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Acuity, crowding, reading and fixation stability

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Abstract

People with age-related macular disease frequently experience reading difficulty that could be attributed to poor acuity, elevated crowding or unstable fixation associated with peripheral visual field dependence. We examine how the size, location, spacing and instability of retinal images affect the visibility of letters and words at different eccentricities. Fixation instability was simulated in normally sighted observers by randomly jittering single or crowded letters or words along a circular arc of fixed eccentricity. Visual performance was assessed at different levels of instability with forced choice measurements of acuity, crowding and reading speed in a rapid serial visual presentation paradigm. In the periphery: (1) acuity declined; (2) crowding increased for acuity- and eccentricity-corrected targets; and (3), the rate of reading fell with acuity-, crowding- and eccentricity-corrected targets. Acuity and crowding were unaffected by even high levels of image instability. However, reading speed decreased with image instability, even though the visibility of the component letters was unaffected. The results show that reading performance cannot be standardised across the visual field by correcting the size, spacing and eccentricity of letters or words. The results suggest that unstable fixation may contribute to reading difficulties in people with low vision and therefore that rehabilitation may benefit from fixation training.

Keywords: Fixation stability; Spatial interference; Crowding; Acuity; Positional noise

1. Introduction

Age-related macular disease (AMD) is the leading cause of visual impairment in industrialised countries and affects around 18 million people (World Health Organisation, 2004). AMD causes an absolute or relative scotoma in central visual field, with a sparing of peripheral vision. People with AMD are forced to use non-foveal retina for visually guided behaviour and often adopt, either with training (Nilsson, Frennesson, & Nilsson, 1998) or spontaneously, a single non-foveal retinal area known as a Preferred Retinal Locus (PRL,(Schuchard & Fletcher, 1994; Timberlake et al., 1986) for this purpose.One of the most common complaints in AMD is that reading with residual peripheral vision is slow and difficult, even if a dominant PRL has developed (Legge, Rubin, Pelli, & Schleske, 1985). Reading with peripheral visual field is also much slower in normally sighted observers (Chung, Mansfield, & Legge, 1998; Latham & Whitaker, 1996; Legge et al., 1985). There are a number of differences in visual processing between central and peripheral visual field that could in principle account for the fall-off in reading performance with eccentricity and to the reading deficit in AMD.

1.1. Visual acuity

Text cannot be read if the letters or words cannot be resolved and it is well known that visual acuity declines rapidly in the peripheral visual field (Millodot, 1966). Acuity deficits can be corrected by adjusting the size and/or contrast of targets to equate visibility across the visual field (Johnston, 1987; Levi, Klein, & Aitsebaomo, 1985; Melmoth, Kukkonen, Makela, & Rovamo, 2000; Melmoth &

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Rovamo, 2003; Watson, 1987; Whitaker, Makela, Rovamo, & Latham, 1992). As letter size increases above resolution threshold, there is an initial improvement in reading rates at all eccentricities. The maximum rate is reached at around 2–3 times resolution size and there is no further increase in reading speed with increased size (Chung et al., 1998), for review see (Whittaker & Lovie-Kitchin, 1993), until eventually, at very large letter sizes, reading rates start to decline again (Rubin & Turano, 1992). The minimum letter size at which reading rate reaches asymptotic levels is termed the *critical print size*. In line with the fall-off in visual acuity, critical print size increases with eccentricity, but the asymptotic maximum reading rate falls with eccentricity at any letter size (Chung et al., 1998; Latham & Whitaker, 1996).

1.2. Crowding

Under some conditions, alphanumeric characters that are reliably identified in isolation can no longer be identified when they are closely surrounded by other optotypes (Bouma, 1970; Townsend, Taylor, & Brown, 1971) or contours (Flom, Weymouth, & Kahneman, 1963). This effect is known as *crowding, spatial interference* or *local contour interaction.* The spatial extent of crowding increases in the peripheral visual field (Bouma, 1970) even with carefully scaled target images (Chung, 2002). It is therefore possible that crowding reduces the visibility of adjacent letters or words (or increases spatial interference among them) in the periphery and it is this that slows reading. Efforts to increase reading rates by minimising crowding have produced only modest improvements. While increasing the spacing between lines of text can increase reading speed (Arditi, Knoblauch, & Grunwald, 1990; Chung, 2004), no improvements have been achieved by increasing the spacing between letters within words and peripheral reading rates are uniformly slower than foveal rates at any inter-letter spacing (Chung, 2002). Alternating the contrast polarity of adjacent letters can reduce crowding under some conditions (Liu & Arditi, 2000) but not others (Hess, Dakin, & Kapoor, 2000), however it does not produce any improvement in reading rates (Chung, 2005).

1.3. Perceptual/visual span

Reading is further constrained by the number of letters that can be identified in a single fixation. In foveal vision, approximately 4 letters on either side of fixation can be identified in a single presentation (O'Regan, 1990), which is termed the visual span. The number of letters that influence other aspects of reading behaviour, such as eye movement and fixation timing, is known as the perceptual span and this extends beyond the visual span to the right (for English readers) of fixation up to 15 characters (McConkie & Rayner, 1976), see (Rayner & Pollatsek, 1989) for review. Visual and perceptual spans decrease in peripheral visual field, even when letter size and contrast are scaled to compensate for acuity changes with eccentricity (Legge, Mansfield, & Chung, 2001) and this could impair letter or word recognition and oculomotor control in reading. Visual spans are typically measured with three letter trigrams, but the contribution of crowding among the trigram letters has not been systematically studied, so it remains unclear whether changes in the visual span with eccentricity can be compensated with appropriately scaled stimuli. Furthermore, even when scaled in size or contrast for visibility, the letters of the trigram are necessarily at differing eccentricities, so it is possible that part of the decline in visual or perceptual span may be attributed to changes in acuity or crowding with eccentricity.

