flankers, and spacing as in this study, and fit their data with complex mathematical functions but did not determine the critical spacing in terms of bar widths that would be useful to peripheral letter chart design nor did they examine the effects of contrast. Lastly, although Tripathy and Cavanagh.[49] did measure the angular critical spacing in the periphery using low-contrast letters, they used contrast to equate the effective visibility of stimuli of various sizes, whereas we systematically varied contrast and measured acuity.

We have shown that, in the periphery, the nominal critical spacing is smaller when acuity was assessed using low-contrast letters than with high-contrast letters. The weaker effect of

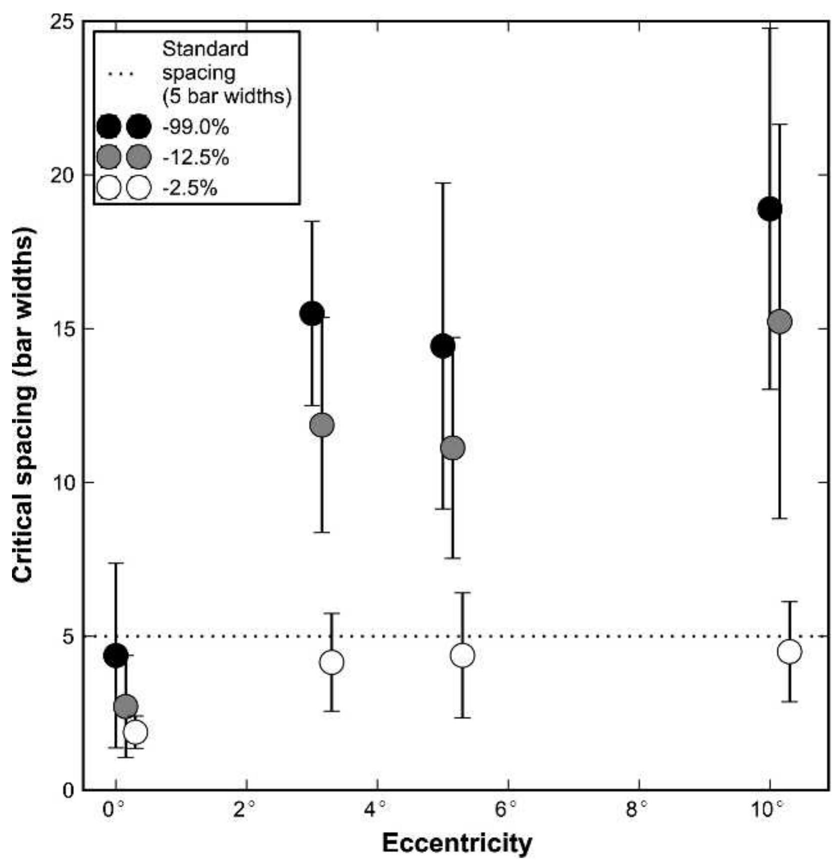


**FIGURE 4.**
Critical spacing plotted as a function of eccentricity for contrasts of −99% (black dots), −12.5% (gray dots), and −2.5% (white dots). Each point represents the average of the five subjects, and error bars indicate the standard deviation. The dotted line shows the spacing of standard chart designs following Bailey-Lovie guidelines, which have 1 letter width (5 bar widths) between each character. Values that fall below the dotted line indicate acuity measurements not limited by crowding based on the letter spacing of a standard letter chart; acuity measurements that fall above the line will be limited by crowding with the letter spacing recommended by the Bailey-Lovie chart design. We chose to show the critical spacing for −12.5% contrast to illustrate that, for the commercially available low-contrast versions of the Bailey-Lovie or ETDRS charts, which have a contrast close to −12.5%, the letter spacing is smaller than the critical spacing in the periphery. Hence, acuity measured using these low-contrast charts for patients who cannot view foveally may underestimate the peripheral acuity.

