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ORIGINAL ARTICLE

Dependence of Reading Speed on Letter Spacing in Central Vision Loss

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ABSTRACT

Purpose. Crowding, the difficulty in recognizing a letter in close proximity with other letters, has been suggested as an explanation for slow reading in people with central vision loss. The goals of this study were (1) to examine whether increased letter spacing in words, which presumably reduces crowding among letters, would benefit reading for people with central vision loss and (2) to relate our finding to the current account of faulty feature integration of crowding.

Methods. Fourteen observers with central vision loss read aloud single sentences, one word at a time, using rapid serial visual presentation. Reading speeds were calculated based on the rapid serial visual presentation exposure durations yielding 80% accuracy. Letters were rendered in Courier, a fixed-width font. Observers were tested at 1.4× the critical print size (CPS), three were also tested at 0.8× CPS. Reading speed was measured for five center-to-center letter spacings (range: 0.5–2× the standard spacing). The preferred retinal locus for fixation was determined for nine of the observers, from which we calculated the horizontal dimension of the integration field for crowding.

Results. All observers showed increased reading speed with letter spacing for small spacings, until an optimal spacing, beyond which reading speed either showed a plateau, or dropped as letter spacing further increased. The optimal spacing averaged 0.95 ± 0.06× [±95% confidence interval] the standard spacing for 1.4× CPS (similar for 0.8× CPS), which was not different from the standard. When converted to angular size, the measured values of the optimal letter spacing for reading show a good relationship with the calculated horizontal dimension of the integration field.

Conclusions. Increased letter spacing beyond the standard size, which presumably reduces crowding among letters in text, does not improve reading speed for people with central vision loss. The optimal letter spacing for reading can be predicted based on the preferred retinal locus.

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Key Words: reading, crowding, central vision loss, low vision, age-related macular degeneration

Reading is difficult and slow for many low vision patients, especially those who have lost their central vision, and thus have to rely on their peripheral vision for visual tasks. The leading cause of central vision loss is age-related macular degeneration (AMD), which is also the leading cause of visual impairment in developed countries.[1–4] Given that reading is the most frequent clinical complaint as well as the primary goal of patients with AMD seeking visual rehabilitation,[1,5,6] it is of utmost importance to understand the limiting factors on reading in peripheral vision, and to devise rehabilitation methods or strategies that could improve reading performance for people with central vision loss.

Following the onset of central vision loss, most people with the condition eventually adopt a retinal location close to the border of the central scotoma, the preferred retinal locus (PRL), as the reference location for visual tasks.[7–10] The location of the PRL could change for different tasks and under different lighting levels,[11–14] but in virtually all cases, the PRL is located away from the anatomical fovea. Because reading involves the recognition of letters, and that it has been known for a long time that letters are easier to read when they are in isolation than when they are presented with nearby letters (as in the case of words),[15] especially in the periphery,[16–18] the phenomenon of *crowding* has long been suggested as a viable explanation of slow reading in peripheral vision. However, the more pronounced crowding effect found in peripheral vision are mostly findings obtained using letter recognition tasks. There exist very few studies that compared the magnitude and/or the spatial extent of crowding with reading performance, by manipulating the stimulus in a comparable way. One study modulated the spatial extent of crowding in normal peripheral vision by manipulating the contrast polarity of adjacent letters.[19] Letters were ren-

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dered black on a gray background (normal contrast polarity), or white on a gray background (reversed contrast polarity). When observers were asked to identify the orientation of the target (a letter T oriented in different orientations), the spatial extent of crowding was found to be greater when the target and its flankers shared the same contrast polarity (i.e., all letters were either black-on-gray or white-on-gray), and smaller when the target and its flankers had opposite contrast polarity (i.e., a mixture of black-on-gray and white-on-gray letters; see also Kooi et al.[20]). However, when the same observers were asked to read text with alternate letters rendered in opposite contrast polarity, their reading speeds were virtually identical to those obtained when all the letters had the same contrast polarity. This finding implies that despite a reduction of crowding when adjacent letters had opposite contrast polarities, the manipulation did not benefit reading. Another study, capitalizing on the classical finding that the magnitude of crowding between letters is reduced (or the performance accuracy of letter identification is higher) when the separation between letters increases,[16,21] found that reading speed in normal peripheral vision does not benefit from increased letter spacing beyond the standard spacing found in printed text.[22] Although these studies convincingly show that the reduction in crowding does not benefit reading speed in normal peripheral vision, there is no published evidence showing whether or not a similar lack of benefit on reading speed would be found in people with central vision loss. There are at least two reasons to believe that people with central vision loss might show a different dependence of reading speed on letter spacing. First, to date, we still do not have conclusive evidence that the normal periphery is a good model for people with central vision loss. Second, given that most of the PRL locations are close to the central scotomas, the retinal regions corresponding to the PRL locations may not be as healthy as the normal retina. It is conceivable that the visual system may need to pool information over a larger area to establish a more reliable signal of a visual target, thus increasing the spatial extent of crowding. Therefore, the primary goal of this study was to examine whether or not a simple manipulation of text to reduce crowding, namely, increasing the letter spacing as in a previous study[22] would benefit reading for people with central vision loss. From a scientific point of view, our result would indicate whether or not the normal periphery is a good model for visual processing for people with central vision loss. From a practical point of view, the result would provide us with information as to what the optimal letter spacing in text should be for people with central vision loss.

