Small Effect of Interline Spacing on Maximal Reading Speed in Low-Vision Patients with Central Field Loss Irrespective of Scotoma Size

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PURPOSE. It has been suggested that crowding, the adverse low-level effect due to the proximity of adjacent stimuli, explains slow reading in low-vision patients with absolute macular scotomas. According to this hypothesis, crowding in the vertical dimension should be released by increasing the vertical spacing between lines of text. However, studies with different experimental paradigms and only a few observers have given discrepant results on this question. The purpose of this study was to investigate this issue with a large number of patients whose macular function was carefully assessed.

METHODS. MP1 microperimetry examination was performed for each low-vision patient. Only eyes with an absolute macular scotoma and no foveal sparing (61 patients with AMD, 90 eyes; four patients with Stargardt disease, eight eyes) were included. Maximal reading speed was assessed for each eye with French sentences designed on the MNREAD test principles.

RESULTS. The effect of interline spacing on maximal reading speed (MRS) was significant although small; average MRS increased by 7.1 words/min from standard to double interline spacing. The effect was weak irrespective of PRL distance from the fovea and scotoma area and regardless of whether an eccentric island of functional vision was present within the scotoma.

CONCLUSIONS. Increasing interline spacing is advisable only for very slow readers (<20 words/min) who want to read a few words (spot reading). Vertical crowding does not seem to be a major determinant of maximal reading speed for patients with central scotomas. (Invest Ophthalmol Vis Sci. 2010;51:1247–1254) DOI:10.1167/iovs.09-3682

Patients with low vision who have binocular absolute scotomas are forced to use peripheral parts of their retina to see (eccentric viewing). When asked to fixate a target, they usually use a single preferred retinal location (PRL) and can achieve relatively good fixation stability after at least some adaptation.1–7 However, reading text, or even words, is extremely difficult for these patients.8,9 Eccentric viewing implies that any visual factor degraded in the periphery is a potential limiting factor of eccentric reading performance. Acuity is logically such a limiting factor but it is not the only one.10 Crowding is thought to be another major limiting factor of eccentric reading because the spatial extent of this detrimental phenomenon is proportional to eccentricity.11,12 Crowding refers to the difficulty of identifying a character surrounded by adjacent stimuli (when compared with the identification of an isolated character) and has received considerable interest in recent years in the context of reading.13,14

One potential source of crowding when reading a page of text is the presence of lines of text above and below the line currently read. Different experimental approaches have been used to study whether increasing the vertical distance between successive lines might improve reading performance. The first approach, rapid serial visual presentation (RSVP), is the classic way of studying eccentric vision in the context of low vision: words are sequentially displayed at a constant eccentric location, whereas observers with normal sight keep fixating a visual target.15

With RSVP, 100% improvement in maximal reading speed was found when comparing double interline spacing with standard interline spacing.16 This dramatic improvement was, however, not replicated in a second approach in which a macular scotoma was simulated with a gaze-contingent paradigm: observers with normal sight read a continuous text (page-mode reading) with visual parameters similar to those used in the initial RSVP study.17 The largest improvement in reading speed found in this study was only 8% when the standard interline spacing was doubled. Finally, a third approach was performed in eight low-vision patients (eight eyes) who had to read continuous text displayed on a piece of white paper.18 The results did not show any improvement at all as a function of interline spacing. It is difficult to account for these discrepancies and thus to have a clear understanding of the effect of interline spacing on maximal reading speed. On the one hand, there is a very large (100%) significant effect16; on the other hand, there is a very small17 or absent18 effect.

We, therefore, decided that a study with a large number of patients was required to investigate this issue with sufficiently large statistical power. In addition, two key factors that can interfere with the effect of interline spacing were controlled in our study. The first factor able to modulate the effect of interline spacing was the presence of an island of spared vision within the macular scotoma. When reading with such an island, adjacent lines of text (above and below) are likely to be masked by the scotoma, irrespective of interline spacing. This condition would thus prevent any influence from adjacent...
reading. In addition, some patients may use different PRLs during fixation. Moreover, some patients can use different PRLs during fixation.

FIGURE 1. Illustration of the interaction hypothesis with a vertical PRL. Small (left) and large (right) interline spacing are displayed with the same large character size (the rectangle represents the screen). The probability that increasing interline spacing will induce a release from crowding is higher with small scotomas than with large scotomas. Gray discs: scotomas; black ellipses: crowding areas.

