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Page mode reading with simulated scotomas: A modest effect of interline spacing on reading speed

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Abstract

Crowding is thought to be one potent limiting factor of reading in peripheral vision. While several studies investigated how crowding between horizontally adjacent letters or words can influence eccentric reading, little attention has been paid to the influence of vertically adjacent lines of text. The goal of this study was to examine the dependence of page mode reading performance (speed and accuracy) on interline spacing. A gaze-contingent visual display was used to simulate a visual central scotoma while normally sighted observers read meaningful French sentences following MNREAD principles. The sensitivity of this new material to low-level factors was confirmed by showing strong effects of perceptual learning, print size and scotoma size on reading performance. In contrast, reading speed was only slightly modulated by interline spacing even for the largest range tested: a 26% gain for a 178% increase in spacing. This modest effect sharply contrasts with the dramatic influence of vertical word spacing found in a recent RSVP study. This discrepancy suggests either that vertical crowding is minimized when reading meaningful sentences, or that the interaction between crowding and other factors such as attention and/or visuo-motor control is dependent on the paradigm used to assess reading speed (page vs. RSVP mode).

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1. Introduction

Observers with age-related macular disease (AMD) have a scotoma in their central visual field, forcing them to use spared peripheral retinal regions to see. One recurrent complaint in this disease is that text reading is either impossible or very slow (Rubin, 2001). Therefore, an accurate knowledge of the factors which improve these patients' reading speed is important in order to display texts with the most optimal visual format. It is established for instance that reading speed greatly benefits from increased contrast and character size (Legge, Rubin, & Luebker, 1987; Legge, Rubin, Pelli, & Schleske, 1985). These visual factors are helpful as they compensate for the reduced acuity associated with higher eccentricities. However, evidence that maximum reading speed obtained after text magnification in the periphery is always lower than in the fovea suggests that reduced acuity is not the only limiting factor (Chung, Mansfield, & Legge, 1998).

Another visual factor which could have adverse effects on peripheral reading is crowding (also known as lateral masking): in this well-known phenomenon, visual acuity for a single letter is degraded when it is flanked by adjacent letters (Bouma, 1970). As reviewed recently (Pelli, Palomares, & Majaj, 2004), the spatial extent of crowding is proportional to eccentricity (Bouma, 1970; Latham & Whitaker, 1996; Levi, Hariharan, & Klein, 2002; Strasburger, Harvey, & Rentschler, 1991; Toet & Levi, 1992). Therefore, there are more and more potential stimuli which can induce lateral masking by entering the crowding zone as one is forced to read with higher eccentricities. For this kind of reason, crowding is often thought to be partly responsible for the poor reading performance of low vision patients

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with macular scotomas (Fine, 2001). However, from the few studies which have tested this hypothesis, evidence that minimizing crowding is able to improve reading rate is mixed. On the one hand, using the classical RSVP paradigm (Rubin & Turano, 1992), no improvements have been obtained by increasing the spacing (beyond the standard spacing) between letters within words (Chung, 2002). On the other hand, still using RSVP stimuli, it was shown that increasing the vertical distance between words did improve reading (Chung, 2004): normal observers read aloud sequences of six semantically unrelated short words (4 or 5 letters) presented one at a time on a monitor (earlier work with normally sighted observers had shown a moderate effect of interline spacing on reading speed (Bentley, 1921; Paterson & Tinker, 1932; Van Overschelde & Healy, 2005; Vanderplas & Vanderplas, 1980)). These RSVP target words were either vertically flanked by other words or unflanked. The results showed that reading speed in the periphery dramatically increased with vertical spacing and was always slower than reading speed measured with unflanked words. While this work was taken as evidence that decreasing vertical crowding allows a faster reading rate for normally sighted observers, an opposite conclusion was reached in a study reported in abstract form by the same group: AMD patients who read passages (100 words) of continuous text rendered at five interline spacings read at the same rate whatever the interline spacing (Jarvis, Chung, Woo, Hanson, & Jose, 2003). There are several reasons which could explain this discrepancy. First, the characteristics of the text (word length, semantic relationships between words,...) used in the RSVP experiment (Chung, 2004) are very different from those used in the clinical study (Jarvis et al., 2003). Second, it is possible that vertical crowding may have different properties in normally sighted observers and in AMD observers. Third, visual, visuomotor and attentional processes involved in the RSVP paradigm might not be the same as those used in reading with eye movements (i.e. page mode reading).

In order to clarify these issues, we have investigated reading performance with an artificial scotoma paradigm (Fine & Rubin, 1999a, 1999b, 1999c; Wensveen, Bedell, & Loshin, 1995). A gaze-contingent display was used to create an artificial scotoma at the gaze location while normally sighted observers read continuous text on a monitor: one meaningful sentence, made up of 3 or 4 lines, was displayed on each trial. The choice of each French sentence was constrained by principles similar to those used in the MNREAD acuity charts (Ahn, Legge, & Luebker, 1995; Legge, Ross, Luebker, & LaMay, 1989). These charts are commonly used both in clinical exams and in psychophysical experiments to characterize reading performance of each observer. Each chart contains one single sentence presented on three justified lines. In a clinical exam, print size is decreased from one chart to the other until observers are unable to read. For each sentence, reading speed is measured so that, eventually, a curve can be fitted to the data. The usual aspect of this curve is an increase of reading speed with print size up to a certain size (called Critical Print Size—CPS) where reading speed saturates. The maximum reading speed ($R_{\max}$) and the CPS are taken as the two major parameters summarizing each observer's reading performance. The design of each sentence is constrained by several strict criteria (e.g. high-frequency of the words, simple syntax). The general goal is to reduce the potential influence of high-level factors, such as syntactic complexity, which would make some sentences much more difficult to read than others. Thus, one major advantage of MNREAD sentences, when measuring reading speed, is their great sensitivity to low-level visual factors, a crucial asset in order to optimize the ability to detect subtle effects relying on early visual processes. In order to test the validity of our paradigm, especially the low-level sensitivity of the newly designed MNREAD-like French sentences, our first goal was to replicate some key signatures observed either in RSVP studies or in the clinical literature for patients with macular scotomas: the decrease of reading speed with smaller print sizes (Legge et al., 1985; Mansfield, Legge, & Bane, 1996) and with larger scotomas (Cummings, Whittaker, Watson, & Budd, 1985; Ergun et al., 2003; Sunness, Applegate, Haselwood, & Rubin, 1996). With the same purpose, we also assessed learning processes as they evolved over the course of the first 8 h necessary to perform experiments 1 and 2 (Chung, Legge, & Cheung, 2004; Fornos, Sommerhalder, Rappaz, Pelizzone, & Safran, 2006; Sommerhalder et al., 2003, 2004).