1.4. Fixation stability

For conventional text, reading rate is correlated with fixation stability (Crossland, Culham, & Rubin, 2004; McMahon, Hansen, Stelmack, Oliver, & Viana, 1993; McMahon, Hansen, & Viana, 1991) and decreases for text that is externally destabilised on a computer screen (Parish & Legge, 1989). There is evidence that visual acuity is reduced for characters that are rendered temporally unstable by eye or body vibration (Lange & Coermann, 1962), possibly because of blurring due to temporal integration by the visual system. However, smooth motion does not affect acuity or crowding (Bex, Simmers, & Dakin, 2003) and Vernier (alignment) hyperacuity is unaffected by high levels of positional uncertainty (Badcock & Wong, 1990), suggesting that for some conditions and tasks, the visual system is capable of overcoming dynamic changes in retinal images. Sawtooth image motion that simulates opto-kinetic nystagmus increases crowding (Chung, Legge, & Tjan, 2002) so it is possible that part of the reduction in reading rate associated with fixation instability could be attributed to elevated levels of crowding for unstable letters or words. Parish & Legge (1989) applied equivalent noise analysis (Barlow, 1956) to reading performance as a function of stimulus uncertainty. From their equivalent noise fits, the authors inferred that intrinsic positional noise for reading was on the order of 5 character widths (up to 87 deg^2 for the largest letter size). They identified this noise with saccade length variability and argued that such variability could underlie reduced reading rates in the peripheral visual field and for people with low vision.

The contribution of controlled eye movements to reading has been examined with Rapid Serial Visual Presentation (RSVP) of text, which involves presenting words one at a time at a fixed retinal location and thus abolishes the need for eye movements. RSVP can produce significant increases in rate of reading in normally sighted observers (Rubin & Turano, 1992) suggesting that eye movement planning and execution imposes a load on reading speed. However, while reading rates can significantly increase with RSVP, the improvement is smaller in peripheral than central visual field and low vision observers with central field loss remain worse than age-matched controls at the same retinal location (Rubin & Turano, 1994).

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These lines of evidence converge on at least four interacting factors at the basis of reading difficulty in the peripheral vision of normally sighted observers and for low vision observers with central field loss. In principle it should be possible to scale these parameters to compensate for visual changes across the field, but previous attempts to achieve this have been unsuccessful, possibly because each study has confounded one or more of these parameters. In the present study we used a novel paradigm that controlled each of these parameters separately in an attempt to standardise the visibility of letters, inter-letter crowding and fixation stability. Under these conditions, we aimed to standardize reading performance across the visual field and across observers with differing levels of visual function.

2. Methods

Stimuli were generated on a PC microcomputer running Windows XP and MatLab software with routines supplied with the Psychophysics Toolbox (Brainard, 1997) A GeForce4 MX440 graphics card was used to drive a La Cie Electron 22 Blue 21″ monitor running at 75 Hz and with a mean luminance of 50 cd/m^2. The luminance of the monitor was calibrated with a Minolota CS100 photometer and was used to correct the gamma function of the display. In all tasks, eye movements were monitored with a Cambridge Research Systems Video Eyetracker Toolbox with 1 deg precision at 50 Hz temporal resolution. Gaze position was calibrated before each run with a 12 point target. Direction of gaze was recorded during trials. If the observer's gaze strayed more than 0.5 deg from the fixation point during the stimulus presentation, a warning tone was sounded and the trial was discarded (overall, less than 2% of trials were excluded for failure to fixate).

The three authors and two naïve observers participated (mean age of 34.6, age ranging from 20 to 51 years). All had unaided (4 observers) or corrected (1 observer) visual acuities of 6/6 or better and whose visual acuity, contrast sensitivity, flicker sensitivity, colour vision were normal and that had no known coexisting ocular disease. The eye tracker is monocular and so observers viewed the screen with their dominant eye while wearing a patch over their non-dominant eye. Informed consent was obtained from each observer after the nature and purpose of the experiment had been explained, and the tenets of the Declaration of Helsinki were followed.

2.1. Experiment 1: Visual acuity, the effect of letter size

The acuity target was a tumbling "T" letter composed of a horizontal and vertical bar of equal length that formed a T of upright, right, upside-down or left orientation, at random from trial to trial. The targets were presented for 500 ms with abrupt onset and offset. The observer's task was to fixate a small square at the centre of the screen and to identify the orientation of the target letter by pressing the corresponding arrow key (←↑→↓) on the computer keyboard.

When text is presented in conventional (horizontal) format, letter position within a word (and therefore letter visibility) is confounded with eccentricity—which is known to affect acuity, crowding and visual span. We avoid this confound by presenting target letters, crowded targets and words on an arc of constant retinal eccentricity. We cannot easily destabilise fixation in normally sighted observers to simulate oculomotor deficits in AMD, so instead we introduce positional uncertainty on the stimuli in an attempt to simulate the visual conditions experienced by observers with unstable fixation.

The target was presented on an arc of 4° or 8° eccentricity in the lower visual field. The target's location on the arc was drawn from a normal distribution whose standard deviation was 0° (completely stable target) or from 1° to 64° (circular angle, rather than visual angle, see Fig. 1a) in log spaced steps, which increased positional uncertainty. These standard deviations correspond to arcs whose length (in degrees of visual angle) ranged from 0.07° to 4.5° visual angle at 4° eccentricity and 0.14° to 9° visual angle at 8° eccentricity. The positional uncertainty was normally distributed to simulate the distribution of fixations observed in low vision observers and the range of standard deviations exceeded that observed in this population (Culham, Fitzke, Timberlake, & Marshall, 1993). All levels of positional uncertainty were randomly interleaved on a single run. The position of the target letter was updated every 40 ms (3 video frames), to produce dynamic position shifts at 25 Hz. This temporal frequency was selected to simulate some of the temporal dynamics of fixation previously observed in patients with AMD (Crossland et al., 2004). Crossland and colleagues instructed their patients to maintain steady fixation on a small disk using their PRL. In their study, eye positions were recorded for 10 s at 250 Hz with a SMI eye tracker. The Fourier transform of gaze shift between successive eye position samples showed that eye movement magnitude fell exponentially with eye movement temporal frequency, reaching around 35.6% of the maximum value at 25 Hz and 24% of maximum at 37.5 Hz (the next temporal frequency that could be simulated on a 75 Hz monitor). The photopic critical duration for temporal summation under our conditions asymptotes around 50 ms (Kahneman & Norman, 1964), so we adopted a 25 Hz update rate (40 ms) in order to avoid limiting the visibility of targets with a shorter presentation duration. Positional uncertainty was applied only along the radius of the arc to ensure that targets were always at fixed eccentricity. The eccentricity of the targets would have been confounded if they had been moved horizontally and/or vertically instead of radially along the arc. In pilot sessions with both horizontal and vertical uncertainty, we found that the target frequently appeared near the fovea at high levels of uncertainty and was thus easily identifiable.