The secondary goal of the study was to relate our finding to the current understanding of crowding. A current account of crowding is that because the visual system integrates features from objects within regions referred to as integration fields (also known by different terminologies such as the isolation field,[23] integration zone,[24] perceptive hypercolumn,[25] combining field,[26] etc. In this article, we will adopt the term integration field.[27] An integration field refers to the region over which features from objects are combined to form a percept. This is the basis of the feature integration theory related to how we perceive objects.[28] Integration fields are not the same as Ricco's areas. Ricco's area relates to the detection of small objects. Integration fields relate to the combination of readily detectable features for object perception.), if features from nearby objects fall within the same integration field, then these features would be integrated erroneously, forming an incorrect percept of the objects.[23,24,26,27,29–31] To avoid this undesirable inappropriate feature integration, nearby objects need to be separated from one another by a distance greater than the dimension of the integration field.[26,27] In the normal periphery, some of the known properties of the integration field include (1) the shape of the integration field is anisotropic and oriented radially with respect to the fovea, with the radial dimension being greater than the tangential dimension[18,26,27,32]; (2) the size of the integration field scales with eccentricity, with the half radial dimension approximating half the eccentricity at which the field is centered[16,18,26,27,32]; and (3) inward-outward asymmetry whereby along the radial dimension, the flanker further away from fixation needs to be separated from the target letter by a distance greater than that between the target and the flanker closer to fixation.[16,18,32,33] Applying the concept to reading, letters of a word may need to be separated from one another by a distance such that adjacent letters do not fall within the same integration field. Fig. 1 is a schematic representation of how the size and shape of an integration field changes according to its location with respect to the fovea, and how the number of letters falling within an integration field could affect whether or not the letters are recognizable. In this figure, a phrase "their house" is presented above the fovea (represented by the gray cross). Three integration fields are depicted as ellipses a, b, and c, according to properties 1 and 2 as stated above (although property 3 is relevant, in real life text is printed with regular spacing among letters, instead of having scaled spacing depending on where observers look, therefore in this article, integration fields will be represented by ellipses that are symmetrical with respect to the center, instead of egg-shaped to take into consideration the inward-outward asymmetry). Ellipse a, centered directly above the fovea, is small enough that only letter *t* falls within this integration field; therefore, this letter should be easily recognizable. For ellipse b that centers on letter *e*, the horizontal dimension of the integration field matches the spacing between *e* and its adjacent letters *h* and *i* such that these adjacent letters fall just on the border of the integration field, allowing recognition of these three letters. However, for ellipse c, the size of the integration field is so large that many letters fall within the integration field. In this case, individual letters would

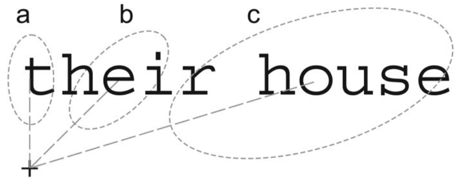

FIGURE 1.

A cartoon representation of how the size and shape of the integration field changes according to its location with respect to the fovea. A phrase "their house" is presented above the fovea (represented by the cross). Three ellipses a, b, and c represent three integration fields that centered at different locations with respect to the fovea. These ellipses are drawn according to the known properties of integration fields in the normal periphery. Ellipse a is small enough such that it isolates the letter *t*, as a result, the letter *t* can be recognized easily. For ellipse b that centers on letter *e*, the adjacent letters *h* and *i* fall just on the border of the integration field, consequently, letters *h*, *e*, and *i* should also be recognizable. For ellipse c, because too many letters fall within the integration field, individual letters would not be recognizable.

not be recognizable, and thus reading would suffer. One way to make these letters recognizable would be to increase the separation between adjacent letters. In other words, the size of the integration field places a direct limitation on the letter spacing for reading, at least in the normal periphery.

In relation to our study, if the properties of the integration field at the PRL of an observer with central vision loss are similar to those at the same retinal location in the normal periphery, and if the size of the integration field limits the optimal letter spacing for reading, then the optimal letter spacing for reading should match the size of the integration field based on the retinal location of the PRL. Here, we attempted to determine whether the size of the integration field, which changes in a systematic way based on the retinal location in the normal periphery, could explain the optimal letter spacing for reading for our group of observers with central vision loss.

METHODS

Observers

Fourteen observers with central vision loss participated in this study. Twelve of the observers had AMD (AMD1 to AMD12: aged 73–89) and two had Stargardt disease (S1 and S2: aged 57 and 62). All observers demonstrated central vision loss as assessed using the Amsler's grid or a Rodenstock 101 scanning laser ophthalmoscope (Rodenstock, Munich, Germany). Characteristics of the observers are given in Table 1. This research followed the tenets of the Declaration of Helsinki, and the protocols of the study were approved by the institutional review board. All observers gave oral and written consent after the procedures of the experiment were explained, and before the commencement of data collection. Testing was binocular. Near additions appropriate for the testing distance were provided for each observer, otherwise no other magnifiers were used during testing.

TABLE 1.
Visual characteristics of the observers

Observer	M/F	Age	Diagnosis	Acuity (logMAR) OD	Acuity (logMAR) OS	Years since onset
AMD1	F	88	AMD	1.02	1.02	16
AMD2	F	89	AMD	1.00	1.80	15
AMD3	M	72	AMD	0.80	Prosthesis	1
AMD4	F	82	AMD	0.50	0.52	9
AMD5	F	73	AMD	0.66	0.48	7
AMD6	M	67	AMD	1.08	1.80	3
AMD7	F	81	AMD	0.80	0.44	7
AMD8	F	74	AMD	0.54	1.12	6
AMD9	F	76	AMD	0.40	0.62	6
AMD10	M	84	AMD	0.56	0.70	8
AMD11	M	84	AMD	0.44	0.50	19
AMD12	M	85	AMD	0.70	0.74	11
S1	M	57	Stargardt	1.10	1.10	40
S2	F	62	Stargardt	0.58	0.58	29

AMD, age-related macular degeneration.

