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INVITED REVIEW

Reading in the presence of macular disease: a mini-review

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Abstract

Purpose: Reading is vital to full participation in modern society. To millions of people suffering from macular disease that results in a central scotoma, reading is difficult and inefficient, rendering reading as the primary goal for most patients seeking low vision rehabilitation. The goals of this review paper are to summarize the dependence of reading speed on several key visual and typographical factors and the current methods or technologies for improving reading performance for people with macular disease.

Important findings: In general, reading speed for people with macular disease depends on print size, text contrast, size of the visual span, temporal processing of letters and oculomotor control. Attempts at improving reading speed by reducing the crowding effect between letters, words or lines; or optimizing properties of typeface such as the presence of serifs or stroke-width thickness proved to be futile, with any improvement being modest at best. Currently, the most promising method to improve reading speed for people with macular disease is training, including perceptual learning or oculomotor training.

Summary: The limitation on reading speed for people with macular disease is likely to be multi-factorial. Future studies should try to understand how different factors interact to limit reading speed, and whether different methods could be combined to produce a much greater benefit.

Introduction

In healthy eyes, vision is most acute when an object of interest falls within the *fovea* — the region of the retina that packs the highest density of cone photoreceptors and shows the least convergence from photoreceptors to ganglion cells. However, to tens of millions of people worldwide who suffer from disorders or diseases of the eyes that lead to irreversible damages to the fovea, vision becomes blurry, distorted or even lost when they try to use their fovea. Depending on the stage of the disease, people with macular disease may retain their central vision, have a central island surrounded by a ring scotoma (foveal sparing), or have complete central vision loss. When central vision is lost in both eyes, most people eventually adopt a (or sometimes, more than one) retinal location outside the damaged region of their retina as the surrogate for their fovea. This location is often referred to as the preferred retinal locus (PRL).

This paper focuses on how reading is affected when individuals have bilateral central vision loss.

The leading cause of damages to the foveal, or more generally, the macular region is age-related macular degeneration (AMD), which is also the leading cause of visual impairment in the elderly population in developed countries.¹ Despite recent developments in the use of anti-VEGF agents to treat AMD, these treatments are only effective for specific forms or stages of the disease; and in many cases, these treatments only halt or slow down the progression of the disease, instead of curing the disease. Thus, many individuals with AMD still battle with the dysfunctioning of their macula, which leads to a loss of their central vision.

Considering that there is essentially no promising cure for AMD or other forms of macular diseases, many patients with macular disease are referred for low vision rehabilitation to receive help to cope with their visual goals. The primary goal for patients attending low vision clinics is

reading.^{2,3} This is not surprising given that approximately 86% of clients seeking low vision rehabilitation had problems reading,⁴ and that the ability to read correlates strongly with the quality of life of patients with macular disease.^{5,6} Therefore, methods targeting at improving reading performance for patients with macular disease are of utmost importance in visual rehabilitation.

In low vision clinics, the most conventional method to help patients with macular disease to read is the use of magnifiers, which can be in the form of optical magnifiers such as hand magnifiers and high power reading glasses, or electronic magnifiers such as closed-circuit televisions or portable hand-helds. The principle of magnification is to render the retinal images of letters or text much larger than the size of the macular lesion, so that a smaller portion of letters or text falls within the macular lesion. Although magnifiers help patients read small print, reading speed remains slower when compared with the reading speed of people who could use their fovea to read. For example, in normal vision, reading speed measured using drifting text can reach 250 words per minute (wpm); whereas for people with AMD, reading speed could be 10 times slower.⁷ It is widely believed that the slower reading speed demonstrated by people with macular disease is due to the necessity to use peripheral vision to read.

If the slower reading speed demonstrated by patients with macular disease is simply due to the use of peripheral vision, then understanding the limitations and potentialities of the normal periphery for reading may be informative for us to understand the reading difficulties of patients with macular disease; after all, it is much easier to recruit and test participants with normal vision than participants with macular disease. As such, many previous studies have examined various visual factors on reading in the normal peripheral vision, and extrapolated the interpretation to patients with macular disease. However, several recent reports have shown that results obtained in the normal periphery could differ significantly from those obtained from patients with macular disease, suggesting that the normal periphery may not be a valid model for patients with macular disease.⁸ Therefore, in this paper, we will review primarily studies that were performed on participants with macular disease, but brief references to the normal periphery will be included where appropriate.

Visual factors limiting reading in macular disease

Peripheral vision differs from central vision in many ways. At the retinal level, the highest density of cone photoreceptors is found at the foveola, the center of the fovea, with the density of cone photoreceptors falling off sharply as the distance from the foveola (eccentricity) increases, reaching a

plateau beyond $\sim 15\text{--}20^\circ$ eccentricity.^{9,10} The convergence of the cone photoreceptors onto a single ganglion cell also increases with eccentricity. At the visual cortex level, the amount of striate cortex corresponding to 1° in the visual field (cortical magnification) decreases as the retinal eccentricity increases.^{11,12} All these mean that images falling within the central macular area are represented with greater fidelity in the visual pathway than images falling in the peripheral retina, accounting for the higher capability to see fine details in the central macular area. For example, acuity is the highest at the foveola and decreases steadily with eccentricity.¹³ For fixed-size stimuli, contrast sensitivity is also highest at the fovea, and decreases with eccentricity.¹² In addition to the worse acuity and contrast sensitivity, normal peripheral vision is known to suffer more from the crowding effect — the increased difficulty in recognizing an object in the presence of other objects.^{14,15} Given that text usually comprises multiple letters and words, crowding could represent a significant bottleneck on the recognition of letters and words, the fundamental stages of the reading process.

Considering the known differences in visual capability between foveal and peripheral vision, one logical question to ask is whether the poorer reading performance in peripheral vision can be compensated for by optimizing text to account for the differences in visual capability. Here, we are going to review several key properties of the visual system that have been studied, and whether or not reading performance in people with macular disease could be enhanced by optimizing certain characteristics of text to better match the properties of the peripheral visual system.