Our second goal was to investigate the effect of interline spacing on reading performance both in terms of speed and accuracy. Interline spacing was defined as the ratio of vertical between line distance to print size (x-height). We studied values of interline spacing either above or below the standard spacing ($1X$). A value smaller than the standard spacing is interesting for two main reasons. The first practical reason is that it allows us to increase the range of interline spacings tested. With our paradigm, the highest interline spacing possible was twice the standard ($2X$) provided that print size was not larger than 1.3°. The second reason is that interline spacings smaller than the standard are commonly used in newspapers (often around 0.85 the standard spacing). Unfortunately, these small spacings were not studied in the eccentric reading experiments of Chung's (2004) work. Many AMD patients wish to read newspapers and they usually use magnifiers which keep interline spacing constant (since interline spacing is defined relative to print size). From the perspective of developing reading aids based on image processing (which could for instance be included within CCTV aids), it seemed important to us to investigate whether increasing interline spacing in addition to print size would benefit these newspapers readers.

To achieve the two previously defined goals, and taking into account the size constraints imposed by our paradigm, the following compromise was chosen to organize the sequence of experiments. In experiments 1 and 2 (scotoma size: 6° and 10°, respectively), the largest print size was set to 2° because pilot studies indicated that smaller values did not allow the curve of reading speed vs. print size to saturate for many observers. This saturation was necessary in order to calculate a Critical Print Size (CPS) for each observer. These individual CPS values (actually $0.8 * \text{CPS}$) were then used in experiment 3 as they were small enough to study with our paradigm the largest interline spacing (namely $2X$) tested in Chung's (2004) RSVP study.

2. General methods

2.1. Subjects

Two of the authors and 5 naïve observers participated in the experiments (age ranging from 23 to 43 years). The naïve observers had never been subjects in experiments using artificial scotomas. All had normal or corrected-to-normal vision. 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.

2.2. Apparatus

Stimuli were displayed on a 21-in. CRT color monitor (GDM-F520, Sony, Japan) driven by a PC computer running custom software developed in C with the libraries provided with the eyetracker (GDI library was used for graphics). The monitor refresh rate was 100 Hz (frame duration: 10 ms).

Observers sat in a reclining chair with their eyes at a distance of 40 cm from the monitor. Their neck was comfortably maintained by a custom-built foam restraint fixed on the chair to minimize head movements. This restraint was adjusted so that it was not in contact with any part of the eyetracker. We did not use a standard chin-rest because it would have induced head jitter when observers read aloud. Observers viewed the screen with their dominant eye while wearing a patch over the contralateral eye. The room was dimly lit.

At the viewing distance of 40 cm, the average separation between adjacent pixels subtended 0.04° of visual angle (display area: $51.2° \times 38.4°$, 1152×864 pixels). With the smallest print size—0.26°—(see definition below) used in pilot studies, this spatial resolution produced 5 pixels in the vertical dimension for a lowercase 'x'. This was therefore just above the critical sampling density found in Legge et al. (1985).

2.2.1. Sentences

On each trial, a sentence in black characters was drawn on a white background set to maximum available luminance (100 cd/m^2). The characteristics of the sentences were constrained by principles similar to those used in the MNREAD acuity charts (Ahn et al., 1995; Legge et al., 1989). Sentences were extracted from French novels obtained from Project Gutenberg (www.gutenberg.org). They were all from the same author (A. Dumas) in an attempt to produce a homogeneous style. None of the observers had read a novel by this author since childhood. We assumed that text from such an author had a difficulty level well below the education level of our observers who were all at least of graduate level. The sentences were selected to have lengths, including spaces and commas, between 40 and 60 characters, and to only contain words from the 20000 most frequent words in written French, according to a word-frequency table derived from the Lexique 3 database (http://www.lexique.org). Only sentences were used that contained no punctuation other than a period or commas. Accents and apostrophes, which are very common in French, were accepted characters. The period at the end of each sentence was not displayed. With these constraints, a total of 2261 sentences were generated.

Sentences were displayed in Courier font, a fixed-width font. The primary purpose of choosing a fixed-width font was to maintain a constant level of horizontal crowding between adjacent characters. This was also the reason why Chung et al. (2004) in their RSVP study of the effect of vertical word spacing used a Courier font. Sentences were displayed within a virtual box (centered in the middle of the screen) whose width was 17 characters. Only the left-hand side of each line was justified as for instance in Crossland and Rubin (2006). Right-hand justification was not used because it would have often produced very large spaces between words, thus inducing different levels of horizontal lateral masking between words. Hyphenation was used to fill in as much space of each line as possible (Fornos et al., 2006). As a result, each sentence was displayed over 3 or 4 lines depending on the number of characters (cf. Fig. 1).

We define print size as the vertical visual angle in degrees subtended by a lowercase 'x' (x-height). Interline spacing is defined in the classical way as the center-to-center (equivalent to baseline-to-baseline) distance between two adjacent lines (e.g. http://www.plainlanguagenetwork.org/type/utbo350.htm). It is conveniently expressed as a ratio relative to x-height. Interline spacing must not be confused with "leading" which, in the printing trade, refers to the strips of lead alloy that were placed between lines of text in the original printing press and is the height of the blank space between lines (cf. Fig. 2).

Our measurements with text printed in Courier font using the standard (single) interline spacing indicate that the ratio between center-to-center distance and x-height is equal to 2.6 (identical to that already measured by Chung (2004)). The standard interline spacing ($1X$) in our experiments was therefore set to 2.6 times the x-height. This is very close to the interline spacing of $2.24X$ used in each MNREAD chart (Steve Mansfield, personal communication).

The circle symbols in Fig. 3 show center-to-center distance in degrees corresponding to the standard interline spacing ($1X$) as a function of the print sizes used in this work. The same figure shows with cross symbols the center-to-center distances corresponding to a null leading: this corresponds to a $0.72X$ interline spacing (this value will vary with different fonts whose descents and ascents have different sizes relative to x-height). With values smaller than $0.72X$, leading would be negative thus causing a superimposition of the lower and upper parts of letters like p and b respectively called descents and ascents.

In experiments 1 and 2, the standard interline spacing ($1X$) was used with two other interline spacings: $0.85X$ and $1.25X$. For each observer, the 3 interline spacings were combined with several print sizes. The highest print size was always 2° and the other values were decreased by 0.15 log steps (multiplicative factor: 1.4): i.e. 2°, 1.43°, 1.02°, 0.73° and 0.52°.