The second important factor, which should be controlled when studying the possible role of crowding, is the estimated eccentricity at which reading occurs. The reason is that the extent of crowding is proportional to eccentricity (this is actually the key signature of crowding). More precisely, the crowding area is an ellipse pointing toward the fovea whose radial extent from its center is approximately equal to half the eccentricity. Thus, with a vertical PRL, for instance, the vertical crowding extent (half the length of the long axis of the ellipse in degrees of visual angle) is half the value of the eccentricity (Fig. 1). When patients read at maximal speed, with the largest character sizes available in the setup (as illustrated in Fig. 1), the amount of vertical crowding results from an interaction between reading eccentricity and interline spacing. At large eccentricities (with big scotomas), the probability that adjacent lines are contained within the crowding area irrespective of interline spacing is relatively high. Therefore, increasing interline spacing should not have a very large effect. In contrast, at small eccentricities (with small scotomas), increasing interline spacing is more likely to displace adjacent lines outside the crowding area and should thus induce a larger effect. Therefore, an important hypothesis to be tested in a regression model is an interaction hypothesis: the effect of interline spacing (expressed in the usual way, e.g., standard vs. double) on maximal reading speed should decrease as a function of reading eccentricity. To estimate the reading eccentricity used on average across ocular fixations (Reading a text continuously displayed on a page—page mode reading—implies a sequence of ocular fixations, separated by saccades, along the lines of text.), the distance between the fovea and the PRL is an obvious candidate. However, some patients can use different PRLs during fixation. Moreover, some patients do not use the same PRL in a fixation task and during reading. In addition, some patients may use different PRLs.

FIGURE 2. Distribution for the 65 patients of (A) time since binocular scotoma diagnosis and (B) number of visual rehabilitation sessions.

PATIENTS AND METHODS

Patients

Data of 90 eyes from 61 patients with diagnoses of AMD are presented. We also present data of eight eyes from four patients with Stargardt disease (ages 21, 27, 60, and 60). Whenever possible, both eyes of each patient were tested. For these 65 patients, the distribution of time (in years) since binocular scotoma diagnosis is shown in Figure 2A (the bar on the extreme right corresponds to the oldest patient with Stargardt disease). The number of visual rehabilitation sessions received by the patients ranged from 0 to 80 (Fig. 2B). Eighteen patients were using a low-vision aid in their daily lives at the time of the experiment (two patients with a magnifier, two with microscopic eyewear, eight with telescopic eyewear, and six with a video magnifier).

Inclusion/Exclusion Criteria

Each patient had a confirmed diagnosis of AMD or Stargardt disease from an ophthalmologist and had no other significant disease except for a binocular scotoma. Patients with a history of neurologic disease or cognitive impairment were not included. Patients were recruited over a 2-year period from referrals to the Low Vision Clinic at the La Timone Hospital (Marseille, France). The research was conducted in
accordance with the tenets of the Declaration of Helsinki. Informed consent was obtained from all participants before testing.

Microperimetry

Microperimetry examination was performed with a microperimeter (MP-1; Nidek Technologies, Padova, Italy). A fundus photograph was taken after the perimetry examinations. Each patient was seated with the head on the headrest of the instrument. The nontested eye was patched. By default, a red cross (2°–4°) was projected in the middle of the viewing area, and participants were asked to look at this stimulus at all times. Before starting the examination, the operator checked that the patient was able to maintain fixation with a PRL. Then the operator selected a high-contrast reference area on the fundus image, thus triggering the start of the examination. This reference area, which is used by the MP1 to track the eye across time, has to be placed close to the optic disc in such a way as to include at least one of the bifurcations of the major vessels leading out of the optic disc. For some eyes, the optic disc was not visible on the fundus image because the scotoma was large and the PRL was in the temporal hemiretina (MP1 field of view, 45°). In this case, the experimenter slowly moved the fixation cross away from the center to induce gradual displacements of the patient’s eye (while maintaining the initially established PRL) until the optic disc was visible on the fundus image.