Spatial resolution

Using a rapid serial visual presentation (RSVP) paradigm in which words are presented one at a time at the same location on the display, Chung *et al.*¹⁶ reported that like in normal foveal vision, reading speed in normal periphery improves with print size, up till a critical print size beyond which further increase in print size does not improve reading speed (Figure 1). The rate of increase of reading speed with print size is similar across eccentricities from the fovea to 20° , averaging 2.32 (on log-log axes), implying that the response to magnification is similar between the fovea and the periphery. However, there are also key differences between the fovea and the periphery. The range of print sizes for which reading speed could be measured is shifted toward larger print sizes in the periphery. In other words, reading acuity (the smallest print size that can be read) and critical print size are all larger in the periphery than at the fovea (increased from 0.16° at the fovea to 2.22° at 20° eccentricity). More importantly, even when print sizes are made large enough, maximum reading speed still drops

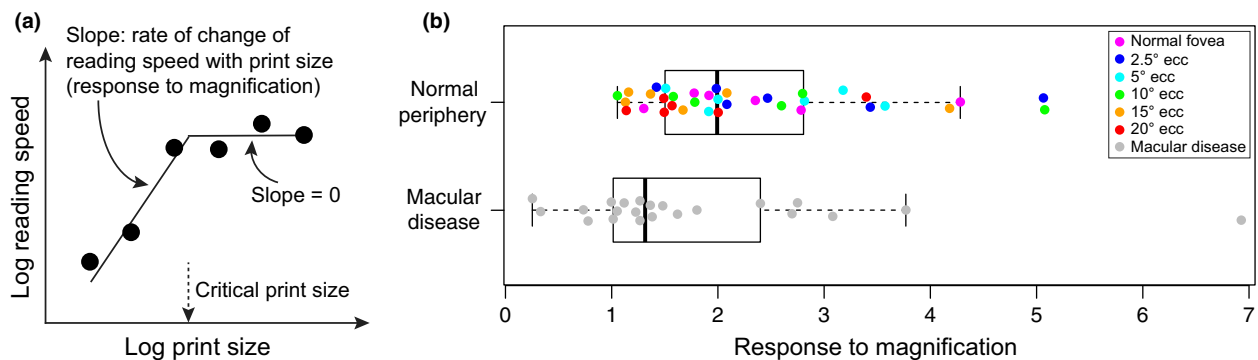


Figure 1. (a) Reading speed shows a strong dependence on print size for print sizes smaller than the critical print size, beyond which reading speed is independent of print size. When plotted on log-log axes, the data could be fitted using a two-line fit, where the slope of the first line represents the change of reading speed with print size, or, the response to magnification.¹⁶ The slope of the second line is constrained to be zero. (b) Boxplots comparing the rate of change of reading speed with print size (the slope of the first line as depicted in (a)) between the normal periphery and people with macular disease (unpublished data). Each circular symbol represents the slope from one participant (macular disease: gray) or from one eccentricity (normal periphery, various colors, data based on Chung *et al.*¹⁶).

from an average of 807 wpm at the fovea to 135 wpm at 20° eccentricity. These results are consistent with the reports of Chaparro & Young¹⁷ and Latham & Whitaker¹⁸ who also showed the superiority of foveal vision in supporting reading.

Using methods similar to those of Chung *et al.*¹⁶ with the exception of larger print sizes, we found that reading speed showed a smaller increase with print size for people with macular disease than for people with normal vision. Figure 1 plots the rate of increase of reading speed with print size for 22 participants with macular disease, which falls within a range of 0.25 to 6.93. For comparison, similar measurements obtained in the normal periphery¹⁶ are also plotted.

Even with magnification, people with impaired vision often read slower than people with normal vision. Using a drifting-text method in which a sentence drifted across a monitor from right to left, Legge *et al.*^{7,19} found a sharp transition from near-perfect reading to error-prone reading as drifting speed increased. This characteristic was demonstrated by both normally sighted⁷ and visually impaired participants.¹⁹ The drifting rate at which this transition occurred was defined as the maximum reading speed. Legge *et al.*⁷ showed that normal reading speed improved with print size up to approximately 0.3°, reaching a plateau at approximately 250 wpm for print sizes ranging between 0.3 and 2°. Further increase in print size led to a decrease in reading speed. Not surprisingly, participants with visual impairment all required larger print than those with normal vision to reach their maximum reading speed. The dependency of reading speed on print size is different between those with intact central field and those without. Those with intact central field demonstrated that reading speed increased with print size, then reached a plateau for a

range of print sizes, before dropping for larger print sizes, a characteristic similar to that demonstrated by people with normal vision. In contrast, participants with central field loss seemed to show a monotonic improvement of reading speed with print size, at least up to the largest print size (20°) tested in the study. The median of the maximum reading speed of visually impaired participants with intact central field was 130 wpm, compared with 25 wpm for those with central field loss, confirming that the presence of central vision loss, instead of a reduction in spatial resolution *per se*, is an impediment to reading speed.

Effects of contrast, contrast polarity and illumination

In addition to an acuity deficit, many people with macular disease also suffer from a loss in contrast sensitivity.^{20,21} Previous studies have shown that contrast sensitivity is a better predictor than visual acuity for daily activities such as face recognition, object recognition and mobility.^{22–24} In normal vision, reading speed is quite tolerant to text contrast until text contrast decreases to approximately 10%,^{25,26} below which reading speed depends critically on contrast. In the normal periphery, as long as print is made large enough so that reading speed is not limited by print size, the critical contrast required to support maximum reading speed is similar between the fovea and the periphery.²⁶

Not surprisingly, people with macular disease require a higher critical contrast to reach their maximum reading speed. Rubin and Legge²⁷ showed that for a group of 19 participants with low vision of various etiologies, the critical contrast averaged 34%, compared with ~10% at the normal fovea. This averaged value did not depend on whether or not participants had intact central vision.

Furthermore, the authors showed that for most of the low vision participants, even when their contrast deficit was compensated for, their maximum reading speed remained lower than that at the normal fovea, suggesting additional limiting factors on their reading performance.

A factor that is related to, but not the same as text contrast is the contrast polarity of text. Contrast polarity refers to whether the text is darker than its background, as in normal printed text (*normal-polarity*); or whether the background is darker than the text (*reverse-polarity*). People with normal vision do not show a systematic difference in reading speed between the normal- and the reverse-contrast polarity conditions.⁷ This also applies to the normal periphery.²⁸ For people with low vision, those with cloudy media (e.g. cataracts) could read 10–50% faster with reverse-polarity text than with normal-polarity text.¹⁹ Although the advantage of reading reverse-polarity text has not been observed specifically for participants with macular disease,^{19,27} those who also have cataracts or other forms of cloudy media are still likely to benefit from reading reverse-polarity text.