In experiment 3, a single print size (80% of each individual CPS) was used in combination with 3 interline spacings: $0.72X$ (leading = 0), $1X$ and $2X$.

2.3. Materials

2.3.1. Eye recording

Subjects' gaze location was recorded 500 times per second with an EyeLink II eye tracker (EL II—head-mounted binocular eyetracker—SR Research Ltd., Mississauga, Ont., Canada) using the head compensation mode.

2.3.2. Gaze accuracy

Before each experimental block, a 9-point gaze calibration was performed followed by a 9-point validation. Calibration and/or validation were repeated until the validation error was smaller than 1° on average and smaller than 1.5° for the worst point. The four calibration dots close to the corners were located at ±22.4° horizontally and ±16° vertically from the center of the screen (±19.7° horizontally and ±14.1° vertically for the corners' validation dots).

We checked gaze accuracy of our setup over periods of 10 s (viewing was still monocular). Gaze error in the center of the screen was 22 min arc. At corners' locations not coincident with those of the calibration and validation dots (±17° horizontally and ±12.6° vertically), mean gaze error was 55 min arc.

Each trial was triggered by the observer who pressed a button while he/she was fixating a central fixation dot. This was used to perform an offset correction (called "drift correction" in the EL II terminology) at the beginning of each trial. A high-frequency sound was produced if the offset was

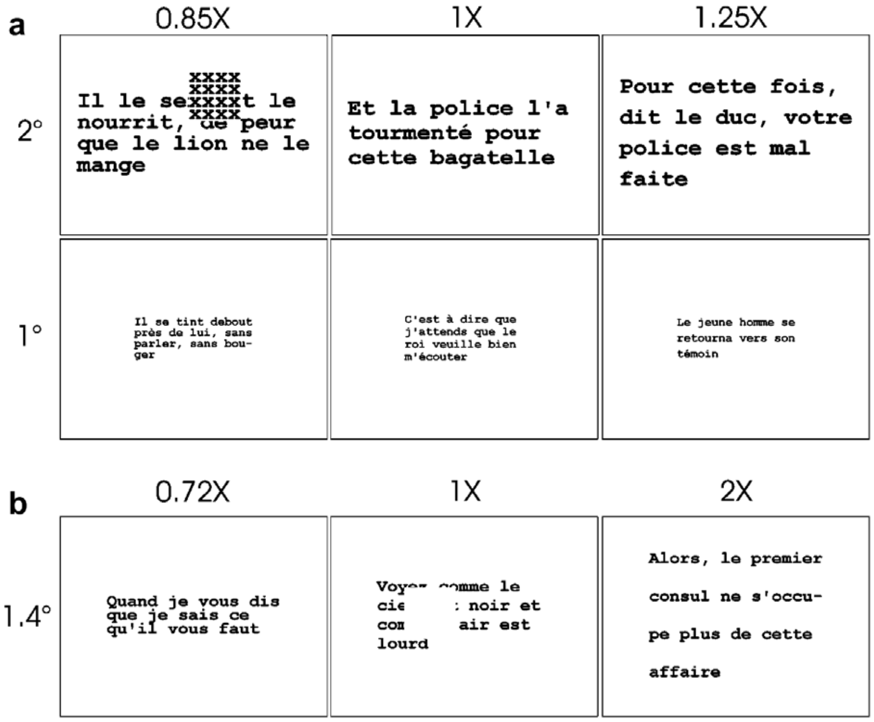

Fig. 1. Examples of sentences used in the experiments. The scale of sentences with respect to the screen area is preserved. Print size is represented on the left. (a) The three columns represent the interline spacings used in experiments 1 and 2. A 10° mask is shown in the top left graph. (b) Experiment 3: a single print size and a larger range of interline spacings were used. The $0.72X$ spacing corresponds to a null leading. A textured mask and a blank mask (middle column) were used in experiment 3.

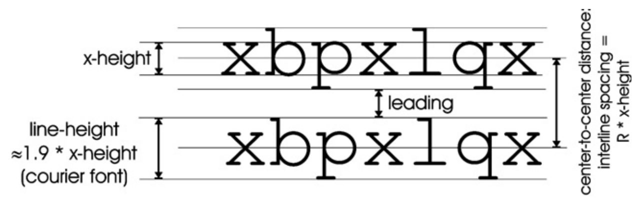

Fig. 2. Definitions of x-height, line-height, interline spacing and leading.

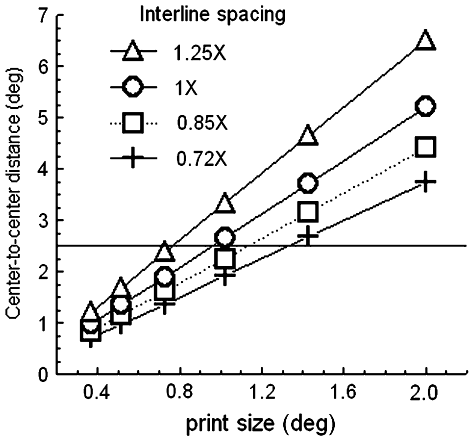

Fig. 3. vertical center-to-center distance in degrees as a function of print size for different interline spacings. The $0.72X$ interline spacing corresponds to a null leading and was only used in experiment 3. The horizontal line represents the approximate crowding extent when scotoma size was 6° (see Section 5). The symbols refer to the letter sizes used in experiments.

larger than 2° (offsets are mainly caused by slippage of the eyetracker headband with respect to the head, and they induce an adverse mismatch between actual and measured gaze location). In addition, an important point of our methodology is that the offset correction values applied to each trial were stored for future analysis. This allowed us to perform a crucial offline control of our data. A given trial (n) was kept in the analysis only if the offset correction measured at the beginning of trial $n+1$ was smaller than some threshold value (in degrees of visual angle). For the data reported in this study, the threshold value was set to 2° so that, with the smallest scotoma size (6°) and the worst offset (2°), the actual gaze location was still surrounded by a masking area of at least 1° in radius. The median offset measured over all experiments was close to 0.5° for all observers and 85% of offset values were smaller than 1.5°.