The location of the mid point of the unstable target in the lower visual field was chosen at random each trial from a normal distribution with a mean at 270° (directly below fixation) and a standard deviation of 64°

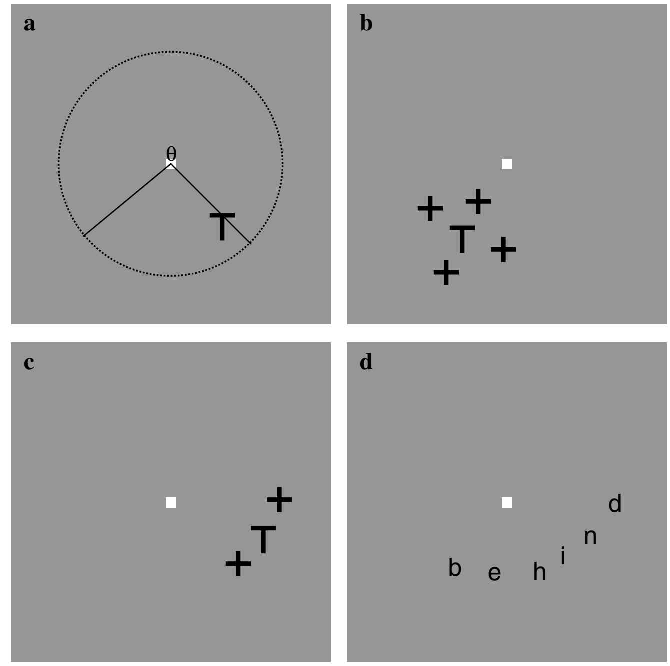

Fig. 1. Illustrations of single frames from our dynamic stimuli. Targets were placed on an invisible arc that was 4° or 8° from a central fixation mark. The position(s) of the target(s) were updated rigidly every 40 ms from a normal distribution, with circular standard deviation (θ) ranging from 0° to 64°. The target was a single oriented letter T in the acuity task (a) that was surrounded by 4 (b) or 2 (c) flanking + elements in the crowding experiments. In the reading task, the letters of each word were in Arial font at a size and spacing determined by the acuity and crowding experiments, and were placed randomly along the arc.

divided by the standard deviation of the trial (or 1° if the positional standard deviation was zero). This ensured that targets across all conditions fell within the same range of positions in the lower visual field. Without this control, targets with low levels of spatial uncertainty would always fall around the same retinal location across trials, while targets with large amounts of uncertainty could occupy positions into nasal and temporal visual field. This could potentially have confounded the results with any acuity or crowding inhomogeneities around the visual field. This control ensured that the range of potential retinal locations was the same for all levels of target uncertainty (e.g., the target with the lowest level of uncertainty was presented—stationary—anywhere on the same arc as the target with the highest level of uncertainty). Illustrations of single frames of the dynamic acuity stimuli are shown in Fig. 1a.

The size of the target was under the control of a staircase (Wetherill & Levitt, 1965), that reduced the size of the target by 1 dB (1/20 log unit or $10^{0.05}$) after 3 correct responses and increased its size by 1 dB following 1 incorrect response and thus concentrated observations at a size producing 79% correct identification of the target orientation. Sub-pixel accuracy was obtained by linear interpolation between pixels. The staircase terminated after 10 reversals or 50 trials, whichever occurred first. The raw data from a minimum of four runs for each condition (at least 180 trials per psychometric function) were combined and fit with a cumulative normal function by least χ^2 fit (in which the data are weighted by the binomial standard deviation, calculated from the observed proportion correct and the number of trials tested at each level). Acuity thresholds were estimated from the 75% correct point of the psychometric function. 95% confidence intervals on this threshold were calculated with a bootstrap procedure, based on 1000 data sets simulated from the number of experimental trials at each level tested (Foster & Bischof, 1991)

2.2. Experiment 2: Crowding, the effect of letter spacing

The crowding target was a tumbling "T" letter as in the acuity experiment. The target was flanked on each side by a "+" symbol composed of a horizontal and vertical line of the same length and width as those forming the target. The size of the target and flanking symbols was fixed at twice threshold acuity size for each eccentricity and level of positional uncertainty, as determined in the acuity experiment. The target and flank symbols were presented for 500 ms with abrupt onset and offset. The target was positioned on an arc of 4° or 8° eccentricity at a position randomly drawn from a normal distribution as in the acuity task. The four flanking + symbols were presented around the target, one on each side – one more foveal, one more peripheral, one clockwise and one anti-clockwise of the target. Illustrations of single frames of the dynamic 4 flank stimuli are shown in Fig. 1b. The locations of all five elements were updated every 40 ms from a random distribution with standard deviation of 0° or from 1° to 64° on log spaced steps, randomly interleaved each run, as in the acuity task. The same spatial uncertainty was applied to all elements, so they moved as a rigid group as would occur with unstable fixation. The distance between the target and flanking symbols was under the control of a staircase (Wetherill & Levitt, 1965), that reduced the centre:centre separation between the target and flanks by 1 dB after 3 correct responses and increased its separation by 1 dB following 1 incorrect response. Threshold crowding spacing and 95% confidence intervals were estimated as for the acuity task.

This experiment measured the spatial extent of crowding with a flank on all four sides of the target. However, letters in RSVP text are flanked on only two sides, horizontally. To estimate the critical letter spacing for RSVP, we repeated the above experiment with only two flankers present, one clockwise and one anti-clockwise of the target, as illustrated in Fig. 1c.

2.3. Experiment 3: Reading

The reading material was presented in RSVP format with Arial sans serif font. The size of each letter was scaled at twice resolution size for each eccentricity and uncertainty level, as determined in the acuity experiment. Twice the threshold acuity size in pixels was multiplied by a factor of 1.8182 to convert to font size in points for a lower case letter. This estimate was obtained empirically by measuring the screen height of a lower case letter 'x' presented at a range of point sizes with the PsychophysicsToolbox 'Drawtext()' function (as used in our experiments). The centre:centre spacing between adjacent letters was fixed at twice the threshold spacing for each eccentricity and uncertainty level measured in the crowding experiment with two flanking elements. This spacing (Chung, 2002) produces near maximal reading rates whilst the stimuli occupy minimal visual space. Although it may have been possible to generate higher reading rates with slightly larger letters, we used this near-optimal size and spacing to avoid ceiling effects. The letters in each word were positioned on an arc of 4° or 8° eccentricity and the mid point of each word was centered at a location randomly drawn from a normal distribution. The locations of all letters were updated every 40 ms from a random distribution with standard deviation of 0° or from 1° to 32° on log spaced steps, randomly interleaved in each run, as in the acuity and crowding tasks. The orientation of all letters was vertical. Positioning the letters on an arc of fixed eccentricity meant that words were curved (see Fig. 1d for illustrations of a typical frame from our dynamic stimuli). We do not think this manipulation affected the results because we show below that reading speeds with such curved text are comparable to reading speeds reported under similar conditions (letters 2 times threshold acuity size and spacing) in other studies using horizontal text and observers subjectively reported that the task was no more difficult than reading conventional text. The over-riding advantage of this mode of text presentation is that it ensured that all the letters in all the words were equally scaled for resolution size, crowding and eccentricity, while our manipulation of positional uncertainty simulated unstable fixation with controlled eccentricity.