The first examination was static perimetry with Goldmann V stimuli displayed for 200 ms (Fig. 3). The spatial pattern of the stimuli was determined by the operator who defined a polygonal area surrounding the scotoma directly on the fundus image. Previous perimetry examinations could be jointly used to help define the extent of the scotoma. In this semiautomatic pattern mode, the software then proposed (based on the polygon area) a number of stimuli that could be modified by the experimenter. Typically, the experimenter tried to include at least 80 stimuli within the area. The decision of increasing or decreasing this predefined number depended on several key characteristics of the patient (ability to sit steadily and to maintain attention, fatigability, cooperativity). Initial intensity of the stimuli was determined by an automatic search of the optimal values for four points uniformly distributed across the pattern (pretest option). A 4–2 threshold strategy was then used.

The second examination was kinetic microperimetry (eight outward directions) performed with Goldmann V stimuli at maximum intensity. The center of the radiating trajectories was set as close as possible to the macula center. Three or four isopters (with the same stimulus intensity) were successively measured, each providing an automatic measure of the scotoma area (in squared degrees).

Perimetry data were registered with the color fundus photograph offline. The area of the scotoma was measured as the average of the three or four measures obtained in the kinetic examination. When these measures were not reliable (because of islands of spared vision within the scotoma), the area was measured by hand from the static microperimetry map (superimposed on the polar grid in degrees). Threshold values were ignored, and points were counted as either seen or unseen.

We systematically checked that the perimeter of the absolute scotoma was surrounding the fovea location (most patients seen at the low-vision clinic have absolute scotomas). The patient’s fovea location was estimated as the point whose horizontal and vertical coordinates, relative to the optic disc, were, respectively, 15.5° and −1.5°. These values were based on our measurements averaged across healthy controls and were in close agreement with previous measures using the MP-1 microperimeter (Nidek Technologies).27–28 Whenever foveal sparing was detected (14 eyes from 12 patients), we systematically observed that the fovea was used to fixate the cross and that fixation patterns measured during the perimetry examination were very stable (>90% fixations within 4°). These eyes were removed from the analysis (five fellow eyes of these eliminated eyes were kept in the analysis).

Finally, once eyes with spared foveae were eliminated, static microperimetry maps were scrutinized to detect eccentric islands of functional vision within the scotoma. A categorical factor (referred to as island) with two levels was created, depending on the presence or absence of such islands.

Reading Speed

Reading speed was measured when patients read aloud single French meaningful sentences displayed on a 21-inch monitor (1152 × 864 pixels). The Times New Roman font was used. Characters were black on a white background of maximum intensity (92 cd/m²). Viewing distance was 40 cm by default but could be reduced to 30 or 20 cm for patients with low acuity. Reading was monocular, and an appropriate correction for near vision, corresponding to the viewing distance, was added over distance prescription. Print size was defined as the vertical angular size of the lowercase letter x (x-height).

Each sentence was created by the following MNREAD principles29 to allow a high sensitivity to low-level factors such as crowding. The sentences were displayed over three lines centered on the screen and were left-right justified. This spatial layout remained the same when print size was varied (i.e., the sentence was zoomed in proportion to print size). In addition to these spatial constraints, the following criteria were used to create a set of sentences as simple and similar as possible in terms of reading speed. First, to control for word frequency, we used the lexical database Manulex based on 54 elementary school textbooks.30 A set of 158 sentences was created so that the included words were within the 10,170 most frequently used words. Second, the syntax was chosen to be as simple as possible. Reading speed was then measured for each of these 158 sentences in 7 children (age range, 7–10 years). None of the words was misread by the children. Sentences whose reading speed was outside the ±1 SD range (across children) were eliminated. This yielded a set of 151 sentences that were kept in the experiment.

We developed software to display the sentences, record the response times and errors for each sentence, and analyze the data. Each sentence was randomly drawn from the set and was never read twice by a patient.

The experimenter triggered the presentation of each sentence by pressing a button and then pressed the same button to indicate that the patient had finished reading the sentence. Three different interline spacings were used (Fig. 4), as follows: standard spacing 1 × (2.6 × x-height), twice the standard spacing 2 × and 0.79 × the standard (the latter spacing corresponds to a null leading; i.e., the bottom of the p in line n is horizontally aligned with the top of the b in line n + 1; see Fig. 4, left graph).