We were extremely cautious concerning another important source of mismatch between actual and measured gaze location (briefly mentioned as "cheating" in Varsori, Perez-Fornos, Safran, & Whatham (2004)) (p. 2694). A few observers, when first confronted with the difficulty of reading with a scotoma, spontaneously discovered that forcibly narrowing their interpalpebral fissure allowed them to read better. This only occurred with small print sizes. The reason is the following. First, gaze location is recorded by measuring the centroid of the pupil area extracted by the EL II eyetracker. However, this centroid does not coincide with the line of sight any longer (the latter defining gaze location) as soon as a part of the pupil is covered more by one lid margin than by the other. In a classic psychophysical display, when the head is vertical and static in front of a vertical screen, looking downwards while narrowing the interpalpebral fissure will mainly cover the lower part of the pupil, thus inducing a measured gaze location higher than the actual one. In our experimental setup, where observers' head is slightly tilted backwards on the reclining chair—the screen being vertical—the same will happen on average if observers narrow the interpalpebral fissure. Therefore, in order to avoid this mismatch, the experimenter continuously checked on the control display whether the pupil area was entirely visible. Every time an observer started to squint, he/she was instructed to keep his/her eyes wide open. This instruction was easily followed so that, except in the preliminary trials with the smallest print sizes, "cheating" was never observed in the experiments.

2.3.3. Artificial scotoma

Gaze location was sent to the display-generating computer through a high-speed Ethernet link and was continuously used to draw a square-shaped scotoma filled with black uppercase 'X' characters on the monitor. In the literature using artificial scotomas, masks are either textured (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981) or black (Fine & Rubin, 1999a, 1999b, 1999c). We chose to use a textured mask in the main experiments because it provides backward temporal masking and thus reduces potential visible persistence of the masked letters (Rayner, 1998). We also run a control condition in experiment 3 with a blank mask (same luminance as background). Two different scotoma sizes were used for each observer ($6^\circ \times 6^\circ$ and $10^\circ \times 10^\circ$).

We estimated the expected delay between an actual eye movement and the screen update in the following way. First, from the technical specifications of the EL II, the delay between an actual eye movement and the time at which the data sample becomes available in the display PC is 5 ms : 3 ms (smallest delay at 500 Hz when filtering is off) + 2 ms (due to the "standard" heuristic filter). We chose to use the EL II heuristic filter (i.e. a data smoothing/averaging algorithm) in order to decrease the sample-to-sample noise. Second, the delay between availability of the sample and actual screen update was constrained by the monitor refresh rate so that the minimum was 0 ms and the maximum 10 ms. The time taken by the software to draw the new image in the video memory was much smaller than 1 ms. In summary, the total delay between actual eye movement and screen update was expected to lie between 5 ms and 15 ms.

We checked these values with an artificial eye (see Appendix A and Fig. 8). The main advantage of this device is that we control the instant at which the physical jump of the artificial pupil occurs. We made 70 readings from the oscilloscope to measure the total delay of our gaze-contingent display: a photocell was positioned on the CRT screen at the location of the "jump" (this location was in the upper part of the monitor). We indeed found that the total delay ranged between 5 and 15 ms (mean: 10.5 ms; 95% CI: ±0.7 ms).

2.4. Procedures

Observers were instructed to read the sentences out loud as quickly as they could without making errors and with the goal of understanding the thoughts contained in sentences. As shown by Carver (1990), these requirements are known to induce a particular reading process (rauding) if and only if the sentences' complexity (semantic and syntactic) is far below the readers' education level. This latter criterion was clearly achieved in our work as subjects were at least of a graduate level and sentences had a very low complexity level (cf. Section 2.2.1). The rauding process, often referred to as "reading for comprehension" mode, is characterized by a "medium" reading rate (around 300 words/min for college students) and is different from other reading processes such as scanning text to find a particular word (around 600 words/min) or reading text to memorize ideas (around 140 words/min).

Thus, the conditions of our study were optimized to induce a reading mode as constant as possible across observers and time. As in most previous relevant studies, the reading-aloud task was used by the experimenter to check whether all words contained in a sentence were correctly identified (see below). A flawless reading-aloud performance does not in itself guarantee that a sentence is fully comprehended. However, there is evidence that the global meaning of a sentence is automatically and efficiently used by patients with central visual loss when they have to read sentences without making errors (Fine & Peli, 1996). Therefore, it seems unlikely that observers with a macular scotoma do not use the global meaning of a sentence to help them identify each individual word.

While reading a sentence, if observers thought that they had made an error, they were instructed to read to the end of the sentence and then go back and correct themselves (as advised in the newly revised version of the MNREAD manual). If at least one word was read incorrectly, the sentence was judged as incorrect and excluded from analysis (Crossland, Culham, Kabanarou, & Rubin, 2005; Crossland & Rubin, 2006). None of the sentences was read more than once by any observer.

Timing started at the instant the sentence was displayed on the screen—this was triggered by an observer button-press. The observer was instructed to press the same button (this stopped the timing and removed the sentence) when he/she had understood the whole sentence even if the last word had not been spelled out yet. In practice, our observers with an artificial scotoma always pressed the button after reading out the last word of the sentence, or after correcting a previously misread word. Reading speed was calculated in "standard-length words" per minute where each six characters counts as one standard-length word (Carver, 1990).

2.4.1. Measurement of Critical Print Size (CPS) and maximum reading speed (R_{max})

To summarize the effect of print size on reading speed, we adjusted the following function (each data point was weighted by the inverse of its variance):

$$\text{reading speed} = R_{\max} + k2 * \exp((-1/\tau) * \text{print size}) \qquad (1)$$

where $R_{\max}$ stands for the asymptotic reading speed and $k2$ is related to the speed growth observed at small print sizes ($k2$ is the distance between $R_{\max}$ and the y-intercept).

This function (with $k2 < 0$) is often used in physics and biology to describe an exponential evolution towards an equilibrium state. In our case, the equilibrium state corresponds to the saturation of reading speed observed when print size becomes sufficiently high. Critical Print Size (CPS) was defined as the print size at which the function reached 90% of the maximum reading speed ($R_{\max}$).

2.5. Design

2.5.1. Experiments 1 and 2

Each observer performed 8 experimental sessions (each lasting about 1 h and performed on different days): the scotoma size was 6° in the 4 sessions of experiment 1 and 10° in the 4 sessions of experiment 2. These 8 sessions (experiment 1 always preceding experiment 2) were always performed within two consecutive weeks.

In the first session of each experiment (hereafter referred to as the "adaptation session"), reading speed was measured with the standard interline spacing (1X). The different print sizes were run in separate blocks (randomly interleaved) of 10 sentences until two blocks were obtained for each print size (20 sentences per print size). This adaptation session allowed observers to get used to reading with a scotoma of a given size. In the three sessions following the adaptation session, still using the same scotoma size, reading speed was measured for the three different interline spacings and for different print sizes. Each randomly chosen combination of interline spacing and print size was run in a separate block containing 10 sentences until two blocks were obtained for each print size (20 sentences per print size).