The source text was randomly selected from the children's novels *Peter Pan* and *The Adventures of Huckleberry Finn*. The materials were downloaded from www.gutenberg.org. This material was selected because it contained standard semantic structure of real reading material (as opposed to random word strings that subjects cannot read fluently) with relatively simple content. The distribution of word lengths in each novel is shown in Fig. 2.

For each trial, one story was chosen at random and ten sequential whole words were imported from a random starting point. The observer's task was to fixate the central cross and to read the text silently. Fixation was monitored with the eye tracker, but we did not reject trials as in the acuity and crowding task. Subjects found it stressful to maintain steady fixation for several seconds and frustrating that trials were excluded for a brief lapse. We therefore provided online visual feedback by the polarity of fixation point; white for good fixation, black for strayed fixation. At the end of the text presentation, the screen was blanked, when the observer was ready (s)he pressed a button that presented the ten words at the fovea. The observer compared the actual words presented with those they read successfully and then self-reported with a button press how many words (0–10) had been identified correctly. Although this test procedure required the observer to assess their own performance, if was preferred over alternative techniques. For example, the method of adjustment (in which observers manually adjust the rate of text presentation to a satisfactory level) is quick, but qualitative. It does not require observers to verify what they thought they saw with what was actually presented and it does not generate a quantitative psychometric function. Alternatively, comprehension tests do not require observers to read every word and depend on memory. Our self-scoring method was much faster than assessment by examiner and allowed us to collect more data in a given time. The method was validated in pilot sessions by having the observer recite the ten words aloud to an independent examiner who judged how many were read correctly. Naïve observers were required to read aloud to the examiner in training sessions and at random monitoring points during formal data collection. There was no difference in performance between the self-reporting and random-monitoring method for any of the observers.

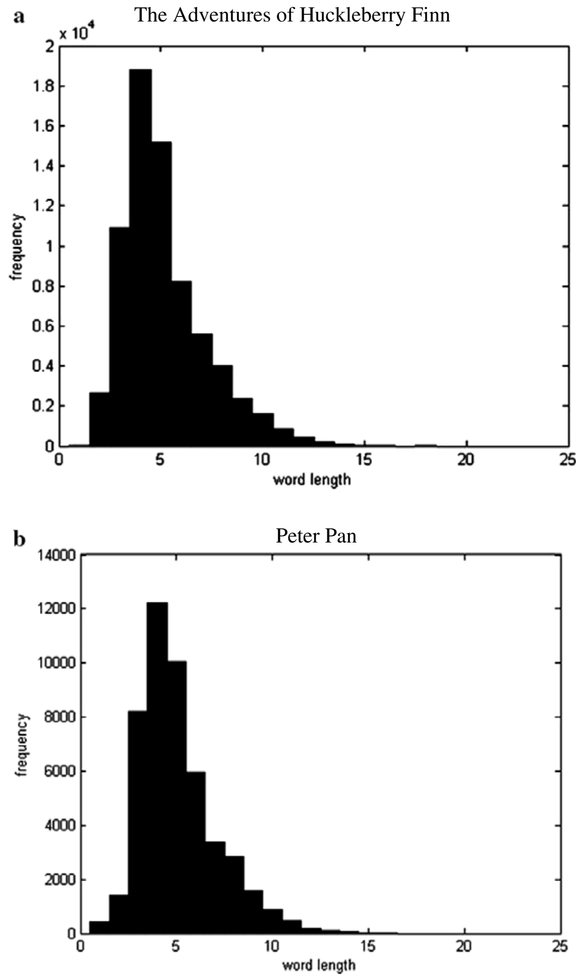

Fig. 2. Distributions of word lengths in the texts from which 10 sequential words were drawn from a random starting point on each trial.

The duration of the text sequence was under the control of a staircase that reduced the duration of each word by 1/3 dB if 8 words or more were correct and increased the duration by 1 dB if fewer than 8 words were identified. Data from a minimum of four runs of 50 trials were combined and fit with a cumulative normal function from which threshold word duration was estimated at the 75% correct point and 95% confidence intervals were estimated as in the acuity and the crowding tasks.

3. Results

3.1. Experiment 1: Visual acuity, the effect of letter size

Fig. 3 shows threshold acuity size as a function of eccentricity and positional uncertainty for five observers as indicated in the legend at 4° (open symbols) and 8° (filled symbols) eccentricity. The results show a decline in acuity with eccentricity (paired t-test: $df = 21$, $t = -15.4$, $p < 0.001$), in good agreement with many previous studies (Chung & Bedell, 1995; Chung et al., 1998; Melmoth et al., 2000; Millodot, 1966). There was no systematic effect of positional uncertainty at either eccentricity. The lines show linear regression fits to the mean data across observers, normalized to the highest acuity for each observer, to correct for their differing acuities (for clarity, the data are presented on log x axis, which is why the linear regression lines appear slightly curved). The slopes (-0.0002 [$\sigma = 0.0008$, $t = 0.62$] and -0.0004 [$\sigma = 0.0002$, $t = 0.73$] for 4° and 8°, respectively) were not significantly different from zero ($p > 0.05$ in both cases). As there was no effect of positional uncertainty at either eccentricity, the authors collected full data sets and the naïve observers collected only key points. These acuity data for each observer were used to scale the size of targets in the crowding and reading tasks.