The examination started with sentences presented at the largest print size available (2.63° at 40 cm, 1.5 logMar): three sentences corresponding to the three interline spacings were successively presented. Another sequence of three sentences was then displayed with a smaller print size (step, 0.1 logMar). Print size was decreased until only a few words per sentence could be read.

Response time for each sentence was transformed into words per minute and corrected for the number of words misread. An exponential function of the form (reading speed = Rmax + k × exp((−1/9 × print size)]) was fit to the data as a function of print size for each interline spacing. Maximal reading speed was defined either as the saturation level Rmax or as the highest observed reading speed (RmaxObs) when critical print size (calculated print size corresponding to 90% of Rmax) was larger than the largest print size used. The latter case usually occurred when the number of data points for each interline spacing was small.

Statistical Analysis

Statistical analysis was based on a linear mixed-effects (lme) model specifying patients and eyes as random factors (eyes are nested within patients). This analysis has been shown to suffer substantially less loss of statistical power, especially in unbalanced designs, than traditional analysis of variance.26,31–35 Here, the eye factor is
unbalanced because we could collect data from only one eye in many patients. In summary, there are different measurements of reading speed (corresponding to the different interline spacings tested) for each eye (first level of grouping; eye), and there are two eyes, or only one, for each patient (second level of grouping; eye within patient). Including the random structure in the model dramatically reduces the risk of type I errors (when compared with standard multiple regression).

We used the lme program (nlme package) in the R system for statistical computing. Likelihood-ratio tests were used to evaluate the significance of terms in the random-effects structure. We fitted different nested models in which only the random-effects structure was changed, and we compared the different models with likelihood-ratio tests. This was performed with the ANOVA program in the nlme package. In a second step, the significance of fixed effects in the model was assessed with conditional F-tests still using the ANOVA program in the nlme package.

The interline spacing factor was centered around the standard interline value (1/100) for ease of interpretation, whereas the other factors were centered around their respective means (mean scotoma area, 157 degrees squared; mean PRL distance from fovea, 9.6°).
RESULTS

The first step in the model-building process for a mixed-effects model is choosing which parameters, if any, should have a random-effects component included to account for between-group variation (first grouping level, eye within patient; second grouping level, patients). This was achieved by performing likelihood-ratio tests (see Patients and Methods). Different mixed-effects models whose random structure varied were compared. They all had the same fixed-effects structure; interline spacing was the only fixed effect in the model. These likelihood-ratio tests showed that the random structure providing the best fit was the following: (a) random intercept for the "eye within patient" effect; (b) random intercept and random slope for the "patient" effect; and (c) no correlation between intercept and slope. The latter result implies that the effect of interline spacing is not proportional to average maximal reading speed.

This random structure was then used to assess the significance of the fixed effects corresponding to our hypotheses. Four fixed effects were included in the main model. Three factors were continuous: interline spacing, PRL distance from fovea (termed PRL distance), and area of scotoma (termed area). One factor—presence or absence of functional island within the scotoma (termed island)—was categorical.

Main effects and interactions between interline spacing and the other factors were tested with this mixed-effects model. Table 1 and Table 2 show the results of this analysis for the random and fixed effects, respectively. Table 1 confirms the observation from separate linear regressions (not shown) that between-patient variability in the intercept (SD = 23.3) is much larger than between-eye variability (SD = 5.2).

Results of the mixed-effects model analysis for the fixed effects are presented in Table 2. The intercept represents the average optimal reading speed (in words/min) obtained when all other factors are null (after having been centered; see Statistical Analysis). For ease of interpretation, the interline spacing factor has been centered with respect to the standard interline spacing factor. Although the main effects of the PRL distance (P = 0.012) and of the scotoma area (P = 0.004) are significant, there is no interaction between interline spacing and these two factors (P > 0.5 in both cases). The fact that both main effects are significant shows that, despite some level of multicollinearity (r = 0.55), both factors provide independent contributions to reading speed and should be kept in the model. Finally, there is neither a main effect of island (P = 0.16) nor an interaction of island with interline spacing (P = 0.46).