At the end of experiment 2, reading speed was measured without any artificial scotoma for the standard interline spacing (1X): each print size was run in a separate block (10 sentences).

2.5.2. Experiment 3

Each observer performed one session with the 6° scotoma. A single print size was used ($0.8 * \text{CPS}$ assessed in exp. 1) in combination with 3 different interline spacings. Four blocks of 10 trials were performed for each interline spacing. This was performed with a textured and a blank mask.

3. Experiments 1 and 2

3.1. Results

3.1.1. Effect of learning

The first session of experiment 1 (about 1 h) was an adaptation phase intended to give observers the

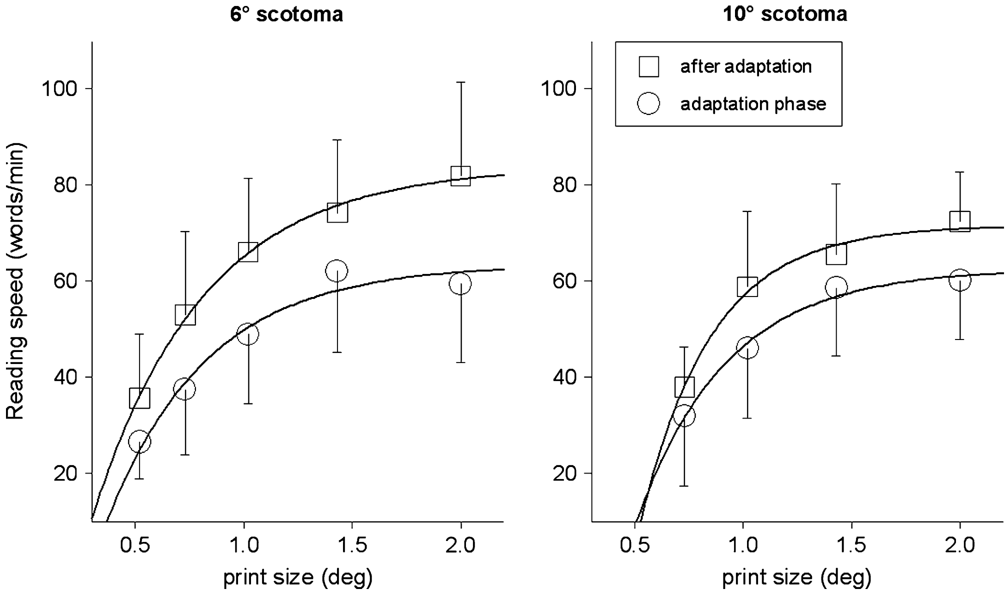

Fig. 4. Experiments 1 and 2: effect of perceptual learning in Experiments 1 (6° scotoma size) and 2 (10° scotoma size). Only data for the standard interline spacing ($1X$) are represented. Error bars correspond to 95% confidence intervals around estimates of the means. The curves represent the best exponential fits obtained with Eq. (1)—see text.

opportunity to learn how to read with a 6° scotoma using the standard interline spacing ($1X$). Reading speed measured during this phase, and averaged across observers, is plotted in Fig. 4 (left panel) with circle symbols. We also measured the proportion of sentences which were read correctly (not shown). As stated in the procedures section, a sentence was judged as incorrectly read if at least one word was not read properly. This proportion, averaged across observers, monotonically increased from 0.8 to 0.95 as a function of print size. This good performance indicates that observers immediately followed the instruction of reading with the goal of understanding. In the three following sessions (each lasting about 1 h), the key factor under study, namely interline spacing, was presented in randomly interleaved blocks to balance learning effects (see Section 2). The corresponding reading speed data for the standard interline spacing ($1X$) are plotted in Fig. 4 (left panel) with square symbols to allow a comparison with the adaptation phase performance (circle symbols). At the group level, the difference in reading speed between the adaptation and the post-adaptation phases is significant (repeated measures ANOVA, $F(1,6) = 21.96$, $p = .003$). No interaction was found between the effects of print size and adaptation (repeated measures ANOVA, $F(4,24) = 2.24$, $p = .09$). Eq. (1) was used to fit the data as shown by continuous lines in Fig. 4 (R^2 values: 0.96 and 0.99). Critical Print Size (CPS) and maximum reading speed ($R_{\max}$) were calculated from these fits. Maximum reading speed ($R_{\max}$) increases from 63 words/min (adaptation phase) to 84 words/min (post-adaptation) whereas CPS stays unchanged (from 1.35° to 1.41°). Percentage of sentences read correctly was similar in the adaptation phase and in the post-adaptation phase.

The temporal design of experiment 2 (10° scotoma) was similar to that of experiment 1 (exp. 2 was always performed after exp. 1). Reading speed data for the adaptation phase are plotted in Fig. 4 (right panel) with circle symbols, while data obtained in the three following sessions for the standard interline spacing are plotted in square symbols. A small but consistent improvement is observed. However, in contrast to experiment 1, the difference in reading speed between the adaptation and the post-adaptation phases is not significant (repeated measures ANOVA—observer DT omitted[1]—$F(1,5) = 4.39$, $p = .09$). Maximum reading speed ($R_{\max}$) increases from 62 to 72 words/min whereas CPS seems again unaffected by adaptation—from 1.39° to 1.24° (R^2 values for the fits: 0.99 and 0.98). Percentages of sentences read correctly are similar to those obtained in experiment 1.

Altogether, results suggest rapid perceptual learning when observers are first confronted with the scotoma, as measured in experiment 1. Considering the results of the post-adaptation phase in more details further suggests that perceptual learning was stabilized at the end of exp. 1: the difference between the two repeated measurements performed during the post-adaptation phase (see Section 2) was close to null. In addition, the stabilization of perceptual learning at the end of exp. 1 is confirmed by the small, and non-significant, difference in reading speed observed in exp. 2 between the adaptation and the post-adaptation phases.

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[1] Adaptation phase data from observer DT were accidentally deleted, and therefore not used here, but their stored graphical representation shows no learning.

3.1.2. Effect of print and scotoma size

Post-adaptation reading speed is shown in Fig. 5 as a function of print size with interline spacing as a parameter. Left and right panels correspond, respectively, to the 6° (exp. 1) and 10° (exp. 2) scotoma sizes. Reading speed, averaged across observers, monotonically increases with print size. Fits based on Eq. (1) are represented by continuous lines for each interline spacing. An important point shown by these data is that reading speed starts saturating only at relatively high print sizes (an average CPS of 1.4° for both scotoma sizes). This is why, based on pilot studies, we had to use the largest print size possible with our display (2°) in order to be able to measure a Critical Print Size (CPS) for each observer. The constraint of using the largest possible print size prevented us from using the largest interline spacing at the same time. However, measuring individual CPS values allowed us to set a single relatively small print size ($0.8 * \mathrm{CPS}$) which was used in experiment 3 with the highest interline spacing.