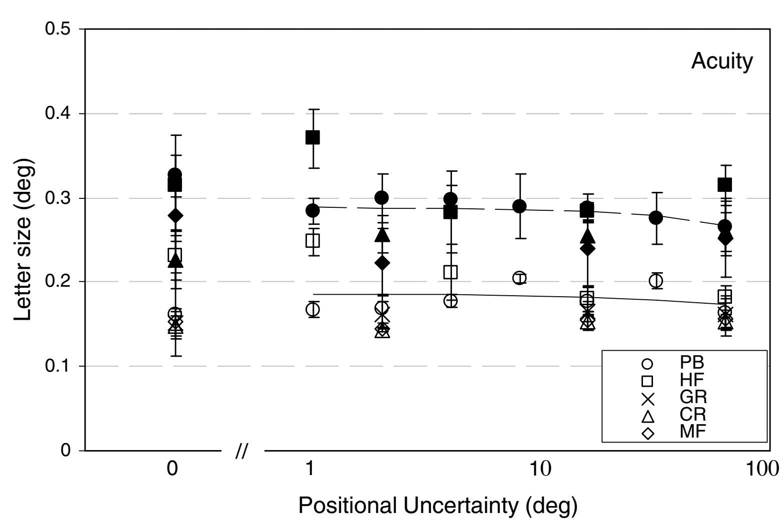

Fig. 3. Acuity as a function of eccentricity and positional instability, for five observers and two eccentricities (4°, open symbols, cross and solid curve, or 8°, filled symbols and dashed curve). The x axis shows the standard deviation in degrees (θ) of the normal distribution from which the target position was sampled at random every 40 ms (see Fig. 1). The y axis shows the size (in degrees of visual angle) of the target T at which its orientation was correctly identified on 75% trials. Error bars show ±95% confidence intervals. Curves show linear regression fits to the mean data across observers at each level of positional instability.

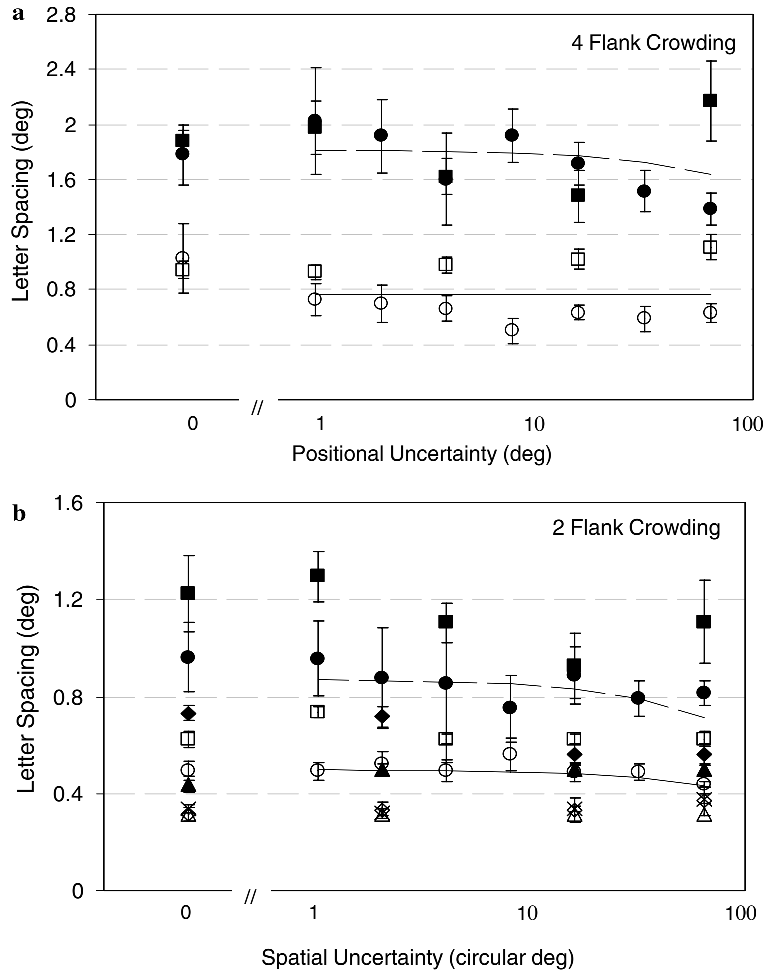

Fig. 4. (a) Crowding by four flanks as a function of eccentricity and positional instability, for 2 observers (PB and HF, symbols as in Fig. 3). The size of the target letter T and flanking + symbols were twice the threshold size measured in the acuity task. (b) Crowding by 2 flanks (one clockwise one anticlockwise of the target) as a function of eccentricity and positional instability, for 5 observers (symbols as in Fig. 3). The x axis shows the standard deviation in degrees (θ) of the normal distribution from which the target position was sampled at random every 40 ms. The y axis shows the separation (in degrees of visual angle) between the target T and each of four flanking + symbols at which the target orientation was correctly identified on 75% trials. Error bars show ±95% confidence intervals. Curves show linear regression fits to the mean data across observers at each level of positional instability.

3.2. Experiment 2: Crowding, the effect of letter spacing

Fig. 4 shows the spatial extent of crowding as a function of eccentricity and positional uncertainty for up to five observers at 4° (open symbols) and 8° (filled symbols) eccentricity. Fig. 4a shows data from the condition with four flanking elements for two observers, Fig. 4b shows analogous data for five observers from the condition with two flanking elements. The results show an increase in the spatial extent of crowding with eccentricity (paired t-test: $df = 12$, $t = -13$, $p < 0.001$; paired t-test: $df = 21$, $t = 11.5$, $p < 0.001$ for 4 and 2 flankers, respectively) and with the number of flanking elements (paired t-test: $df = 12$, $t = 5.5$, $p < 0.001$; paired t-test: $df = 12$, $t = 13.3$, $p < 0.001$ for 4° and 8°, respectively). Both these observations are in good agreement with many previous studies (Bex et al., 2003; Bouma, 1970; Chung et al., 1998; Toet & Levi, 1992). As in the acuity task, there was no systematic effect of positional uncertainty on crowding for any number of flanking elements. The lines show linear regression fits to the mean data across observers, normalized to the largest crowding area for each observer, to correct for inter-subject differences. The slopes for the 4 flank condition (−0.00 [$\sigma = 0.0024$, $t = 0.04$] and −0.0014 [$\sigma = 0.0014$, $t = 1.06$] for 4° and 8°, respectively) and the 2 flank condition (0.0001, [$\sigma = 0.0007$, $t = 0.15$]; and −0.0014 [$\sigma = 0.0012$, $t = 1.17$]), were not significantly different from zero ($p > 0.05$ in all cases). The data from the two flank condition were used to scale the inter-letter spacing in the reading task. The size of the letters in the reading task was scaled at twice threshold acuity size, as in the crowding task.