In low vision clinics, good illumination is often a recommendation given to patients with macular disease.^{29,30} The beneficial effect is unlikely to be due to an increase in text contrast, because the reflectance of the dark ink or the background does not change with illumination. Therefore even though the absolute amount of light reflected off the dark ink area or the background changes with illumination, the relation between them remains the same. Rather, the benefit could be due to an increase in the depth of focus, which results from the constriction of the pupils under bright illumination, as well as the better visual performance associated with photopic light levels. Eldred³¹ measured reading speed for six illumination levels for a group of 18 participants with AMD. The six illumination levels included the standard one (484 lux) recommended by the Illumination Engineering Society for reading books, magazines and newspapers, and five other levels that ranged between 2.2 and 15.6× higher than the standard illumination (1076–7532 lux). Sixteen of her 18 participants required an illumination level higher than the standard to read at their fastest reading speed. For 11 of them, the fastest reading speed was obtained at the highest two illumination levels which were 12.2–15.6× higher than the standard illumination. These results were corroborated by a study of Bowers *et al.*³² who measured reading performance for a group of 20 participants with AMD at six levels of task illuminance ranging from 50 to 5000 lux. These authors found that an illumination level of at least 2000 lux was necessary for patients with AMD to maximize their reading performance. Seiple *et al.* further showed that the benefit of increased illumination on reading is restricted only to smaller print sizes.³³

Crowding

It is often more difficult to discern the fine details of an object when it is surrounded by other objects than when it is presented alone. This is the *crowding* phenomenon.^{15,34} Crowding has been suggested as a fundamental bottleneck for object recognition, including letter recognition.^{15,34} Because the magnitude and extent of crowding are both larger in the normal periphery than at the fovea,^{35,36} and because people with macular disease must rely on their peripheral retina to read, it is commonly believed that crowding is the primary factor limiting reading for these individuals.

A classical observation of crowding is that the recognition of a letter is often degraded when the letter is surrounded closely by other letters, but improves when the separation among the letters increases. Pelli *et al.*³⁷ showed that a word is unreadable unless its letters are separately identifiable. Therefore, if crowding leads to difficulty in identifying individual letters within a word, then by increasing letter separation, crowding will be alleviated which should in turn, lead to improved letter recognition and reading. Further, since crowding is more prominent in the periphery than at the fovea, the letter spacing to avoid the effect of crowding on reading should be larger in the periphery than at the fovea. Chung³⁸ tested these predictions in the normal fovea and periphery by measuring RSVP reading speed for five letter spacings (defined as the center-to-center separation between adjacent letters), ranging from 0.5× to 2× the standard letter spacing (1.16× the width of the lowercase letter *x*) for the Courier font used. As long as the letter size was made large enough in the periphery such that letter size was not a limiting factor on reading speed, the critical letter spacing (the smallest spacing that yielded the maximum reading speed) was found to be similar at the fovea and in the periphery, and was not different from the standard spacing. In a separate study, Chung³⁹ examined whether or not reading speed could be improved with larger-than-standard letter spacing for a group of fourteen participants with macular disease. Like in the normal fovea and periphery, as long as the letter size was made large enough, the critical letter spacing for participants with macular disease was very similar to the standard letter spacing. In other words, participants with macular disease also did not benefit from increased letter spacing in text, which presumably would have reduced the crowding effect. These results could be interpreted to mean that crowding does not limit reading, or that although increased letter spacing might have reduced crowding, it also leads to other undesirable consequences, such as breaking up the whole-word shape,⁴⁰ with the result that there is no net observed benefit of increased letter spacing on reading. To address the potential confounding factor that increased letter spacing breaks the word shape, Chung and Mansfield²⁸

measured reading speed using a text manipulation that is effective in reducing crowding without affecting letter spacing — using text with letters that alternated in their contrast polarity. Crowding is more substantial when a target and its flanking elements are highly similar, and less when the target differs from the flankers.^{41,42} Therefore, the prediction was that reading speed would be higher using alternating-polarity text (alternating white and black letters within a word), when compared with text with all white or black letters. Contrary to this prediction, reading speeds were found to be highly similar for alternating-polarity text and text with all white or black letters. Potentially, alternating the polarity of adjacent letters might have improved letter recognition, but the benefit might have been offset by other undesirable effects such as the breaking of regularity across letters and the tendency to group letters of the same polarity — effects that hinder the processing of letters to form words.

In relation to reading, crowding can occur between letters or between words. So far, we see that there is not much of a benefit on reading speed by reducing crowding at the letter level. How about at the word level? Chung⁴³ measured RSVP reading speed for sequences of random words that were flanked above and below by words of the same word length, for a range of vertical word spacings (multiples of the standard vertical spacing) in the normal fovea and periphery. For the Courier font used, the standard vertical word spacing measures $2.6\times$ the height of the lowercase *x*. At the fovea, she found that the critical (the minimum) vertical word spacing that allowed observers to reach their maximum reading speed was close to the standard vertical word spacing. In the normal periphery, the critical vertical word spacing was extrapolated to be between $3\times$ and $4\times$ the standard vertical word spacing. These results suggested that larger vertical word spacing, or line spacing in passages, would benefit people with macular disease. Chung *et al.*⁴⁴ measured reading speeds using passages of newspaper articles of 100 words for a group of eight participants with AMD. Five line spacings, ranging from the standard spacing to $4\times$ the standard spacing, were tested. Surprisingly, none of the participants exhibited a dependence of reading speed on line spacing. This lack of a benefit of line spacing apparently was not due to methodology differences between measuring reading speed using passages or sequences of random words, because in a control experiment, reading speeds were measured for sequences of random words for half of the participants and still, there was very little benefit of increased vertical word spacing on reading.

Visual span

During conventional reading, our eyes move along a line of text with a sequence of saccades in the direction of reading,

interspersed with pauses, or fixations. Fixations are brief periods of time, lasting around 250 ms,^{45,46} during which information from the reading materials is being extracted and processed. The spatial region over which information about letter identity is being extracted during a single fixation is referred to as the *visual span*. In relation to reading, visual span is often expressed as the number of characters that can be recognized reliably in a single fixation.^{47–49} A concept that is often confused with the visual span is the perceptual span. Perceptual span includes other text cues, such as word length and the spacing between adjacent words,⁴⁷ which provide important information to guide saccadic eye movements during reading.⁴⁶ Perceptual span is always larger than visual span, at least in normal vision. Although we acknowledge that demands other than purely sensory factors could limit reading performance, to unravel the effects of sensory and other factors on reading, we will focus our discussion on visual span, instead of perceptual span.