Stimuli

Oral reading speed was measured using single sentences from the same set of sentences as in previous studies.[19,22,34,35] Each sentence contained between 8 and 14 words (average = 10.9 ± 1.7 [standard deviation]) and included only words that were among the 5000 most frequently used words in written English, according to word-frequency tables derived from the British National Corpus.[36] Words were rendered in Courier, a fixed-width font, and were presented as black letters (2 cd/m^2) on a white background (144 cd/m^2). A fixed-width font, instead of the more popular proportional-width fonts, was used, because it was easier to manipulate and specify the letter spacing. Also, a previous study has shown that Courier offers some advantages (reading acuity, critical print size [CPS], and maximum reading speed) over Times, a popular font with proportional-width spacing that is often seen in newspapers or magazines.[37] Stimuli were generated using a Visual Stimulus Generator graphics board (VSG 2/5; Cambridge Research Ltd, Rochester, UK) controlled by a workstation (Dell Precision 650; Dell, Austin, TX) and presented on a 24-inch color graphics display monitor (Model GDM-FW900; Sony, New York, NY). The resolution of the display was 1280 × 960 pixels at a frame rate of 80 Hz. The temporal dynamics of the display were verified using a photo-detector and an oscilloscope.

Psychophysical Procedures

Psychophysical procedures used to measure reading speed were identical to those used in a previous study that examined the effect of letter spacing on reading in normal peripheral vision.[22] In brief, on each trial, a single sentence was chosen randomly from a pool of 2630 sentences and presented using the rapid serial visual presentation paradigm,[38,39] in which words were presented one at a time, left justified on the display for a fixed exposure duration. Each testing condition (print size or letter spacing, more details are mentioned later in the text) was tested in two separate blocks of trials. In each block of trials, we used the Method of Constant Stimuli to randomly present sentences at five- or six-word exposure durations (three sentences per duration) that spanned a range of approximately one log unit. The number of words read correctly was recorded for each sentence. A word was scored as being read correctly as long as the observer said the word correctly, irrespective of its word order within the sentence. A cumulative-Gaussian function was used to fit each set of data (based on 30–36 sentences, or a total of an average of 330–396 words presented) relating the percentage of words read correctly as a function of word exposure duration, from which we derived the criterion reading speed based on the exposure duration that corresponds to 80% reading accuracy. This criterion reading speed is the reading speed we report for each condition in this article. All observers practiced the task of reading using the rapid serial visual presentation paradigm for approximately 30 min, until they were comfortable with the task, before actual data collection. Data for the practice trials are not included in this article.

We defined letter spacing as the center-to-center separation between adjacent letters of a word, and normalized it with respect to the standard spacing that is adopted for printed text for the Courier font. By measuring the center-to-center spacing between adjacent letters for text rendered in Courier for a large range of print sizes,

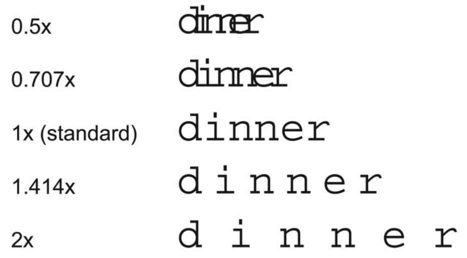

FIGURE 2.

The word "dinner" rendered in the five letter spacings used in the study. The nominal values of these five letter spacings are given in the left column.

we determined that the standard spacing is 1.16 times the width of a lowercase "x." Following our previous study in normal vision,[22] we tested five letter spacings: 0.5, 0.707, 1, 1.414, and 2 times the standard spacing. Fig. 2 shows samples of the word "dinner" rendered in these five spacings. At the smallest spacing (0.5×), there was some overlapping between adjacent letters.

Considering the wide range of visual acuities of our observers, and their need to use different print sizes for them to read, we examined the effect of letter spacing on reading speed for a nominal print size, 1.4× the CPS (defined as the smallest print size that allows an observer to read at his/her maximum reading speed[34,37]) across all observers. To determine the CPS (and thus the print size used for examining the effect of letter spacing), we first measured reading speed for five to six print sizes, using Courier font rendered at the standard letter spacing, following the procedures outlined above. The order of testing the different print sizes was randomized. Then, we fit each set of reading speed vs. print size data using a bilinear fit (on log-log axes) with the slope of the first line free to vary and the slope of the second line constrained at zero (implying that reading speed stays constant for print sizes exceeding the CPS). The intersection of these two lines represents the CPS. (Other functions have been used to fit reading speed vs. print size data, including the "uncrowded span model"[26,40] and an exponential-decay function.[41] Although all these functions, including the bilinear fit, provide an adequate estimate of the maximum reading speed, only the bilinear fit provides an intuitive and straightforward method to estimate the CPS, given by the intersection of the two lines. Intuitively, this corresponds to the smallest print size at which the maximum reading speed is still attainable. For the uncrowded span model and the exponential-decay function, because the rate of change of reading speed with print size varies around the "cliff" region, it is difficult to define a CPS. Instead, a threshold print size is often used, one that depends on the criterion chosen, e.g., print size that corresponds to 80% of the maximum reading speed.) The intersection of these two lines represents the CPS. Curve fitting was accomplished using Igor Pro (Wavemetrics Inc., Oregon), which utilizes a Levenberg–Marquardt iterative algorithm to search for the coefficient values that minimize χ^2. The experimental data were weighted by the inverse of the standard error of each threshold estimate during curve fitting. Fig. 3 shows a sample set of reading speed vs. print size data, obtained for observer AMD10. After deriving the CPS, reading speed was then measured for the five letter spacings at 1.4× CPS. The order of testing the different letter spacings was randomized. With the exception of observers AMD10, AMD11, and AMD12, all observers completed testing in two sessions, with the first session devoted to the derivation of CPS and the effect of letter spacing on reading speed was examined in the second session (a week after the first session). Observers AMD10, AMD11, and AMD12 attended a third session in which the effect of letter spacing on reading speed was also assessed using a smaller print size (0.8× CPS). As we shall see later, data obtained using a smaller print size allow us to better understand the relationship between the empirically determined optimal letter spacing for reading and the predicted size of the integration field based solely on the retinal location of the PRL.