3.3. Experiment 3: Reading

Fig. 5 shows the reading speed as a function of eccentricity and spatial uncertainty for five observers at 4° (upper panel) and 8° (lower panel) eccentricity. Reading speed is

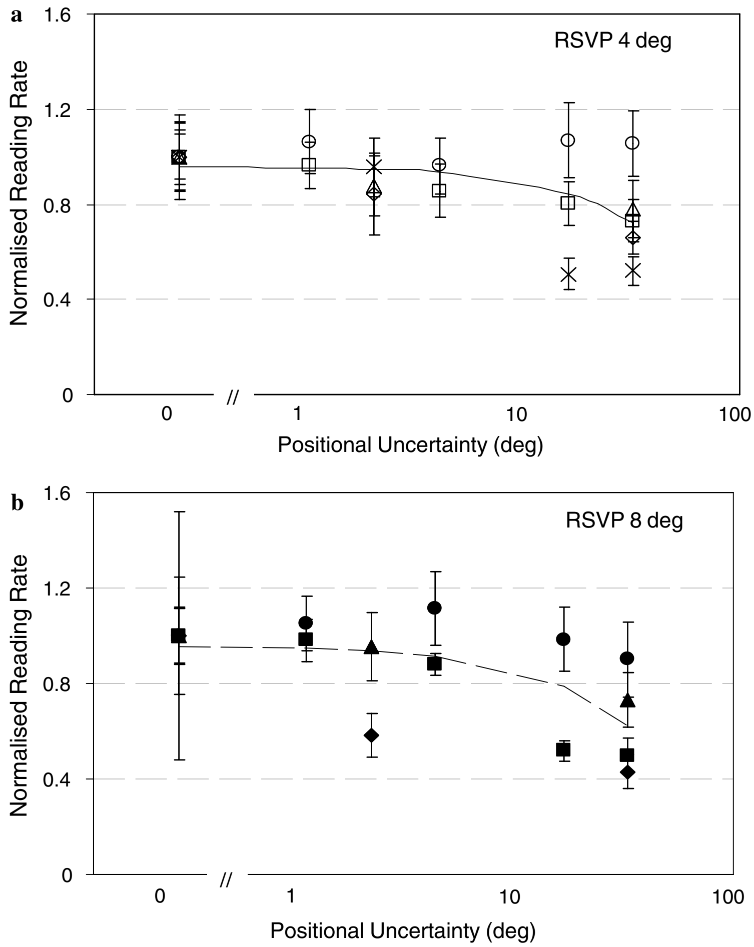

Fig. 5. Reading rate as a function of eccentricity (4°, Fig 4a; and 8°, Fig 4b) and positional instability, for five observers (symbols as in Fig. 3) normalised to their rate for reading stationary text. The x axis shows the standard deviation in circular degrees (θ) of the normal distribution from which the target position was sampled at random every 40 ms. The y axis shows the relative number of words that could be read in one minute with 75% correct identification. Error bars show ±95% confidence intervals. Baseline reading speeds for stationary text in words per minute at 4° were: PB = 167, HF = 294, GR = 209, CR = 166, MF = 167; and at 8° were: PB = 115, HF = 219, CR = 76, MF = 62. Curves show linear regression fits to the mean data across observers at each level of positional instability.

defined as the rate of presentation of ten sequential words (in number of words per minute for continuous presentation) producing correct identification of 75% words. Owing to large differences in baseline reading speeds across observers, the data shown for each subject have been normalized to their rate for stationary text for clarity (absolute reading rates in words per minute are shown in the figure legend). The results show a decrease in reading speed with eccentricity, in good agreement with many previous studies. Unlike the acuity and crowding tasks, there was a significant reduction in reading speed as spatial uncertainty increased that was greater at 8° (36%, mean across observers) than at 4° (25%) eccentricity. The curves show linear regression fits to the mean data across observers, normalized to their rate for stationary text. The slopes showed a significant decrease in reading rate with spatial uncertainty at both eccentricities (-0.00754 [$\sigma = 0.0019$, $t = 3.91$, $p < 0.01$] and -0.01053 [$\sigma = 0.0037$, $t = 2.82$, $p < 0.025$] for 4° and 8°, respectively). Note that this decrease in reading speed occurred even though the size and spacing of the letters was scaled so that they were equally visible at all eccentricities and uncertainty levels. The rates of reading under our conditions are slower than the maxima reported in previous studies. For example Latham & Whitaker (1996), reported RSVP reading speeds between 250 to 300 wpm, even at 10 deg eccentricity for 5 word sentences; and Chung et al. (1998) reported RSVP reading speed reaching 300–400 wpm at 5 deg eccentricity, and 250–300 wpm at 10 deg eccentricity for sentences between 8 and 14 words long. Both groups reported reading speeds that were slower for smaller sub-optimal letter sizes, like those used in this study.

4. Discussion

The results confirm many previous studies which have shown that acuity decreases (Millodot, 1966) crowding increases (Bouma, 1970) and reading rate decreases (Chung et al., 1998; Latham & Whitaker, 1996) in the peripheral visual field. In the present study, we show that crowding and reading rates are worse even with stimuli that have been carefully scaled in size, inter-letter spacing and for eccentric placement to equate the visibility of all component letters across the visual field. These data indicate that it may not be possible to standardize reading rates across the visual field by compensating for reduced acuity, elevated crowding and eccentric position to equate the visibility of letters within words. The use of RSVP here and elsewhere (Rubin & Turano, 1992, 1994) obviates the need for controlled eye movements so oculomotor control problems alone do not account for the reduction in reading rate in the periphery either.

4.1. Perceptual and visual span

Although we have not directly measured perceptual or visual span, it remains a possibility that reading rates in the peripheral visual field reflect a reduced perceptual or visual span. Nevertheless, our reading experiment contains data that bear directly on visual span. Here we used RSVP presentation, so the role of *perceptual* span on eye movement control is not relevant. However, let us assume that visual span (the number of letters that can be identified in a single fixation) is a critical factor in reading and set aside other determinants such as context (Goodman, 1967; Reicher, 1969) and word shape cues (Cattell, 1886; Smith, 1969). In our study, observers were required to fixate the central cross and were therefore unable to make saccadic eye movements within the words. Therefore, under these conditions, visual span and word recognition are effectively equivalent and both can be measured by the maximum word length that can be identified in a given interval, or analogously the time required to identify a word of a given length. We found that in all cases observers were able to read all 10 words if the presentation duration was sufficiently long (psychometric function fits to the number of words read as a function of word presentation duration always reached 100% correct at the longest exposure durations tested by the staircase). Therefore, when the exposure duration is long enough, observers are able to read words of any reasonable length (Fig. 2 shows the distribution of word lengths in the reading material) under our conditions of corrected size, crowding and eccentricity. It is therefore possible that reading speed (at least under our conditions) and visual span measure the same quantity—and both show that there is a trade-off between the number of features (single letters or groups of letters) that can be identified in a given temporal interval (Legge, Ahn, Klitz, & Luebker, 1997).