In the normal fovea, the visual span is approximately 10 characters for high-contrast, reasonably sized letters ($\sim 0.3\text{--}1^\circ$ in *x*-height).^{47–49} Legge *et al.* proposed the shrinking span hypothesis to account for slow reading in the normal periphery, and for people with macular disease who must use their periphery.^{47,48} According to the hypothesis, the visual span becomes smaller in the periphery, which means that fewer characters can be recognized in a single fixation. Consequently, the eyes need to make more fixations to read a line of text, resulting in increased reading time, thus slowing down reading. Legge *et al.*⁴⁸ used two different methods to test this hypothesis. First, they measured the reading time required to read words of different word-lengths at a range of retinal eccentricity, and found that reading time increased with word length, but this dependence was higher in the periphery than at the fovea. Second, they tried to isolate the bottom-up sensory limitation on the capacity to recognize letters by asking participants to identify sequences of three random letters (trigrams) at various locations left and right of fixation. The result is a plot of recognition accuracy as a function of letter position left and right of fixation, the *visual-span profile*, demonstrating how recognition accuracy drops with letter position from fixation (*Figure 2*). The visual-span profile changes in the periphery — recognition accuracies are reduced across all letter positions (despite letters are scaled to compensate for the reduced resolution in the periphery) and that the profile becomes narrower in shape. For example, when expressed as the number of letters recognized, the size of the visual span (for a recognition accuracy of 80% and a trigram presentation duration of 125 ms) shrinks from 11 characters at the fovea to 3.5 characters at 10° eccentricity.⁴⁸ The size of the visual span is further reduced when the presentation duration is shorter or when the

recognition accuracy criterion becomes more stringent. These findings support the shrinking span hypothesis in explaining the slow reading in peripheral vision.

Cheong *et al.*⁵⁰ adopted the trigram method to measure the visual span for a group of participants with AMD. In the presence of AMD, the profile of the visual span may show irregular shape in that letter recognition accuracy may drop drastically at letter positions that correspond to the central scotoma (*Figure 2c*). Therefore, a better way to quantify the size of the visual span is to express it as bits of information transmitted, where 4.7 bits represent a letter recognized at 100% accuracy.^{48,49} Essentially, recognition accuracy at each letter position is converted to bits of information transmitted, and the size of the visual span then represents the sum of the bits of information transmitted across all letter positions. For the nine participants who had eccentric fixation (they also tested four participants with central fixation), the size of the visual span (median of 20.6 bits) was significantly smaller than the visual span obtained in the normal periphery (median of 29.0 bits).⁵⁰ These findings were consistent with the shrinking span hypothesis in explaining the slow reading exhibited by people with macular disease who must rely on their peripheral vision. In the next section, we shall see that the relationship

between reading speed and the size of visual span could be made even stronger when temporal factors are considered.

Temporal processing

Reading is not simply a spatial task. Even though most people with macular disease do not read as if they are participating in a speed reading contest, they do expect to read at a reasonable speed. Thus, temporal processing could be a factor limiting reading. Cheong *et al.*⁵¹ found that the temporal threshold for letter recognition was much longer for a group of participants with macular disease (in the range of 159–5881 ms, compared with 13 ms in the normal fovea). Further, they observed a significant association between the increased temporal threshold for letter recognition and the reduced reading speed for the participants. In another study, Cheong *et al.*⁵⁰ examined the relationship between visual span and reading speed for 13 participants with AMD. The authors found that information transfer rate, a variable representing the combined effects of a reduced visual span and slower temporal processing of letters, is a better predictor of reading speed for their AMD participants than the size of visual span alone. Based on these findings, Chung⁵² tested whether or not temporal threshold

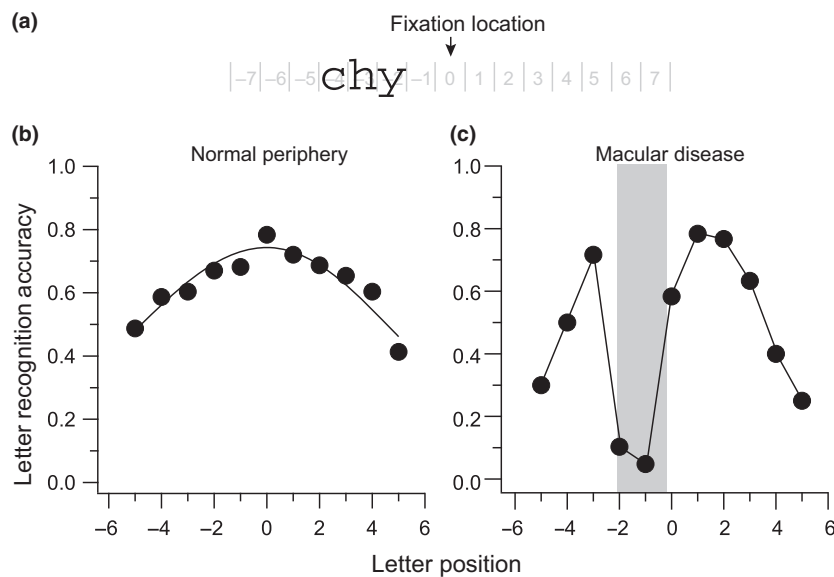


Figure 2. (a) The trigram method for measuring visual span. On each trial, a trigram of three random letters (shown here in Courier font) is presented at various letter positions left or right of fixation (shown here in gray, but in the actual testing, participants do not see the letter positions nor the numbers referring to the letter positions). Participants' task is to identify the three letters. (b) After many trials of the trigram presentations, letter recognition accuracy is computed for each letter position (negative [positive] values represent letter positions left [right] of fixation). Traditionally, the data are fitted using a split-Gaussian curve, with the peak of the curve occurring at zero (fixation) and accuracy dropping on either side of fixation. A simple way to quantify the size of the visual span is to determine the width of the split-Gaussian curve for a given letter recognition accuracy criterion and express it as number of characters. An alternative method to quantify the size of the visual span is to express it as the sum of information transmitted (in bits) across all letter positions, where 4.7 bits represent 100% recognition accuracy at a given letter position. (c) An example of a visual-span profile obtained for a participant with macular disease,⁵² where letter recognition accuracy drops to close-to-zero at letter positions (spanning approximately two letter positions left of fixation in this example) that correspond to the location of the central scotoma (gray shaded region).

for letter recognition is amenable to training and whether that would lead to faster reading speed for people with macular disease. After six sessions of training, temporal threshold was reduced by 3.3×, with an accompanied improvement in reading speed of 44%. All these findings are consistent with the fact that temporal processing could be a major factor limiting reading speed for people with macular disease.