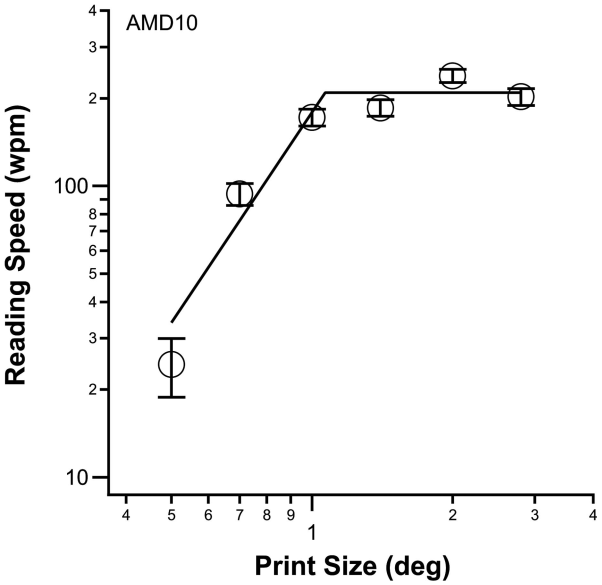

FIGURE 3.

Reading speed (wpm) is plotted as a function of print size (deg) for observer AMD10. This sample set of data illustrates how we derived the critical print size (CPS), which was subsequently used to present text at a given angular size. For each observer, reading speed was determined for 5 to 6 print sizes. A bilinear fit (on log-log axes) was used to fit the set of data, where the intersection of the two lines represents the CPS. In this example, the CPS is 1.06 degrees; therefore, we used a print size of 1.48° for testing at the nominal print size of 1.4× CPS for this observer. This observer was also tested at a smaller print size (0.8× CPS), which was equivalent to an angular print size of 0.85 degrees.

Measurement of the Location of PRL for Fixation

To relate the optimal letter spacing for reading to the predicted size of the integration field based on the retinal location, we first determined the location of the PRL using a Rodenstock scanning laser ophthalmoscope. Owing to observers' availability, only nine of the 14 observers were available for the PRL measurement. Observers were asked to look at the center of a fixation cross subtending 1 degree (2 degrees for observer S1 because of his acuity) using their preferred eye, which also turned out to be the eye with better acuity in all cases. Fundus images were captured continuously for 30 s at a frame rate of 30 Hz. Offline analyses were performed using custom-written software in MATLAB (Mathworks, Natick, MA), and included a frame-by-frame analysis of the retinal locations that the observer used to fixate the cross. For each observer, the average coordinates of these retinal locations across all frames within a trial and across 3 to 6 trials (minimum 1000 samples) were used to represent the location of the PRL for fixation (fPRL).

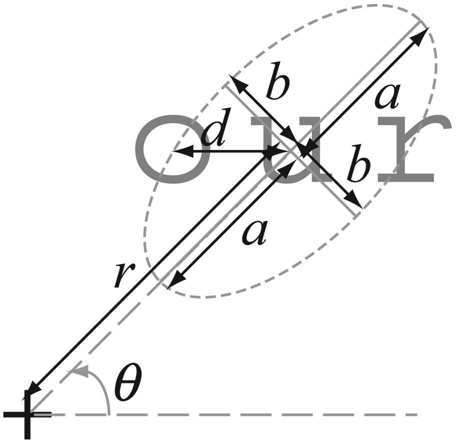

FIGURE 4.

A cartoon representation of the integration field centered at the fPRL of an observer. The cross represents the anatomical fovea. The integration field is represented by the ellipse where *a* and *b* represent the dimension of half of the major and minor axes, respectively. Because our word stimuli were oriented horizontally, the predicted size of the integration field along the horizontal meridian is represented by *d*, which can be determined based on Eq. 1.

Determining the Predicted Size of the Integration Field at the fPRL

Based on our current understanding that the integration field is anisotropic and oriented in such a way that its major axis lies along the radial meridian connecting the center of the integration field with the anatomical fovea,[18,26,27,32] we could represent the integration field at a given retinal location by an ellipse (Fig. 4), according to the following assumptions: (1) the integration field is centered on the position of the "target" letter (in the example given in Fig. 4, the letter *u*); (2) the distance between the center and one of the vertices of the ellipse (half of the major axis) equals 0.5× the retinal eccentricity (Bouma Law)[16,18,26,27,32]; and (3) the ratio between the major and minor axes is approximately 2:1.[18,26,27,32] To construct such an ellipse to represent the integration field for a given observer, we first converted the coordinates of the fPRL into polar coordinates (r, θ), where r is the radial distance between the fPRL and the fovea, and θ is the angle between the horizontal and the meridian joining the fPRL with the fovea. In our experiment, because the word stimuli were oriented horizontally, the minimal spacing between adjacent letters to avoid the letters falling within the integration field would be given by d in the equation below (Fig. 4):

$$d(\theta) = \frac{ab}{\sqrt{(b\cos\theta)^2 + (a\sin\theta)^2}} \tag{1}$$

where a and b represent the dimension of half of the major and minor axes, respectively.