Finally, as already observed in Fig. 4, results clearly show that reading speed is higher with the 6° scotoma size compared to the 10° size (Fig. 5). The amplitude of this effect is probably under-estimated because experiment 2 (i.e. 10° scotoma size), which was always performed after experiment 1 (6° scotoma), benefited from learning effects. In other words, reading speed measured with the 10° scotoma size in exp. 2 would have been expected to be smaller (and the effect larger) if the 10° scotoma experiment had been performed before the 6° scotoma experiment.

3.1.3. Effect of interline spacing

Fig. 5 also shows that the effect of interline spacing measured in experiments 1 and 2 is either small or absent.

For the 6° scotoma size (left panel), performance is similar for the $0.85X$ and $1X$ interline spacings and it is slightly but consistently higher for the $1.25X$ interline spacing across print sizes (5 words/min on average). The effect of interline spacing is significant (repeated measures ANOVA—$F(2,12) = 7.6$, $p = .007$). The two following planned orthogonal comparisons show that the effect of interline spacing is due to the $1.25X$ condition being different from the two other conditions (($0.85X$ and $1X$) vs. $1.25X$ comparison: $F(1,6) = 26.49$, $p = .002$; $0.85X$ vs. $1X$ comparison: $F(1,6) = 0.48$, $p = .51$). The maximum reading speeds for the $0.85X$, $1X$ and $1.25X$ spacings are, respectively, 83.5, 83.6 and 87.6 words/min (R^2 values of the fits are larger than 0.995).

The general pattern of results obtained with the 10° scotoma size was quite similar to that obtained with the 6° scotoma. There is again a small but significant advantage for the $1.25X$ interline spacing. Performance averaged across observers is displayed in Fig. 5 (right panel) and shows indeed a small benefit gained from reading with the $1.25X$ interline spacing (again 5 words/min on average). The effect of interline spacing is significant (repeated measures ANOVA—$F(2,12) = 9.1$, $p = .004$). The two following planned orthogonal comparisons show that the effect of interline spacing is due to the $1.25X$ condition being different from the two other conditions (($0.85X$ and $1X$) vs. $1.25X$ comparison: $F(1,6) = 17.2$, $p = .006$; $0.85X$ vs. $1X$ comparison: $F(1,6) = 2.02$, $p = .2$). The maximum reading

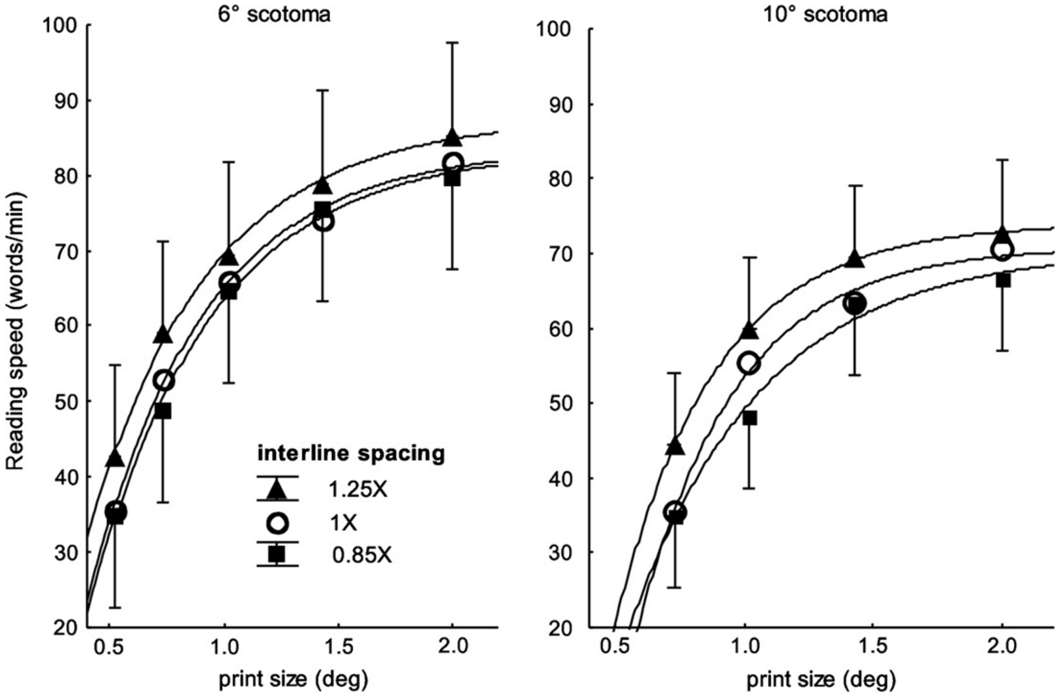

Fig. 5. Experiments 1 and 2: effect of interline spacing on reading speed—means across observers are displayed for the two scotoma sizes. For clarity, negative and positive error bars (95% confidence intervals around estimates of the means) are only shown for the $0.85X$ and $1.25X$ interlines, respectively. The curves represent the best exponential fits obtained with Eq. (1)—see text.

speeds for the $0.85X$, $1X$ and $1.25X$ spacings are, respectively, 70.4, 70.9, and 74 words/min (R^2 values of the fits are larger than 0.98).

We finally wondered whether the effect of interline spacing would be clearer when expressed by the number of sentences which were read correctly. However, this proportion was quite similar for all interline spacings (except for the smallest print size) and was actually quite high—more than 0.9 on average—showing that observers were following the instructions of reading with the goal of understanding.

In summary, we find only an average 5 words/min gain despite a 47% increase of interline spacing (i.e. from $0.85X$ to $1.25X$) irrespective of scotoma size. This gain corresponds to a 6% increase in reading speed at the average observers' CPS. This very modest gain is surprising when compared to the 75% gain reported by Chung (2004) with a 60% increase (close to our 47% increase) in interline spacing.

4. Experiment 3

To allow a more direct comparison with Chung's (2004) work, we made every effort to replicate the conditions of her RSVP paradigm by using the three following modifications. First, we used a single print size which was defined for each observer as 80% of the individual CPS measured with the $1X$ spacing in exp. 1 (for each observer, the average proportion of variance (R^2) accounted by the fits was between 0.91 and 0.99). Observers were tested with a 6° scotoma size which induced an eccentric viewing of about 4°–5° similar to the 5° eccentricity used by Chung (2004). Second, as in the RSVP study, we chose a $2X$ interline spacing as our largest spacing. It must be noted that we could not use a larger value given that our longest sentences consisted of 4 lines of text. Third, we run control conditions where our artificial scotoma was not textured any longer: instead, it was blank and had the same luminance as that of the background. This was to simulate the RSVP paradigm where the area between the fixation dot and the target word was blank.