Oculomotor control

As stated in the previous section, during reading, our eyes move along a line of text with a sequence of saccades in the direction of reading, interspersed with fixations. People with macular disease are known to exhibit poor oculomotor control,^{53–55} therefore if the need to make saccades while reading is eliminated or reduced, people with macular disease may read faster. Rubin and Turano^{56,57} tested this hypothesis by presenting text using RSVP that minimizes the need for readers to move their eyes to the next word. While they found a two- to four-fold advantage in speed of RSVP over conventional page reading for people with normal vision,⁵⁶ the advantage of RSVP over page reading was smaller for people with central vision loss (averaging about 1.5×), implying that inefficient eye movements only partially account for the slow reading of people with central vision loss.⁵⁷

The fact that inefficient eye movements may not be the primary limiting factor on reading speed for people with macular disease is corroborated by the main finding of Bullimore and Bailey.² In that study, the authors examined the relationship between reading speed and three oculomotor characteristics: fixation rate, forward saccade ratio and letters per forward saccade, and found that only the number of letters per forward saccade shows a strong positive correlation with reading speed. The effect of reduced number of letters per forward saccade on reading speed is consistent with the shrinking visual span hypothesis.^{47,58} More recently, Calabrèse *et al.*⁵⁸ showed that the reduced number of letters per forward saccade *per se* cannot fully explain the slow reading speed, but requires either or both of a prolonged fixation duration or an increase in fixation rate. Using a mediation analysis, they showed that the effect of the reduced number of letters per forward saccade on reading speed can be fully accounted for by fixation rate, instead of prolonged fixation duration.

Another oculomotor limitation on reading speed is fixation stability. People with macular disease are known to have poor fixation stability,^{53–55} which has been shown to correlate with reading speed for people with macular disease.^{59,60} This forms the basis of several recent studies evaluating the relationship between oculomotor training, fixation stability and reading speed, which will be

summarized in the section “Eye movements/fixation stability training”.

Typographical factors limiting reading in macular disease

It has long been known that legibility and readability differ across fonts, even for people with normal vision,^{40,61,62} but the effects might be exacerbated for people with impaired vision. However, is there a font that offers readers, especially those with macular disease, the highest reading speed? This has been a long-standing quest in the low vision community. Studies that have examined the effects of font types often compared two or more existing fonts in the same study. Several problems arise for this approach. First, different studies used different outcome measures. The more popular measurements include objective ones such as size legibility and reading speed, and subjective ones such as preference, readability and comfort. Clearly, these measurements do not measure the same characteristics of reading and may or may not be related to one another, making it difficult to compare across different studies. Second, different studies compared different fonts, with some of the fonts not as popular as others. Third, each font has its own combination of characteristics, including the presence of serifs, letter-stroke width, letter spacing, proportional-width vs fixed-width, x-height relative to body size, ascender-descender length etc.^{40,61,62} Therefore, it is unclear whether any effect, if present, is due to the font *per se*, or simply one or more of these characteristics. It is also difficult to “equate” one of these characteristics across fonts to evaluate a specific characteristic. Instead, to evaluate the effect of a specific characteristic, many studies chose to use only one font but manipulated the characteristic in question systematically. Here, we will first briefly summarize the results of studies that simply compared legibility, readability or reading speed for a few fonts, before summarizing the results of studies that used only one font but systematically varied one of the font characteristic.

Font types

The topic of how text characteristics affect reading has been studied extensively as early as the 1930s–1950s by pioneers such as Paterson and Tinker. The book, *Legibility of Print*,⁴⁰ a compilation of much of Tinker’s work, remains an influential body of work on the topic. Paterson and Tinker⁶³ measured reading speeds for ten fonts — Scotch Roman, Garamont, Antique, Bodoni, Old Style, Caslon Old Style, Cheltenham, Kabel Light, American Typewriter and Old English. With the exception of Kabel Light, the rest of the nine fonts are all serif fonts. The authors found that reading speeds were highly similar for the first eight fonts of the list, including the only sans serif font Kabel Light. Compared

with text printed in Scotch Roman, text printed in American Typewriter and Old English were read 5.1% and 16.5% more slowly, respectively. Yager *et al.*⁶⁴ compared reading speed for two fonts, Dutch (serif) and Swiss (sans serif) in a group of normally sighted participants, with text presented as white letters (either 146 cd/m² or 0.146 cd/m²) on a black background. They found that while reading speed for both fonts were highly similar when text luminance was 146 cd/m², reading speed was approximately 11.5% higher for Swiss font than for Dutch font when text luminance dropped to 0.146 cd/m², suggesting that the benefit offered by a particular font may only become apparent when the reading conditions are not ideal.

In relation to people with impaired vision, Mansfield *et al.*⁶⁵ compared reading performance for two popular fonts — Times and Courier. Both fonts have serifs but Times is a proportional-space font, whereas Courier is a mono-space font. They found that while the maximum reading speeds for normally sighted participants were 5% faster with Times than with Courier, maximum reading speeds were approximately 10% slower with Times than with Courier for participants with central vision loss. Additionally, both reading acuity (by 0.10 logMAR) and critical print size (by 0.07 logMAR) were found to be smaller for Courier than for Times. These results suggest that Courier might be a better font for people with central vision loss. These findings were corroborated by those of Tarita-Nistor *et al.*,⁶⁶ who compared reading performance for four fonts — Times New Roman, Courier, Arial and Andale Mono for a group of 24 participants with AMD. Times New Roman and Courier have serifs whereas Arial and Andale Mono do not. On the other hand, Times New Roman and Arial are proportional-space fonts whereas Courier and Andale Mono are mono-space fonts. The authors found that maximum reading speeds were similar across the four fonts, but reading acuity was significantly smaller for Courier than for the other three fonts (by 8–16%). Similar findings that maximum reading speed appeared to vary very little across different font types but reading acuity and critical print size were best for Courier font were reported by Xiong *et al.*⁶⁷ In that study, the authors compared reading performance for five fonts — three popular ones including Helvetica, Times New Roman and Courier, and two fonts specifically designed for low vision readers (Eido and Maxular). After matching the x-height across the five fonts, maximum reading speeds were found to be similar across fonts, but the smallest reading acuity and critical print size were obtained for Courier (as well as Eido and Maxular, see the section “Designs of new fonts”).