RESULTS

Oral reading speed in words per minute (wpm) is plotted as a function of letter spacing in multiples of standard spacing for each observer, for a print size of 1.4× CPS, in Fig. 5. For three observers (AMD10–12), how reading speed changed with letter spacing was also determined for a smaller print size (0.8× CPS). For all observers, reading speed increased with letter spacing for small spacings, until an optimal spacing, beyond which reading speed either showed a plateau, or dropped as letter spacing further increased. To quantify the optimal spacing, we fit each set of data with a bilinear fit (on log-log axes), with the slope of the two lines free to vary (In our previous article reporting similar data collected in the normal fovea and periphery,[22] the slope of the second line of the bilinear fit was constrained to zero. Here, to more accurately describe the data, we allowed the slope of the second line free to vary. Despite the use of a bilinear fit with four free parameters to fit sets of five data points, all curve fit converged properly without problems.). As described earlier, curve fitting was accomplished using Igor Pro. The optimal spacings derived from the curve fitting are summarized in Table 2. Across all observers, the optimal spacing for 1.4× CPS averaged 0.95 ± 0.06× [±95% confidence interval] the standard spacing (range: 0.80–1.20× the standard spacing). Given that the 95% confidence intervals include the value of 1.0 (the standard spacing), our finding implies that for observers with central vision loss, reading speed is already optimal at the standard spacing, and further increase in letter spacing does not lead to faster reading speed, reminiscent of the finding we previously reported for the normal fovea and periphery.[22] This result is also confirmed by a t-test, showing that the optimal spacing for the group of observers was not different from the standard spacing ($t_{(df = 11)} = 1.83$, $p = 0.09$). For the three observers who were also tested at a smaller print size (0.8× CPS), their data show the expected finding that reading speed was lower for 0.8× CPS than for 1.4× CPS. The more interesting and important finding, however, is that the nominal optimal spacing for 0.8× CPS was also close to the standard spacing (averaged 0.98× the standard, identical to the average value for these three observers for 1.4× CPS).

Fig. 5 shows that for some observers, reading speed dropped from the maximum value when letter spacing increased beyond the optimal spacing. To determine whether this effect was significant, we compared the slope of the second fitted line of the bilinear fit with a slope of 0. The comparison was only performed for the 1.4× CPS data, as we only had data for 0.8× CPS from three observers. Across all observers, the slope of the second line averaged −0.35 ± 0.17 [95% confidence interval], implying that the decrease in reading speed with larger letter spacing beyond the standard was significant, as the confidence intervals do not include the value of 0. A t-test confirms that the change of reading speed with letter spacing beyond the standard spacing is significant ($t_{(df = 11)} = 4.24$, $p = 0.0008$).

Comparing the Optimal Letter Spacing with the Predicted Size of the Integration Field

In Fig. 6 we compare the empirically determined optimal letter spacing for reading with the predicted size of the integration field along the horizontal meridian, for the nine observers for whom we had the fPRL measurement. Each unfilled circle represents the empirical value derived from the optimal spacing for reading at a print size of 1.4× CPS for one observer. Values plotted on the abscissa are in degrees of visual angle, and were converted from the nominal optimal letter spacing as shown in Fig. 5 and Table 2 by taking into account the angular print size. Values plotted on the ordinate were calculated based on Eq. 1. The dashed line in the