In addition to these modifications, we decided to use a very small interline spacing, namely $0.72X$. The $0.72X$ interline spacing corresponds to a null leading and is thus the smallest spacing possible with a Courier font (it is actually never used in books or newspapers). Using this small value allowed us to get the highest range of spacings possible since we could not use larger values than $2X$ (see above). Our goal was thus to maximize the effect of interline spacing. Note that values smaller than $1X$ were not used in the RSVP study of eccentric reading (Chung, 2004).

4.1. Results

Results (averaged across observers) with the same textured mask as in the previous experiments are shown in Fig. 6. The effect of interline spacing is significant (repeated measures ANOVA—$F(2,12) = 23.8$, $p < .0001$). The three different conditions of interline spacing are significantly different from each other as shown by the two following planned orthogonal comparisons (($0.72X$ and $1X$) vs. $2X$ comparison: $F(1,6) = 31.3$, $p = .001$; $0.72X$ vs. $1X$ comparison: $F(1,6) = 17.9$, $p = .005$). The amplitude of the effect is larger than in the previous experiments: a benefit of 11 words/min is gained when increasing interline spacing from $0.72X$ to $1X$ and a benefit of 6 words/min from $1X$ to $2X$. As a control, we also run the same experiment by using a blank artificial scotoma (same luminance as background) and found similar gains in reading speed (repeated measures ANOVA—$F(2,12) = 26.1$, $p < .0001$).

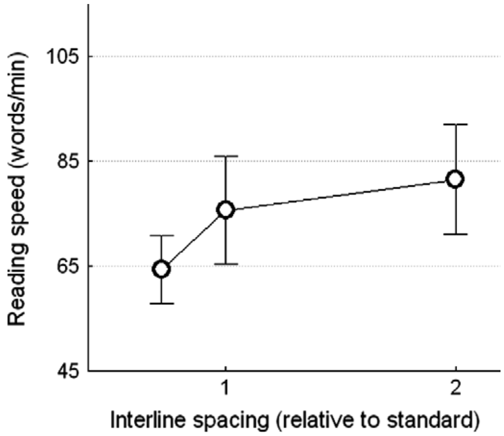

Fig. 6. Experiment 3: effect of interline spacing on reading speed. The scotoma size (6°) induces an eccentric reading of about 4°–5° on average. Print size was set for each observer to 80% of the CPS measured in exp. 1 (mean across observers: 1.16°). Error bars correspond to 95% confidence intervals around estimates of the means.

Despite the very large range of interline spacings used in this experiment, the gain in reading speed is still very moderate. Notably, there is only a modest 8% gain when increasing spacing from $1X$ to $2X$. This contrasts sharply with the 100% gain reported with the RSVP paradigm for the same range of interline spacings and at similar eccentricities (Chung, 2004).

5. General discussion

We have used a gaze-contingent visual display paradigm to simulate an artificial central scotoma while normally sighted observers read meaningful sentences. We have first assessed the effect of three low-level factors which are known to dramatically affect reading speed either in psychophysical or in clinical studies. First, it is known that increasing character size improves reading speed up to a certain size, the Critical Print Size (CPS), where reading speed saturates (Legge et al., 1987, 1985). Second, reading speed decreases with larger scotomas as the latter force patients to read at higher eccentricities (Cummings et al., 1985; Ergun et al., 2003; Sunness et al., 1996). Both signatures were replicated in our work. Finally, in experiments 1 and 2, a clear-cut learning effect is observed between the first session (adaptation phase with 6° scotoma) and the average of the 3 following sessions collected over 3 h (Fig. 4 left panel). This learning effect becomes smaller afterwards, i.e. when comparing reading speed between the fourth session (adaptation phase with 10° scotoma) and the 3 following sessions (Fig. 4 right panel). It seems therefore that efficient adaptation processes take place spontaneously and rapidly when observers are initially confronted with a central scotoma, even in the absence of any instruction aimed at improving performance. Our work thus complements previous studies which investigated learning processes related to eccentric reading either with the RSVP paradigm or in conditions of artificial vision mimicking a retinal implant (Chung et al., 2004; Fornos et al., 2006; Sommerhalder et al., 2003, 2004). Overall, the similarity of our results with those obtained in the clinical literature as well as in RSVP studies suggests that our paradigm is sensitive to the low-level factors influencing eccentric reading. It seems therefore that the modest effects of interline spacing summarized below cannot be attributed to a flaw or a lack of sensitivity of our methodology.

To assess the effect of vertical spacing between adjacent lines of text, interline spacing was classically defined as the ratio of vertical center-to-center distance between lines to *x*-height. This ratio is 2.6 for the standard interline spacing (1*X*, i.e. the "single" spacing used in word processing softwares). A summary of the results collected over the three experiments is represented in Fig. 7. Data were normalized to the 1*X* reading speed which was systematically tested in all experiments. For the 0.85*X* and 1.25*X* spacings (experiments 1 and 2), data were taken from the 1° print size which was close to the mean print size used in experiment 3.

One important goal of our work was to investigate the effect of interline spacings smaller than the standard one (1*X*). We have first tested a 0.85*X* spacing because this value is commonly employed in newspapers: we find that it has no statistically significant detrimental effect on reading performance when compared to the 1*X* spacing whatever the scotoma size (6° or 10°). In contrast, a 0.72*X* spacing, corresponding to a null leading (never used in newspapers), induces a 14% decrease in reading speed. More precisely, the relationship between reading speed and interline spacing seems to be linear (on semilogarithmic axes) beyond the 0.85*X* spacing thus suggesting an exponential law in keeping with previous work (Chung, 2004). However, this relationship breaks down when decreasing spacing from 0.85*X* to 0.72*X* (null leading). This suggests that the null leading induces a disrupting factor which is added to the effect of reduced interline spacing. This additional difficulty might be due to the absence of a conspicuous white horizontal stripe separating the adjacent lines of text, in keeping with results showing that segmentation cues can improve detection of targets embedded in crowded displays (Scolari, Kohnen, Barton, & Awh, 2007).