Our data and others measuring visual span directly (Legge et al., 1997) show that visibility-corrected targets eventually become visible, given sufficient time. This is distinct from acuity, which shows a small increase (from around 0.9 to 0.6 minimum angle of resolution) with exposure duration and reaches asymptote at 400 ms (Baron & Westheimer, 1973; Ng & Westheimer, 2002), and crowding, which shows little or no change with exposure duration (Ng & Westheimer, 2002). We therefore speculate that the additional time required to read with eccentric visual field may be used to move attention serially between letters or word fragments in series for word identification (regardless of whether letter-by-letter or word shape cues—probably both—are used). If visual span decreases in the peripheral visual field, it may be that the additional time is required to shift this reduced visual span over the target word. Both these ideas suggest that it may be the redeployment of visual attention from one peripheral location to another that requires additional time with increasing eccentricity. We are currently examining attention processing in the peripheral visual field to analyze this hypothesis.

4.2. Temporal instability

We examined the effect of target instability on acuity, crowding and reading because fixation is more unstable in low vision observers than normally sighted observers (Crossland et al., 2004; Culham et al., 1993; Rohrschneider, Becker, Kruse, Fendrich, & Volcker, 1995; Schuchard & Fletcher, 1994). A previous study (Culham et al., 1993) showed that reading rate decreases with the degree of positional uncertainty applied to text presented in page mode rather than in RSVP mode, so it is possible that unstable fixation might account for the reduced reading rates in people with low vision. We introduced normally distributed positional uncertainty to our targets to simulate unstable fixation of low vision, while correcting for acuity, crowding and eccentricity effects. The results show that there was little or no effect of positional uncertainty on acuity or crowding even at the highest levels of positional instability. This resistance to temporal modulation is consistent with the resistance to positional noise in hyperacuity (Badcock & Wong, 1990) and in acuity and crowding studies that have used eccentricity-corrected targets (Bex et al., 2003), but not other studies in which eccentricity changes with uncertainty were not controlled (Chung et al., 2002; Parish & Legge, 1989).

For all observers (except PB at 4°), reading rate decreased with positional uncertainty even though the target size, spacing and eccentricity were fixed to equate the visibility of the letters. This result, along with evidence for contextual (Goodman, 1967; Reicher, 1969) and word shape (Cattell, 1886; Smith, 1969) effects, challenges bottom-up models of word recognition that are based on serial letter recognition (Gough, 1972; Pelli, Farell, & Moore, 2003). These results suggest that ocular instability may account for at least part of the enduring reduction in reading speed in low vision observers compared with age-matched control observers at the same eccentricities. Under conditions of unstable fixation, observers with central scotomas suffer a further disadvantage compared with control observers. Unstable fixation constantly changes the retinal locus of visual targets. Dynamic targets that by chance move to a more eccentric location necessarily become less visible (owing

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to reduced resolution and elevated crowding) for all observers. For observers with AMD, unlike normally sighted observers, targets that by chance move closer to fovea also become less visible because they enter the central scotoma. The frequency of these events increases with the magnitude of spatial uncertainty or fixation instability. Observers with central field loss tend to adopt a reading PRL that is close to the scotoma boundary (Schuchard & Fletcher, 1994; Timberlake et al., 1986; Timberlake et al., 2005), probably to exploit the highest residual resolution. Assuming that fixation stability is normally distributed, unstable fixation tends to move the target towards the fovea (and into the scotoma) half the time or to increase the overall eccentricity of the target letter on the other half. Both these events reduce target visibility. Although the fixation stability might not be normally distributed at the PRL (Timberlake et al., 2005), the fixation instability will undoubtedly move targets closer and further away from the fovea, which will reduce target visibility in the same way. This reduced visibility could directly account for the reduced reading rates in low vision observers compared to normally sighted control subjects at the same retinal eccentricities. Taken together the results from low vision observers and our results in normally sighted observers suggest that fixation instability could contribute to reduced reading rates. Collectively, these results suggest that visual rehabilitation efforts should be directed towards improving steady fixation. It would be interesting to know if improvements in reading rates gained following fixation training (Nilsson et al., 1998) are correlated with fixation stability.

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References

Arditi, A., Knoblauch, K., & Grunwald, I. (1990). Reading with fixed and variable character pitch. *Journal of the Optical Society of America A, 7*(10), 2011–2015.

Badcock, D. R., & Wong, T. L. (1990). Resistance to positional noise in human vision. *Nature, 343*, 554–555.

Barlow, H. B. (1956). Retinal noise and absolute threshold. *Journal of the Optical Society of America A, 46*, 634–639.

Baron, W. S., & Westheimer, G. (1973). Visual acuity as a function of exposure duration. *Journal of the Optical Society of America, 63*, 212–219.

Bex, P. J., Simmers, A. J., & Dakin, S. C. (2003). The shape and size of crowding for moving targets. *Vision Research, 43*(27), 2895–2904.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177–178.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Cattell, J. (1886). The time taken up by cerebral operations. *Mind, 11*(277–282), 524–538.

Chung, S. T. (2002). The effect of letter spacing on reading speed in central and peripheral vision. *Investigative Ophthalmology & Vision Sciences, 43*(4), 1270–1276.

Chung, S. T. (2004). Reading speed benefits from increased vertical word spacing in normal peripheral vision. *Optometry and Vision Science, 81*(7), 525–535.

Chung, S. T. (2005). Two approaches to reduce crowding do not lead to improved reading speed in patients with age-related macular degeneration http://www.rnib.org.uk/xpedio/groups/public/documents/PublicWebsite/public_v2005abstractsweds.hcsp#P506_109130.

Chung, S. T. L., & Bedell, H. E. (1995). Effect of retinal image motion on visual-acuity and contour interaction in congenital nystagmus. *Vision Research, 35*(21), 3071–3082.

Chung, S. T., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency characteristics of letter identification in central and peripheral vision. *Vision Research, 42*(18), 2137–2152.

Chung, S. T. L., Mansfield, J. S., & Legge, G. E. (1998). Psychophysics of reading. XVIII. The effect of print size on reading speed in normal peripheral vision. *Vision Research, 38*(19), 2949–2962.

Crossland, M. D., Culham, L. E., & Rubin, G. S. (2004). Fixation stability and reading speed in patients with newly developed macular disease. *Ophthalmic and Physiological Optics, 24*(4), 327–333.

Culham, L. E., Fitzke, F. W., Timberlake, G. T., & Marshall, J. (1993). Assessment of fixation stability in normal subjects and patients using a scanning laser ophthalmoscope. *Clinical Vision Sciences, 8*(6), 551–561.