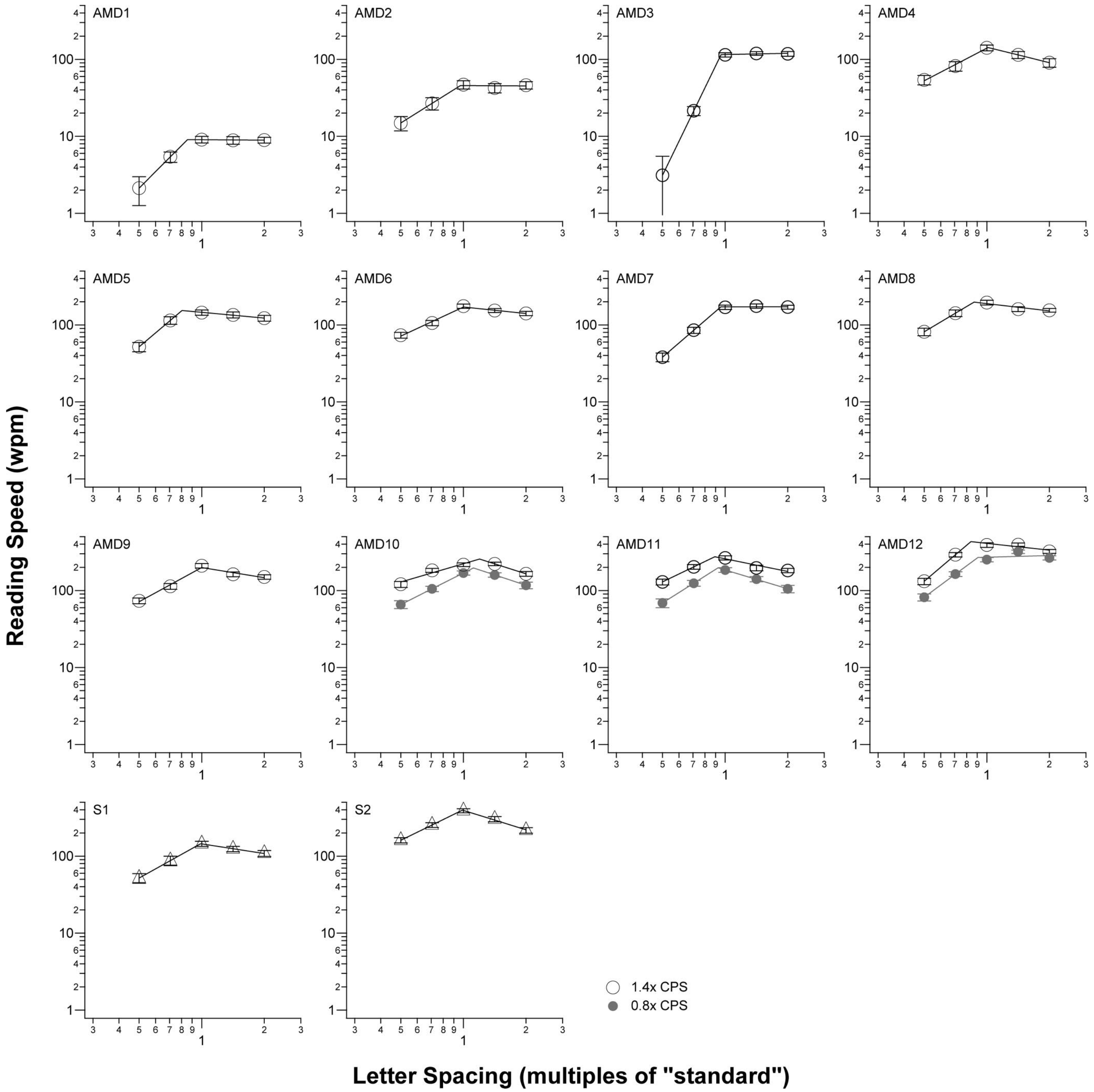

FIGURE 5.

Reading speed (wpm) is plotted as a function of letter spacing (multiples of standard spacing) for the 14 observers with central vision loss. Twelve (AMD1–AMD12) observers had AMD, whereas the other two had Stargardt disease (S1 and S2). Unfilled circles represent data obtained using a print size equivalent to 1.4× CPS, determined separately for each observer. If plotted, gray filled circles (smaller in size) represent data obtained using a print size equivalent to 0.8× CPS. Lines shown are the best-fit lines based on the bilinear fit where the intersection of the two lines represents the optimal letter spacing for reading.

figure represents the unity line. In general, the empirical and predicted values show a good relationship with each other, although the empirical values are all larger than the predicted values, except for one observer. These data seem to suggest that there is a close relationship between the size of the integration field based on the fPRL location, and the optimal letter spacing for reading. But is it really so? Data from the three observers who were tested at a print size of 0.8× CPS are also included in Fig. 6 (small filled gray symbols). Although these data more or less follow the trend for 1.4× CPS, for the same observer, the data for the two print sizes are definitely different. We shall return to this in the Discussion.

DISCUSSION

Despite substantial crowding demonstrated in normal peripheral vision, previously we showed that reading speed does not im-

TABLE 2.
Empirically determined optimal letter spacing for reading and the calculated horizontal dimension of the integration field for the 14 observers

Observer	Print size	Optimal letter spacing (multiples of standard)	Optimal letter spacing (degrees)	Calculated horizontal dimension of integration field (degrees)
AMD1	1.4× CPS	0.854×	3.921	
AMD2	1.4× CPS	0.968×	5.556	
AMD3	1.4× CPS	0.956×	1.759	
AMD4	1.4× CPS	1.014×	0.910	0.906
AMD5	1.4× CPS	0.804×	1.656	0.952
AMD6	1.4× CPS	1.000×	11.410	
AMD7	1.4× CPS	0.954×	3.508	
AMD8	1.4× CPS	0.869×	1.383	0.861
AMD9	1.4× CPS	1.000×	2.298	1.295
AMD10	1.4× CPS	1.196×	3.158	1.621
	0.8× CPS	1.118×	1.683	1.621
AMD11	1.4× CPS	0.892×	2.472	0.682
	0.8× CPS	0.925×	1.379	0.682
AMD12	1.4× CPS	0.839×	2.657	1.696
	0.8× CPS	0.906×	1.638	1.696
S1	1.4× CPS	0.987×	13.030	7.645
S2	1.4× CPS	0.990×	2.157	1.162

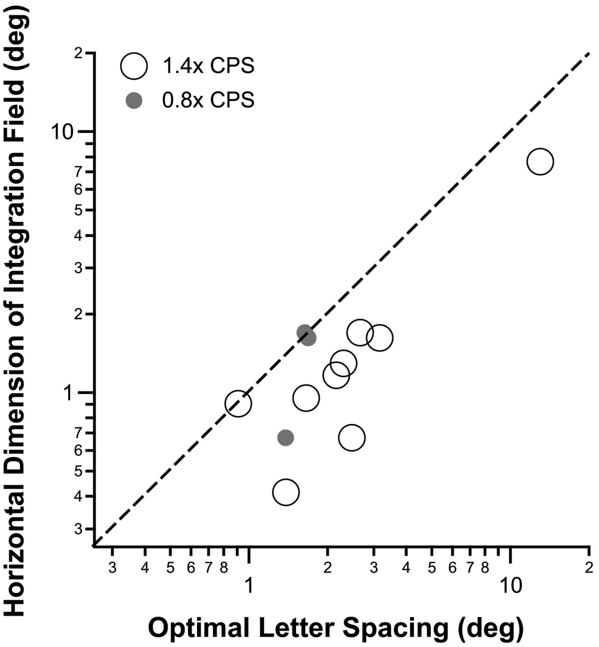

FIGURE 6.
The predicted dimension of the integration field along the horizontal meridian is plotted as a function of the empirically determined optimal letter spacing for reading (converted to degrees of visual angle), for nine of the 14 observers. Each unfilled symbol represents the data for one observer tested at a print size of 1.4× CPS. Three observers were also tested at a print size of 0.8× CPS, and the relationship between the predicted and measured values is plotted as small gray filled symbols.

prove with larger letter spacing beyond the standard spacing in normal periphery.[22] In this study, we extend the result to show that in 14 observers with central vision loss, who presumably have to rely on their peripheral retina to read, their reading speeds also do not benefit from increased letter spacing beyond the standard.