Although the mixed-effects model shows a correlation between eyes within patients, it is possible that including each eye of each patient in the analysis could bias the results because there is evidence that acuity, reading performance, and PRL location are dominated by the better eye. Therefore, we performed an additional analysis including only the better eye (When acuity was the same in both eyes, the better eye was defined as the one having the smallest scotoma size.) for each of the 65 patients. The new estimates were similar (±3%) to those from the previous model, and, most important, the effect of interline spacing was still highly significant (P < 0.001). The only difference was that the effects of scotoma area and of PRL distance were not significant any longer (the corresponding standard errors were 65% higher, mainly because of the smaller number of eyes in the analysis).

We performed two analyses showing that the inclusion of the categorical PRL location factor did not reveal any significant effect (analysis 1: top, bottom, right, or left quadrant; analysis 2: vertical vs. horizontal quadrants). This lack of effect seems consistent with the following observations. With a horizontal PRL, adjacent lines induce tangential crowding (along the small axis of the crowding ellipse) so that the extent of vertical crowding is smaller than with a vertical PRL. However, although the vertical crowding extent is twice as large with a vertical PRL, there is only one adjacent line of text susceptible to induce crowding (because the other adjacent line is occluded by the scotoma). It is thus possible that the net global

<table>
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<th>Table 1. Results of the Mixed-Effects Model Analysis for the Random Effects</th>
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<tr>
<td>Table 2. Results of the Mixed-Effects Model Analysis for the Fixed Effects</td>
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- Maximal reading speed increases by 7.1 words/min. A scatterplot of the individual estimates (for each eye) of slope and intercept is presented in Figure 5.

Table 2 shows that the effect of interline spacing is significant (P < 0.0001) but weak (only 7.1 words/min per unit of interline spacing). Although the main effects of the PRL distance from the fovea (P = 0.012) and of the scotoma area (P = 0.004) are significant, there is no interaction between interline spacing and these two factors (P > 0.5 in both cases). The fact that both main effects are significant shows that, despite some level of multicollinearity (r = 0.55), both factors provide independent contributions to reading speed and should be kept in the model. Finally, there is neither a main effect of island (P = 0.16) nor an interaction of island with interline spacing (P = 0.46).

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* Interaction between two factors.
crowding effect is relatively similar when the PRL is horizontal or vertical.

Assumptions underlying the mixed-effects models were checked with diagnostic plots. Homoscedasticity of residuals was indicated by the absence of a relationship between residuals and regressors. The assumption of normality of residuals was assessed with a normal probability plot (normal q-q plot). None of the points, except one, exhibited any substantial discrepancy from a straight line.

One patient with Stargardt disease (RA) diverged from the general pattern of results. Her results are briefly described in the context of the other three patients with Stargardt disease. For these three patients, the pattern of results is the same as that observed in patients with AMD, namely a weak or an absent effect of interline spacing. However, for both eyes of the patient RA, an intriguing improvement of reading speed was observed as a function of interline spacing. The amplitude of the interline spacing effect was very large when linear regression was performed for each eye (28 words/min for LE and 67 words/min for RE). The amplitude of the effect was still very large when assessed with the mixed-effects model (24 words/min for both eyes). The only factor that seemed to uniquely characterize the patient RA was that her disease appeared earlier (at age 14) than for the other Stargardt patients.

**Discussion**

We report the effect of interline spacing on optimal reading speed for 61 patients with AMD (90 eyes) and for four patients with Stargardt disease (eight eyes). Static and kinetic microperimetry maps, obtained with the MP-1 microperimeter, were used to control for the interactions between interline spacing and relevant scotoma characteristics. Importantly, we also used these maps to ensure that eyes kept in the analysis systematically had an absolute scotoma whose area covered the fovea location.

Using a mixed-effects model for the statistical analysis, our main finding is that increasing interline spacing results in a very large improvement of maximal reading speed. The gain in reading speed is 7.1 word/min when increasing spacing from the standard to the double interline spacing. This result is observed irrespectively of scotoma size and PRL distance from the fovea (absence of significant interaction). Given that the extent of crowding is proportional to eccentricity, this result suggests that vertical crowding is not a limiting factor of reading speed for low-vision patients with an absolute macular scotoma. It could be argued that the effect of crowding is minimized when patients read with a spared island of vision within the scotoma. This would be expected when the lines of text above and below the line being read are masked by the scotoma irrespective of interline spacing. However, our results show that the effect of interline spacing was the same regardless of whether such islands (not coinciding with the fovea) were present within the scotoma.