Flom, M. C., Weymouth, F. W., & Kahneman, D. (1963). Visual resolution and spatial interaction. *Journal of the Optical Society of America, 53*, 1026–1032.

Foster, D. H., & Bischof, W. F. (1991). Thresholds from psychometric functions: Superiority of bootstrap to incremental and probit variance estimators. *Psychological Bulletin, 109*, 152–159.

Goodman, K. (1967). Reading: a psycholinguistic guess game. *Journal of the Reading Specialist*, 126–135.

Gough, P. B. (1972). One second of reading. In Mattingly Kavanagh (Ed.), *Language by ear and by eye*. Cambridge, MA: MIT Pres.

Hess, R. F., Dakin, S. C., & Kapoor, N. (2000). The foveal 'crowding' effect: physics or physiology? *Vision Research, 40*(4), 365–370.

Johnston, A. (1987). Spatial scaling of central and peripheral contrast-sensitivity functions. *Journal of the Optical Society of America A, 4*, 1583–1593.

Kahneman, D., & Norman, J. (1964). The time-intensity relation in visual perception as a function of observer's task. *Journal of Experimental Psychology, 68*, 215–220.

Lange, K., & Coermann, R. (1962). Visual acuity under vibration. *Human Factors, 4*, 291–300.

Latham, K., & Whitaker, D. (1996). A comparison of word recognition and reading performance in foveal and peripheral vision. *Vision Research, 36*(17), 2665–2674.

Legge, . E., Ahn, S. J., Klitz, T. S., & Luebker, A. (1997). Psychophysics of reading-XVI. The visual span in normal and low vision. *Vision Research, 37*(14), 1999–2010.

Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research, 41*(6), 725–743.

Legge, G. E., Rubin, G. S., Pelli, D. G., & Schleske, M. M. (1985). Psychophysics of reading-II. Low vision. *Vision Research, 25*(2), 253–265.

Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Research, 25*, 963–977.

Liu, L., & Arditi, A. (2000). Apparent string shortening concomitant with letter crowding. *Vision Research, 40*(9), 1059–1067.

McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society, 8*, 365–368.

McMahon, T. T., Hansen, M., Stelmack, J., Oliver, P., & Viana, M. A. (1993). Saccadic eye movements as a measure of the effect of low vision rehabilitation on reading rate. *Optometry and Vision Science, 70*(6), 506–510.

McMahon, T. T., Hansen, M., & Viana, M. (1991). Fixation characteristics in macular disease. Relationship between saccadic frequency, sequencing, and reading rate. *Investigative Ophthalmology & Vision Sciences, 32*(3), 567–574.

Melmoth, D. R., Kukkonen, H. T., Makela, P. K., & Rovamo, J. M. (2000). The effect of contrast and size scaling on face perception in foveal and extrafoveal vision. *Investigative Ophthalmology & Visual Science, 41*(9), 2811–2819.

Melmoth, D. R., & Rovamo, J. M. (2003). Scaling of letter size and contrast equalises perception across eccentricities and set sizes. *Vision Research, 43*(7), 769–777.

Millodot, M. (1966). Foveal and extra-foveal acuity with and without stabilized retinal images. *British Journal of Physiological Optics, 23*, 75–106.

Ng, J., & Westheimer, G. (2002). Time course of masking in spatial resolution tasks. *Optometry and Vision Science, 79*(2), 98–102.

Nilsson, U. L., Frennesson, C., & Nilsson, E. G. (1998). Location and stability of a newly established eccentric retinal locus suitable for reading, achieved through training of patients with a dense central scotoma. *Optometry and Vision Science, 75*(12), 873–878.

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their roles in visual cognitive processes* (pp. 395–453). New York: Elsevier.

Parish, D. H., & Legge, G. E. (1989). Psychophysics of reading. IX. The stability of eye position in normal and low vision. Unpublished Manuscript http://vision.psych.umn.edu/~legge/read9.pdf.

Pelli, D. G., Farell, B., & Moore, D. C. (2003). The remarkable inefficiency of word recognition. *Nature, 423*, 752–756.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading*. Englewood Cliffs NJ: Prentice-Hall.

Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology, 81*, 275–280.

Rohrschneider, K., Becker, M., Kruse, F. E., Fendrich, T., & Volcker, H. E. (1995). Stability of fixation: results of fundus-controlled examination using the scanning laser ophthalmoscope. *German Journal of Ophthalmology, 4*(4), 197–202.

Rubin, G. S., & Turano, K. (1992). Reading without saccadic eye-movements. *Vision Research, 32*(5), 895–902.

Rubin, G. S., & Turano, K. (1994). Low-vision reading with sequential word presentation. *Vision Research, 34*(13), 1723–1733.

Schuchard, R. A., & Fletcher, D. C. (1994). Preferred retinal locus—a review with applications in low vision rehabilitation. *Ophthalmological Clinics of North America*, 243–256.

Smith, F. (1969). Familiarity of configuration vs. discriminability of features in the visual identification of words. *Psychonomic Science, 14*, 261–262.

Timberlake, G. T., Mainster, M. A., Peli, E., Augliere, R. A., Essock, E. A., & Arend, L. E. (1986). Reading with a macular scotoma.I. Retinal location of scotoma and fixation area. *Investigative Ophthalmology & Vision Sciences, 27*(7), 1137–1147.

Timberlake, G. T., Sharma, M. K., Grose, S. A., Gobert, D. V., Gauch, J. M., & Maino, J. H. (2005). Retinal location of the preferred retinal locus relative to the fovea in scanning laser ophthalmoscope images. *Optometry and Vision Science, 82*(3), 177–185.

Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32*(7), 1349–1357.

Townsend, J. T., Taylor, S. G., & Brown, D. R. (1971). Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics, 10*, 375–378.

Watson, A. B. (1987). Estimation of local spatial scale. *Journal of the Optical Society of America A, 4*(8), 1579–1582.

Wetherill, G. B., & Levitt, H. (1965). Sequential estimation of points on a psychometric function. *British Journal of Mathematical and Statistical Psychology, 18*, 1–10.

Whitaker, D., Makela, P., Rovamo, J., & Latham, K. (1992). The influence of eccentricity on position and movement acuities as revealed by spatial scaling. *Vision Research, 32*(10), 1913–1930.

Whittaker, S. G., & Lovie-Kitchin, J. (1993). Visual requirements for reading. *Optometry and Vision Science, 70*(1), 54–65.