Similar to the findings in the normal periphery, reading speed for observers with central vision loss is lowest for the smallest letter spacing (0.5× the standard). At this spacing, portions of adjacent letters overlap with one another. Therefore, the low reading speed is likely to be a consequence of overlap masking of letter strokes. For larger letter spacings, reading speed improves and reaches the maximum at around the standard spacing, then either remains at the maximum value or drops from the maximum for spacings beyond the standard. Why doesn't reading speed benefit from increased spacing given that crowding is reduced among letters? Previously, Yu et al.[35] explained this lack of a benefit of increased letter spacing on reading in normal peripheral vision as due to the size of the visual span. Visual span refers to the number of characters that can be recognized in a single fixation.[42,43] Based on the high correlations obtained between the size of the visual span and reading speed for different stimulus parameters (e.g., letter contrast, print size, retinal eccentricity)[43] and also changes observed in the size of the visual span and reading speed following perceptual learning,[44] Legge and his colleagues suggested that the visual span is the bottleneck on reading.[42–45] In the normal periphery, Yu et al.[35] found that the size of the visual span increased with letter spacing for spacings smaller than the standard, reaching a maximum at the standard spacing, then decreased for larger-than-standard spacings, paralleling the change in reading speed with letter spacing. Presumably, when letter spacings are larger than standard, despite a reduction in crowding among letters of a word, letters are spread further out into larger eccentricities which are associated with poorer acuities, thus explaining why the size of the visual span decreases with increased letter spacing. It follows then that the optimal letter spacing represents a delicate balance between the need to minimize crowding among letters of a word, while at the same time the need to ensure that each letter exceeds the acuity limit at the local eccentricity. This explanation might also apply to observers with central vision loss who have to rely on their peripheral retina to recognize letters and to read.

What then determines the optimal letter spacing for reading? If reading is based on recognition by parts,[46] in this case, parts are letters, then the optimal letter spacing for reading should be the same as the optimal letter spacing for letter recognition, which is how integration fields are defined conventionally.[18,26,27] A property of the integration field is that its size scales with eccentricity in a systematic way.[18,26,27,32] For observers with central vision loss, if the properties of the integration field at the PRL are similar to those at the same retinal location in the normal periphery, then the optimal letter spacing for reading should match the size of the integration field based on the retinal location of the PRL. When we compared the optimal letter spacing for reading determined from our experiment, with the predicted horizontal dimension of the integration field at the PRL, we found a good relationship between the measured and the predicted values (Fig. 6, unfilled symbols), although the measured values are almost always greater than the predicted values. The discrepancies between the measured and the predicted values could be because of the several assumptions that we made. First, the optimal letter spacing for reading was derived from reading performance obtained binocularly, whereas the predicted value was based on the fPRL measurement obtained monocularly. To date, there is no technology that allows us to measure the PRL binocularly; however, by comparing the gaze positions measured monocularly and binocularly for 29 observers with AMD, Kabanarou et al. reported that the majority of their observers (26 of 29) either did not show a shift in gaze position from monocular to binocular viewing, or showed a shift only in the worse-seeing eye.[47] This result implies that for the majority of people with AMD, the PRL used for binocular viewing is the PRL of the better-seeing eye. Second, we assumed that the PRL for reading is the same as the fPRL, which in many observers may not be true.[12–14] Third, the fixation instability of observers with central vision loss[8,9,48] could have increased the noise associated with the measurement. For instance, from trial to trial, even the same target letter could fall on slightly different retinal locations around the fPRL, thus increasing the size of the measured integration field. Fourth, we also assumed that the major:minor axis ratio of the elliptical integration field is 2:1.[18,26,27,32] However, using other ratios only shift the data vertically along the ordinate without affecting the good relationship between the measured and predicted values. Considering all these caveats, it is remarkable that the measured and predicted values demonstrate such a good relationship.

For the comparison described thus far, the measured values were based on a print size that corresponded to 1.4× CPS. If the size of the integration field depends solely on the retinal eccentricity, and if crowding is really limited by spacing, not size of objects,[26] then it follows that the angular size of the optimal spacing for reading should be the same for a print size of 1.4× CPS as for a smaller print size. In other words, the maximum reading speed for a smaller print size should occur at a larger nominal letter spacing. We tested this prediction by obtaining additional measurement of reading speed as a function of letter spacing for three AMD observers (AMD10–12) using a print size that corresponded to 0.8× CPS. Their reading speed vs. nominal letter spacing data are included in Fig. 5. For these three observers, the nominal optimal letter spacing did not seem to differ between 0.8× and 1.4× CPS. We then converted the nominal optimal letter spacings for 0.8× CPS, derived from the bilinear fit, into the corresponding spacings in angular units and compared these values with the predicted horizontal dimension of the integration field in Fig. 6. Although there were only three observers for whom we had the data for the 0.8× CPS, it is clear that the measured values of the optimal letter spacings, when expressed in angular sizes, are different for the two print sizes.

Fig. 7 is a schematic representation of our results shown in Fig. 6. In panel a, the word "house" rendered at 1.4× CPS and with a standard letter spacing, is centered on an elliptical integration field that is oriented obliquely in the upper right quadrant with respect to the fovea. The dimensions of the integration field are based on the radial distance between the center of the integration field and the fovea, and the assumption of a major:minor axis ratio of 2:1. In this example, the letters *o* and *s* just fall on the edges of the integration field and thus should not affect the recognition of the middle letter *u*.[26] For this print size, the standard letter spacing is sufficient to isolate each individual letters, thus avoiding crowding. What about a smaller print size? If the size of the integration field is fixed with respect to a given retinal location, then for a smaller print size (in this case, 0.8× CPS), the letter spacing would need to increase beyond the standard spacing in order for the letters *o* and *s* to just fall on the edges of the integration field, separating themselves sufficiently from the middle letter *u* so that features from adjacent letters will not be integrated erroneously and cause crowd-

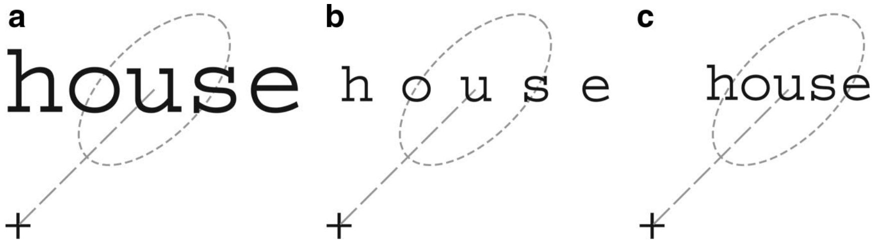

FIGURE 7.