The weak effect of interline spacing confirms the results of two recent studies. In the first study, an absolute macular scotoma was simulated with a gaze-contingent paradigm.17 Two scotoma areas (36 and 100 squared degrees) were tested with each of seven normally sighted observers. Observers had to read single sentences presented over three or four lines on a monitor. The results showed a weak and significant effect of interline spacing on reading speed. In the second study, eight low-vision patients (eight eyes) had to read printed passages of newspaper articles, and the results showed no effect of interline spacing on reading speed.18

The weak or absent effect of interline spacing seems at odds with recent evidence suggesting that crowding is a key limiting factor of reading speed. There is indeed clear evidence that horizontal spacing between letters, instead of visual acuity, is a limiting factor of reading speed when measured with an RSVP paradigm both with observers with normal sight and with subjects with amblyopia.38,39 There are two main reasons that might explain this apparent discrepancy of results. First, these studies have not investigated the effect of vertical spacing, and vertical interactions might have a special status, as suggested by our results. In keeping with this idea, there is already evidence that vertical crowding is less efficient than horizontal crowding when measuring identification of single letters.40 Incidentally, an interesting proposal in this study is that displaying words (especially labels) in vertical columns should be beneficial for low-vision reading. In addition, it is possible that the horizontal alignment of characters and words within a sentence creates a spatial configuration (a Gestalt grouping) that renders the perceptual segregation between lines easier than the segregation between characters. This kind of configurational effect on crowding has been clearly shown in a recent study.41 Second, it is possible that limiting factors of eccentric reading do not have the same relative strengths when reading with the RSVP paradigm or when reading text with eye movements along lines (page mode reading). It is likely that eccentric crowding is a relatively important factor in the RSVP paradigm because the influence of other factors is minimized, namely ocular fixation and joint attentional deployment are efficiently controlled by observers with normal sight. (Getting rid of the influence of oculomotor effects, and of related attentional effects, has actually always been an explicit goal of the RSVP paradigm so as to focus uniquely on the investigation of low-level visual factors.) This interpretation would explain why a very large improvement of reading speed (100%) was found when standard interline spacing was doubled in the RSVP study of Chung16 in observers with normal sight. In contrast, when reading in page mode with a macular scotoma, poor control of eye movement and difficulty in deploying attentional resources cause significant problems that become relatively more detrimental than the crowding effect alone.42-44 A differential effect of a low-level visual factor on reading speed, when studied either with RSVP or with page mode reading, was already commented on in the classical study of Rubin and Turano.15 These authors emphasized that the

![Figure 5](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/932966/)
effect of print size on reading speed was more dramatic in RSVP than in page mode reading because eye movements in page mode induced a ceiling performance that masked the low-level effect of print size.

There are two practical applications of this study. The first application is for patients with AMD who have very low reading speeds (<20 words/min). Although these patients are usually not able to read long texts any longer, they still read price tags or medicine bottles relatively often in their daily lives (spot reading). For instance, a patient whose reading speed is 7 words/min (approximately 8 seconds/word), as measured in our study with a standard interline spacing, is expected to read at 14 words/min (4 seconds/word) with a double interline spacing (a 100% gain). Although this improvement would surely not be perceived by the patient as helpful when reading a long text, it would probably be considered as an efficient and encouraging aid when reading only a few words. Consequently, if only to assist these patients, interline spacing should be increased as much as practical on the tags and labels encountered in daily life.

The second application of the results of this study concerns patients with AMD who have more fluent reading speeds and whose goal is to read relatively long texts (e.g., journal articles) at their maximal speed. For instance, a patient reading at 70 words/min with standard interline spacing would be expected to read only 10% faster with double interline spacing. This small relative benefit suggests that interline spacing should be maintained at the standard value without any significant detrimental effects. The positive consequence of keeping a relatively small interline spacing is that more information can be displayed within a page to facilitate visual search when exploring a large and complex document. These considerations should be taken into account when designing the layout of text specifically proposed for patients with AMD in books or on Web sites.

Acknowledgments

The authors thank Bernard Ridings and Frédéric Chouraqui for their constant support and Jean-Louis Murati and Léontine Kluse for helping them to improve microperimeter examinations.

References