Serifs vs sans-serifs

Serifs are the small lines attached to the end of a stroke in a letter or a symbol. As summarized in the section “Font types”,

studies have compared reading performance for different fonts, usually with a mix of fonts with and without (sans) serifs. For example, Paterson and Tinker⁶³ found that reading speeds were highly similar for eight fonts that included seven serif fonts and one sans serif fonts. Tarita-Nistor *et al.*⁶⁶ showed that reading speeds were similar for the four fonts they tested, which included two with serifs and two without. Xiong *et al.*⁶⁷ also found similar reading speeds for a mix of serifs and sans serif fonts. Based on these results, it seems clear that the presence of serifs is not a limiting factor on reading speed. However, as stated earlier, when comparing different fonts or typefaces, we cannot avoid the potential confounding factors of other font characteristics unless we use a single font and change only the variable of interest. In this case, more conclusive results about the importance of serifs in limiting reading could come from studies that use a single font, with and without serifs.

Other typographical characteristics

Comparing reading performance across a handful of fonts is practical, yet because many of the typographical characteristics covary with one another, it is often difficult to isolate and attribute an effect to a single characteristic. A better approach to study a typographical characteristic of interest is to use a single font and vary the characteristic of interest systematically. Here, we shall review the effect of letter stroke-width, or, referred to as the “weights” in typography. Luckiesh and Moss⁶⁸ compared reading speed using the Memphis font for four letter stroke-widths: Light (standard), Medium (20% bolder than standard), Bold (35% bolder than standard) and Extra Bold (69% bolder than standard). The highest reading speed was found for the Medium and Bold setting, but the advantage was only 2–3% when compared with the speed for the Light setting. Paterson and Tinker⁶³ compared reading speed for standard Roman and boldface print in 200 college students and did not find any difference in reading speed. More recently, Bernard *et al.*⁶⁹ systematically evaluated the effect of varying the letter stroke-widths on reading speed in the fovea and periphery for a group of normally sighted young adults, given that there is a common belief that bolder typeface (thicker letter strokes) is easier to see and might thus enhance reading. They modified the standard Courier font by adding or removing layers of pixels around each letter to create five other levels of letter stroke-widths that ranged between 0.27 and 3.04× the letter stroke-width of the standard Courier font. They found that at both the fovea and the periphery, reading speed was the highest for the standard Courier font but declined substantially for very thin or very thick letter strokes. In other words, reading speed did not benefit from increased letter boldness, contrary to

the common belief that bolder typeface is easier to see. However, when subjective legibility instead of reading speed was used as a performance measurement, Sheedy *et al.*⁷⁰ reported that boldface letters (the authors tested several fonts but simply used the default of boldface for each font) enhanced legibility of letters and words, although the effects were modest (1–10%). Silver and Braun⁷¹ studied perceived readability (a rating given by observers) for warning labels, and found a higher perceived readability rating for boldface type over Roman type (averaged across several fonts: Helvetica, Times and Goudy), and for 10-point print over 8-point print. Nevertheless, whether an enhanced legibility or an improved perceived readability leads to faster reading speed is unclear.

With respect to the visually impaired population, Arditi⁷² developed a fully customizable font, Tailor font, and asked a group of 40 low vision participants to adjust several font parameters, including letter spacing, stroke-width, serif size, x-height and letter-width-to-height aspect ratio to maximize the subjective legibility of the font. He found that the optimum stroke-width setting improved reading acuity by approximately 10%, but he did not measure reading speed nor did he report what was the average setting of the “optimum” stroke-width. Chung and Bernard⁷³ adopted the method used by Bernard *et al.*⁶⁹ to measure how reading speed depends on letter stroke-width for a group of 10 participants with macular disease. Just like at the normal fovea and periphery, reading speed was optimal for the standard Courier font, and declined for the very thin or the very thick stroke-widths. Their results imply that the clinical wisdom that patients with macular disease might benefit from bolder print may only be a myth.

Improving reading for people with macular disease

A major goal of studying the limiting factors on reading is to see if we could devise methods to improve reading ability for people with macular disease. Clinically, the provision of magnifiers and/or teaching patients the techniques of eccentric viewing are almost always the first two steps in addressing the reading goal of patients with macular disease. Comprehensive reviews on these two topics can be found elsewhere.^{74,75} In this paper, we will focus on other attempts to improve reading performance which included modifications of current fonts and/or designs of new fonts that might make reading easier, training or perceptual learning to improve reading performance, and remapping the visual input that fall into the scotoma onto a more functional part of the retina.

Designs of new fonts

A popular question posed by people with impaired vision, education specialists and rehabilitation specialists is which

font is the “best” for people with impaired vision, or whether a specially designed font could alleviate the reading difficulty of people with impaired vision. The word “best” ideally refers to the best reading performance (fastest reading speed, smallest print size read), the most comfortable and pleasing to read. Unfortunately, all these criteria do not go hand-in-hand and very few studies have evaluated more than a couple of these criteria as outcome measures. As summarized in the section “Font types”, there has been substantial effort in investigating the effects of various typographical factors on reading speed, ease and comfort of reading etc. Most of these studies compared an outcome measure using different existing font types, and either did not find a significant advantage of a font characteristic on reading, or the advantage was modest at best. In this section, we will focus the discussion on whether specially designed fonts offer advantages over existing fonts for people with macular disease.

Approximately 20 years ago, the Royal National Institute for the Blind in the United Kingdom sponsored the development of a font for readers with impaired vision, the Tiresias font. Reports from the developers (no longer accessible by the public) showed that there was a strong subjective preference for the Tiresias font over Arial or Times Roman; however, there was no evidence suggesting that Tiresias led to better reading performance. It is unclear that Tiresias remains a recommended font to the visually impaired population.

The American Printing House for the Blind (APH) recommended the use of its APHont font when creating large-print materials for people with low vision. However, there has not been any published scientific evidence suggesting the advantages of the APHont over the more commonly used fonts, such as Arial, Times Roman and Courier.

One of the earliest attempts for a specially designed fonts to improve reading for people with impaired vision was the development of Font Tailor.⁷² Font Tailor is a piece of software that allows users to adjust different parameters of a font to their own liking, thus creating a font that is supposed to enhance legibility. When tested on 40 participants with impaired vision (with a variety of diagnoses), Arditi found substantial variability in the settings for each parameter, leading him to conclude that each participant has his/her own needs in terms of font characteristics. Further, he found that although the final font with all the adjustments improved legibility by an average of 75%, when compared with default settings, the resulting font was not more legible than the standard Times New Roman.