A cartoon representation of the integration field centered on the fPRL of an observer. The cross in each panel represents the anatomical fovea. The size and shape of the integration field are based on the theoretical understanding of the size and shape of integration fields in the normal periphery (Fig. 4) and are drawn to scale (including the print size). In panel a, the word "house" was rendered at 1.4× CPS with a standard letter spacing. The predicted horizontal dimension of the integration field is sufficient to isolate the letters to avoid crowding. Panel b shows that when the same word rendered at 0.8× CPS falls within the same integration field, the letter spacing needs to be larger to isolate individual letters to avoid crowding. However, our result shows that even for 0.8× CPS print size, the nominal optimal letter spacing remained at 1× the standard. Under this condition, the letters are not isolated from one another and are supposed to cause substantial crowding (panel c).

ing (panel b). However, this was not what we found. Instead, we found that the optimal letter spacing for 0.8× CPS was also similar to the standard spacing, as represented in panel c. In this case, the letters *o*, *u*, and *s* all fall within the integration field and should have caused crowding, affecting the recognition of these letters, and in turn, slowing down reading. Indeed, the maximum reading speed obtained for a print size of 0.8× CPS was lower than that for 1.4× CPS, but the effect is small, implying that either crowding is not a major limiting factor on reading, or that some other factors are at play.

We believe that the following reasons might help explain the small reduction in reading speed despite the presumed substantial crowding for the 0.8× CPS. First, there is a difference in task. Traditionally, the spatial extent of crowding has been measured using simple objects such as Gabor patches,[24,49,50] line segments,[51] or optotypes (Landolt Cs, tumbling Es, Ts, random uppercase or lowercase letters, numerals).[16,18–20,23,26,52,53] Some recent studies have used faces as stimuli and found that the integration field is invariant with stimulus type.[54] For these stimuli, the relationship between adjacent objects is random or nonexistent. This is not the case for English words. In common English usage, certain letters frequently appear together.[55] It is possible for an experienced reader to guess a letter given its adjacent letter. In other words, it is not necessary for a reader to identify each letter of a word before he/she could identify the word. In fact, it has been shown that nonadjacent letter pairs (e.g., a pair of letters that occupy letter positions 2 and 4 of a 5-letter word) carry more information about the word identity than adjacent letter pairs,[56–58] suggesting again, that readers may not need to recognize each individual letter of a word. Also, if the beginning or the last letter of a word fall within their own integration field that do not contain other letters of the same word, it is possible for readers, especially those who are experienced, to guess the word simply based on the first and the last letters. Moreover, although the average word length of the words in our sentence set was approximately 5 characters, there are a lot of short words such as *is, in, it, of, to,* which are likely to suffer from very minimal crowding effect. Further, analogous to how readers could guess a word without clearly seeing individual component letters, context of the sentence could also help readers guess a word even if the word is not clearly recognizable to the reader. All these factors could have contributed to the less-than-expected reduction in reading speed, given the size of the integration field in relation to the number of letters that could fall within the integration field simultaneously.

Our finding that the optimal letter spacing for reading is the same for observers with central vision loss as for the normal periphery, and that it is essentially the standard spacing as found in normal printed text, prompts a question of whether this optimal letter spacing is a result of many years of exposure to text rendered at such a standard spacing. This reasoning may be related to the word-shape effect or other whole-letter information, as one could argue that experienced readers are used to seeing certain groups of letters being put together in a standard way to form a particular word. Our finding cannot rule out this higher level of explanation. In fact, because both the smallest (0.5×) and the largest (2×) letter spacings disrupt the word shape (note that 0.707× and 1.414× are not as disruptive; Fig. 2), reading speed is expected to decrease, and this was what we found. Pelli and Tillman showed that for normal reading, individual letters, whole word, and sentence context all contribute to the reading process, with letters contributing approximately 62% and whole-word information contributing approximately 16% of the reading speed.[59] Whether or not the contributions of these three processes of reading are similar in the presence of central vision loss is currently being investigated in our laboratory.

In Fig. 6, the predicted values of the horizontal dimension of the integration field are calculated based solely on the fPRL location. Although the predicted values are not exactly the same as the measured values, especially since the measured values apparently depend on print size, it appears that there is a relationship between the predicted and the measured values. The use of the fPRL location to calculate the size of the integration field is based on the assumption that the properties of crowding at a PRL are the same as those exhibited at the same peripheral retinal location in a normal eye. Simply put, our data seem to imply that the properties of crowding at the PRL are the same as those in the normal periphery. This seems to contradict some of the evidence showing that there is less crowding at the PRL in observers with AMD than in the normal periphery.[60–63] Note however that in the present study, we only determined the size of the integration field along the horizontal meridian. It remains possible that the integration field could shrink in its dimensions along other meridians for people with central vision loss, as shown in Chung and Lin.[62]

In conclusion, by measuring reading speed as a function of letter spacing, we found that the optimal letter spacing for reading for observers with central vision loss is the standard spacing found in standard printed text. Increased letter spacing beyond the standard size, which presumably reduces crowding among letters, does not improve reading speed. The optimal letter spacing for reading can be predicted based on the fPRL of the observer.

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