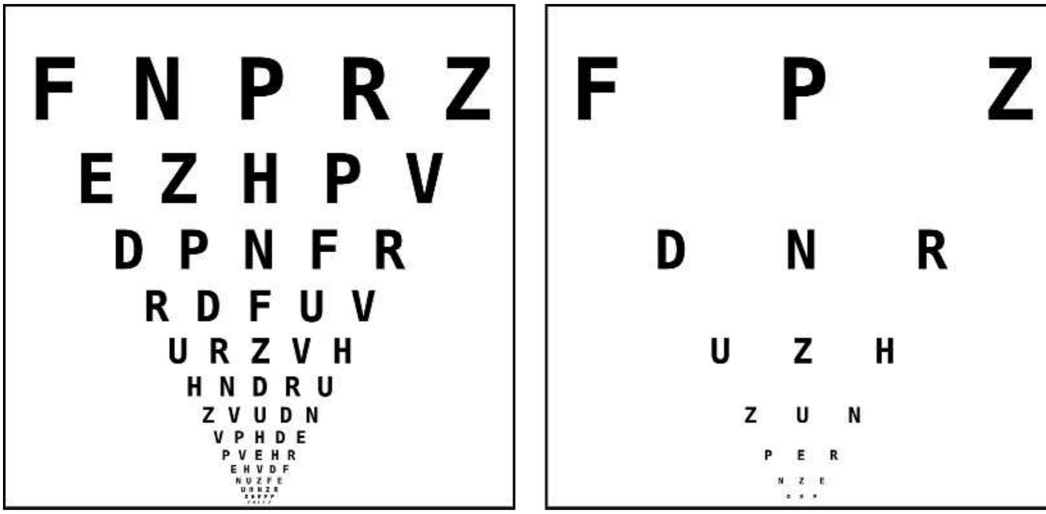


**FIGURE 5.**
Schematic demonstration of a modified Bailey-Lovie/ETDRS chart with 3 letter widths (15 bar widths) critical spacing. Every other line was removed, and every other character of the remaining lines was removed.

crowding on acuity measurement with low-contrast letters has previously been shown in the fovea,[22–27] and here, we report a similar effect in the periphery. The effect of crowding on acuity is even weaker in the periphery, where the low-contrast critical spacing is a third of the high-contrast critical spacing for the lowest contrast (−2.5%), reducing from 15 to 20 bar widths down to 4 to 5 bar widths (see Table 3). At this low contrast (−2.5%), nominal edge-to-edge critical spacing in the periphery was as small as the extent of high-contrast letters in the periphery (4.4 bar widths). Besides determining the critical spacing required for optimal acuity measurement using letter charts with multiple letters, we were also interested in determining the critical contrast for acuity measurement that would make the assessment of low-contrast acuity useful. At the fovea, acuity is independent of contrast above a letter contrast of approximately 24%. In the periphery, this critical contrast is approximately 17%. These findings imply that, if using a letter chart printed in a letter contrast of, for example, 20%, there will be little difference in peripheral acuity between this letter chart and the high-contrast version of the chart, whereas the foveal acuity (the condition which the chart may have been designed for) would exhibit a measurable difference in acuity. In other words, the additional information that could be obtained by measuring low-contrast acuities will be lost. Low-contrast acuity has been shown to be more sensitive in picking up diseases,[16–21] but to benefit from the measurement, the contrast should be low enough to affect acuity, particularly for the specific condition in which it is used, such as in the periphery. Here, we show that the letters should be printed at a (Weber) contrast of 17% or lower for the chart to be useful in helping the diagnosis of diseases or to evaluate how contrast affects acuity. In sum, greater care should be used when using tests based on contrast for measuring acuity in the periphery.

## CONCLUSIONS

This study identified the nominal critical spacing for high-contrast letters in the periphery, finding a critical spacing of approximately 15 to 20 bar widths from 3° to 10° eccentricity in the lower visual field. This translates to a required increase in letter spacing from a one-character gap (5 bar widths) to a 3- to 4-character gap (15–20 bars widths) if a chart is intended for use in the periphery such that the acuity measurement will not be affected by crowding. Thus, modern letter charts, designed to avoid the effects of high-contrast foveal crowding, will exhibit effects of crowding when used in the periphery. Two solutions to this problem were offered: the reduction in acuity caused by crowding can be predicted mathematically, or optotypes should be given greater isolation when charts are used peripherally, such as illustrated in the right panel of Fig. 5.

Decrease in contrast leads to reduced critical spacing (less influence of crowding) for a wide range of contrasts and eccentricities, with a greater reduction in the periphery than in the fovea. Low-contrast charts used in the fovea will yield acuity measurements unaffected by crowding, as noted by numerous previous reports. In the periphery, the decrease in critical spacing is more marked (even less crowding), but the low-contrast peripheral critical spacing may still exhibit more crowding than the 5 bar width spacing of traditional letter charts. The finding that there is a small (but significant) difference between the critical contrast in the fovea versus the periphery implies that care should be taken when comparing contrast-dependent effects based on peripheral acuity measurements.

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## APPENDIX

The appendices are available at http://links.lww.com/OPX/A127 (Appendix 1 - Flom vs. Bouma, quantifying the critical spacing of crowding) and http://links.lww.com/OPX/A128 (Appendix 2 - Two line fit justification, and prediction of crowded acuity).

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