A more recent effort saw the development of the Eido font, a font specifically designed to increase letter legibility in peripheral vision by minimizing confusions among letter groups.⁷⁶ The error rate of recognizing letters in the normal periphery was approximately 30% lower for Eido than for

Courier font. However, this substantial reduction in letter recognition errors did not translate to better reading performance — reading speed, critical print size and reading acuity were found to be similar between Eido and Courier fonts. Potentially, breaking the regularity across letters (e.g. some letters were tilted and there was also a mixing of upper- and lowercase letters) and the introduction of unfamiliarity effects for the Eido font might have hindered the reading process.⁷⁶ The lack of an advantage of Eido over Courier for reading was confirmed by an independent study that compared reading performance for three commonly used fonts — Helvetica, Times New Roman and Courier — with two fonts that claimed to be specifically designed for readers with macular degeneration, Eido and Maxular.⁶⁷ In that study, Eido was found to allow participants with macular degeneration to read at a smaller reading acuity, while Maxular allowed participants with macular degeneration to read at a smaller reading acuity as well as a critical print size, although neither of these two fonts enabled readers to read faster when compared with the three commonly used fonts, and neither of the two fonts offered advantages over Courier.

Perceptual learning/training

Perceptual learning is defined as “any relatively permanent and consistent change in the perception of a stimulus array, after practice or experience with this array”.⁷⁷ It has been shown to be effective in improving performance for many tasks in young as well as older adults with normal vision,^{78,79} at the fovea and in the periphery.^{80–84} Over the past two decades or so, perceptual learning has been shown to be effective in improving certain aspects of functional vision in people with amblyopia, even for adults.^{85,86} As such, it is currently a form of treatment for people with amblyopia.^{85–88} In view of the success of applying perceptual learning to improving functional vision for the clinical population of amblyopia, there is an immense interest in using perceptual learning to improve functional vision for people with macular disease.

Chung⁸⁹ investigated whether or not reading performance could be improved following perceptual learning for people with macular disease. Unlike previous studies on perceptual learning using tasks that mostly tapped into lower-level visual functions, Chung trained her participants using a reading task. Her participants read aloud 300 sentences, presented using the RSVP paradigm, in each training session. After six sessions of training, reading speed improved by an average of 53%. This improvement in reading speed was not accompanied by an improvement in letter-chart acuity, critical print size, fixation stability or a change in the PRL location, suggesting that the improvement represented genuine sensory changes following

training. Tarita-Nistor *et al.*⁹⁰ used a similar experimental paradigm with the exception that words were presented at the reading acuity of participants with macular disease. They reported an improvement in reading time between the first and the last (the fourth) training sessions of 54%, essentially replicating the finding of Chung⁸⁹. Further, these authors reported that the improvement due to training (using an RSVP task) transferred to a continuous-page reading task, binocular acuity and fixation stability. However, there was also a change in the PRL location, prompting the uncertainty of whether the improvements in reading time, binocular acuity and fixation stability were benefits due to a genuine learning effect, or simply because of the adoption of a different PRL location that had better functional capability.

Nguyen *et al.*⁹¹ compared the effectiveness of RSVP with a sensomotoric (a moving-window to present text that requires readers to make reading eye movements) paradigm as a training task to improve reading for a group of participants with juvenile macular disease. They found that for both training tasks, the learning effect transferred to an untrained continuous passage reading task. The median reading speed for 100-word passages improved from 83 to 104 wpm following RSVP training (25% improvement); and from 102 to 122 wpm for the sensomotoric training group (19.6% improvement).

In addition to using reading as a training task, there are several studies that used other sensory training tasks to improve functional vision for people with macular disease. However, as shown by Yu *et al.*⁸⁴ who compared several training tasks and several outcome measures, the largest improvement of an outcome measure was obtained when the training task was specific for that particular outcome measure. For example, if reading speed is the target outcome measure that we would like to improve, then a reading training task would produce the greatest improvement in reading speed, compared with other training tasks.

Eye movements/fixation stability training

Besides perceptual learning, oculomotor training has also shown promise in improving reading for people with macular disease. This is not too surprising given that oculomotor control has long been a standard intervention used in low vision clinics to train patients with macular disease to see better. The most basic training is eccentric viewing training, however, training for better execution of eye movements, especially saccades, has also enjoyed some popularity with training exercises printed in books.⁹² Seiple *et al.*⁹³ compared the effectiveness of three training modules in improving reading speed for participants with AMD: visual awareness of eccentric viewing, control of reading eye movements and reading practice with

sequential presentation of lexical information. After 6 weeks training on each of the three training modules, only training in the control of reading eye movements yielded a significant improvement in reading speed.

As described in the section “Oculomotor control”, fixation stability shows a positive correlation with reading speed for people with macular disease,^{59,60} leading to the general consensus that reading would benefit from training to improve fixation stability. To date, studies that have targeted at training fixation stability are scarce. Several studies that reported an improvement in fixation stability did not simply train fixation stability. Tarita-Nistor *et al.*⁹⁴ used auditory biofeedback to train participants with AMD to relocate their PRL. After five 1-hr training sessions, they reported that fixation stability of their participants improved by 53%, which was accompanied by an increase in reading speed (38%) and a two-line improvement in both reading acuity and critical print size. However, it was not clear whether these improvements were due to the improved fixation stability *per se*, or the use of a different PRL location. Similarly, the study of Daibert-Nido *et al.*⁹⁵ essentially arrived at the same result — biofeedback training improved fixation stability for people with AMD, but all subjects also showed a change in their PRL. Indeed, there have been previous attempts at training another retinal location (the trained retinal locus, “TRL”) to replace the PRL naturally adopted by patients with AMD.^{96,97} However, none of these attempts provided sufficient evidence to support the authors’ choice of the TRL, other than the fact that the authors simply picked a retinal location above the macular lesion, which corresponded to the visual field below the central scotoma. Although an improvement in reading speed was reported in these studies, it is unclear whether the improvement was a result of the use of a different retinal location or simply a training/learning effect, and it was also unclear that the TRL offered better functional performance for all types of visual tasks when compared with the PRL naturally adopted by the participants. From a scientific point of view, it would be instrumental to understand the properties of the different retinal locations relative to the central scotoma and what would make a retinal location the best PRL. Efforts are currently underway to understand how a PRL is chosen, but so far, we know that the PRL does not correspond to the retinal location surrounding a central scotoma with the best visual acuity⁹⁸.

Spatial remapping and other technology

Recent years have seen a flux of development of wearable electronic devices that make use of computer technology to present text in customizable ways to patients with macular disease. Almost all these devices

allow basic manipulations of text that include magnification, contrast enhancement, contrast polarity reversal, changing of text and background colors. Some of the more advanced manipulations may range from presenting text one word at a time or the ability to reformat text into different column widths, to the use of more contemporary technology such as virtual reality (VR) or augmented reality (AR). Currently, the application of VR and AR technology to low vision devices is still limited, and most of the products that make use of such technology are not specifically developed for improving reading, but more for a general-purpose device to help patients see. The major challenges for using wearable electronic devices for people with macular disease in relation to the task of reading are the presence of the scotoma, and that almost none of the technologies address the use of a PRL.

In the 1980s, an electronic remapping system called the Programmable Remapper that was developed at NASA Johnson Space Center saw its application as an assistive device for people with macular disease.^{99–101} This technology, spatial remapping, essentially performs a spatial transformation so that visual input falling within a scotoma would be represented outside the scotoma. The developers of this technology proposed several algorithms to remap the visual input around a scotoma, including “radial eccentric” and “Gausflow”. To test the feasibility of this remapper, Wensveen *et al.*¹⁰¹ measured reading speed for four normally sighted young adults and six normally sighted older adults, while they read sequences of unrelated words in the presence of a simulated circular scotoma. Letters were remapped according to the “radial eccentric” algorithm —stretched and appeared to be magnified and wrapped around the simulated scotoma (although parts of the letter(s) remained obscured by the simulated scotoma). These authors found that reading speed was generally higher with remapping (could be up to 2× faster, although the baseline reading speed was very low) than without remapping. These promising results prompted a follow-up study in which the remapper was tested on participants with macular disease.⁹⁹ In that study, two participants with AMD and one participant with Stargardt disease were tested, each with two types of remapping algorithms, “radial eccentric” and “Gausflow”. Neither of these two algorithms were found to improve reading speed for the three participants. Since then, there was very little follow-up activities on the idea of remapping until very recently. Gupta *et al.*¹⁰² tested a different remapping algorithm that represent text completely outside a scotoma with little distortions. Measuring reading speed for various sizes of simulated scotoma for normally sighted participants, the authors found a general increase in reading speed especially for larger sizes of simulated scotomas. Whether or not this

remapping algorithm could improve reading speed for individuals with a real scotoma remains to be seen.

Summary and concluding remarks

In this paper, we reviewed previous studies in relation to three main questions that concerned reading for people with macular disease: (1) what are the visual factors that limit reading? (2) how does reading depend on the properties of typeface and font types? (3) what are the current methods or technologies that could improve reading performance?

Reading speed for people with macular disease improves with print size, but only for smaller print sizes (smaller than the critical print size). Similarly, reading speed improves with text contrast only when the contrast is below a critical value. For both print size and contrast, even when the critical values are exceeded, reading speed remains lower than that observed for people with normal vision. Contrary to a popular belief that crowding would be a significant bottleneck for reading given that people with macular disease must read using their peripheral vision, to date there is no evidence that reading speed for these individuals benefits from any text manipulations in which crowding between letters or words or lines is minimized for print sizes larger than the critical print size. It remains possible that crowding limits reading speed for smaller print sizes. The reduced size of the visual span, the slow temporal processing of letters and the poor oculomotor control associated with the use of peripheral vision have all been shown to have a significant association with reading speed. These findings have led to studies that examined whether or not these visual properties could be improved through training, and whether or not the improvements, if any, are accompanied by improved reading speed.

Previous studies have also studied how font types or properties of typeface affect reading speed, in the hope that reading speed could be improved if we optimize the properties of text. In general, attempts at improving reading speed by optimizing properties of typeface such as the presence of serifs or stroke-width thickness proved to be futile, with any improvement being modest at best. This could be due to the fact that print has existed for several centuries and that the properties of typeface have already evolved over the years to become optimal. Attempts at designing new fonts to improve letter recognition, especially for people who have to use their peripheral vision, also failed to show any benefit to reading speed. However, findings from previous studies consistently imply that Courier is the best font for reading for people with macular disease.

To date, the most promising method to improve reading speed for people with macular disease is training, whether the intention is to improve the sensory or the oculomotor

system. Modern technologies that make use of virtual reality or augmented reality, or represent the stimulus input fallen within a central scotoma onto other functional parts of the retina are still in their investigational stages. One of the major challenges for these technologies is the necessity to address the use of a PRL (sometimes more than one) instead of the fovea.

Considering the nature of a review paper, here, we only present findings of prior studies as group responses. Individual differences in human behavior are ubiquitous, even in healthy individuals with normal vision. Therefore, it is important to note that the group responses summarized here might not apply to all individuals with macular disease. For instance, in the section “Spatial resolution”, we stated that the response to magnification is less for people with macular disease than for people with normal vision (even in the normal periphery). Individual data plotted in *Figure 1b* clearly showed an outlier with a very different response to magnification than the rest of the participants with macular disease. Such individual differences might present great challenges for the development of rehabilitative strategies or methods, and assistive technology that could benefit every individual patient.

In this review, we tried to summarize and treat each factor or method independently so that we could understand the effect of each factor or the efficacy of each method without any confounds. It is likely, however, that the limitation on reading speed for people with macular disease is multi-factorial and that methods to improve reading could be combined to yield a synergistic effect. Future studies should try to understand how different factors interact to limit reading speed, and whether different methods that could each improve reading speed could be combined to produce a much greater benefit. Another noteworthy point is that even the same methodology does not always produce similar results in the normal periphery and for participants with macular disease. The differences call into question whether the normal periphery is a good model for understanding the functional capability of people with macular disease.

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Conflict of interest

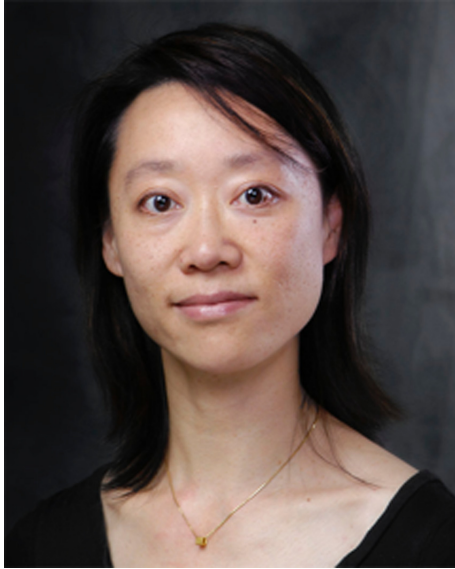
The author reports no conflicts of interest and has no proprietary interest in any of the materials mentioned in this article.

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