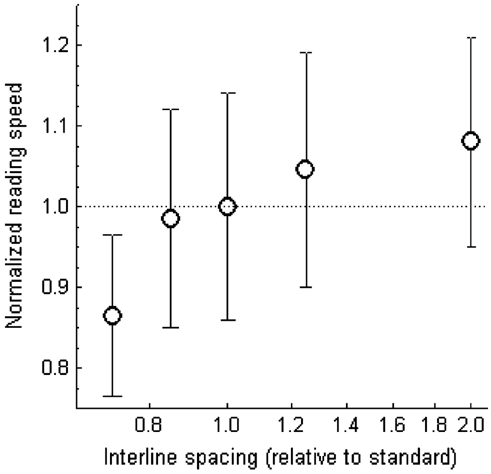

Fig. 7. Summary of the effects of interline spacing measured in the 3 experiments (semilogarithmic axes): reading speed, normalized to the 1*X* condition (see text), is plotted against interline spacing. Error bars represent normalized 95% confidence intervals.

Surprisingly, the strength of the interline spacing effect reported in the present work (i.e. in page mode) is dramatically different from that reported in a recent RSVP study (Chung, 2004), despite great similarity between the visual parameters used in both studies (notably eccentricity and print size). In the latter study, a sequence of 6 four-letter unrelated words was presented in the periphery at 5° or 10°: these words were vertically flanked by other words (only interline spacings larger than 1*X* were tested in peripheral vision). The effect of largest amplitude was that increasing vertical spacing from 1*X* to 2*X* produced a 100% increase of reading speed (print size was individually set to 80% of the CPS). In contrast, in experiment 3, we found that increasing interline spacing also from 1*X* to 2*X* only entailed a modest 8% improvement of reading speed (Fig. 7). A word's eccentricity in page reading mode can be estimated to be slightly larger than half the scotoma radius. We therefore assumed that our observers with a 6° scotoma size read at an average 4°–5° eccentricity, this value depending on the observers' ability to place the scotoma's borders as close as possible to the words (Sunness et al., 1996). Even when considering our transition from a 0.72*X* to a 2*X* spacing (i.e. a 178% increase), which is much larger than the largest difference used in the RSVP study (100% from 1*X* to 2*X*), the gain in reading speed is still very modest, namely only 26%. Possible interpretations of this large discrepancy will be discussed below.

While our results of a small effect of interline spacing are at odds with those of the RVSP study (Chung, 2004), they are consistent with a clinical study of the same group that did not use the RSVP paradigm (Jarvis et al., 2003). Reading speed was measured in nine AMD patients who had to read aloud passages (100 words each) rendered at five interline spacings ($\geqslant 1X$): it was found that reading speeds were virtually the same for all interline spacings tested. The similarity between the results of this clinical study and our work suggests that the effect of interline spacing is dependent on the type of reading (i.e. RSVP versus page mode reading).

What is the relationship between the effect of interline spacing we find and the crowding effect? Although the nature of the crowding phenomenon is still unclear, some of its defining characteristics seem to be widely accepted. It is for instance established that the extent of spatial crowding is proportional to eccentricity (Bouma, 1970; Latham & Whitaker, 1996; Levi et al., 2002; Pelli et al., 2004; Strasburger et al., 1991; Toet & Levi, 1992). If this spatial extent is defined as the center-to-center distance between the two interfering entities, it is about 0.5 times the eccentricity, or slightly lower depending on studies, and it is independent of target- and flanker-size (Pelli et al., 2004). The independence with respect to size is of course highly relevant to our work where print size is systematically varied. With the 6° scotoma used in our study, peripheral viewing takes place at a minimum of about 4°–5° eccentricity. The corresponding crowding zone will thus have a minimal extent of about 2.5° in all directions. This extent is represented in Fig. 3 by the horizontal line. Any point below this line corresponds to an interline spacing condition for which two adjacent lines of text fall within the same crowding area. The first thing to note is that any prediction concerning a potential effect of crowding depends on print size: grossly speaking, crowding effects should be observed for small print sizes, because all the spacings are below the horizontal line, but not for large print sizes. For instance, with the 2° print size, all conditions of interline spacing correspond to situations where vertical distance between adjacent lines is clearly above the crowding extent: thus increasing interline spacing should not change anything as far as crowding is concerned.

With these remarks in mind, we first consider the results of experiments 1 and 2. On the one hand, as shown in Fig. 5, the $1.25X$ interline spacing produces a reading speed (averaged across observers) which is about 5 words/min higher than the $1X$ and $0.85X$ spacings for all print sizes. This implies that this increase when expressed in percentages is larger for small print sizes than for large ones, a result which could thus be interpreted as a crowding effect. On the other hand, the crowding hypothesis predicts that no effect at all should be observed with our large print sizes. If we now consider experiment 3, it should be noted that the print size used ($0.8 * \mathrm{CPS}$) was close to 1° for all observers and that the scotoma size was 6°. In Fig. 3, we can see that a 1° print size places the $0.72X$ condition (cross symbol) within the crowding zone, the $1X$ condition (circle) near the border, and the $2X$ condition far beyond at 5.2° (not shown in the figure). Thus, the ordered improvement of reading performance observed in Fig. 6 as a function of interline spacing seems consistent with the crowding effect. In sum, it seems that the effect of interline spacing could be partly due to crowding processes although some interaction with additional factors might also be considered. For instance, it might be argued that interline spacing has some impact on visuo-motor programming of saccades or on gaze stabilization during fixations. It is thus possible that larger interline spacings provide the oculo-motor system with more optimal landmarks to program a sequence of horizontal saccades.

Whatever the source of the interline spacing effect, future work will have to explain the large discrepancy between results measured in page mode and in RSVP mode. We currently speculate that the causes of this discrepancy might rely on attentional and/or visuo-motor factors. It is known that spatially selective attention is rapidly deployed to the saccadic target before actual execution of a saccade (Awh, Armstrong, & Moore, 2006; Castet, Jeanjean, Montagnini, Laugier, & Masson, 2006; Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986). This process is likely to be disrupted for patients with central visual loss because of the mismatch between the aim of the saccade and the location of the word which the observer wants to read. Moreover, the necessity to make multiple saccades will induce a constant redeployment of the spatial focus of attention. However, the situation is probably quite different when reading in RSVP mode where attention can be efficiently and constantly focussed at a unique location in the visual field. As it is known that spatial attention can dramatically improve detection of targets within crowded displays (Scolari et al., 2007), it is possible that attentional gain combines in a multiplicative way with spacing so that only RSVP readers can benefit from larger interline spacings. Another, non-exclusive, interpretation is that increasing the distance between the target word and the two flanker words diminishes the ability of the latter to capture attention (Jonides & Irwin, 1981; Yantis & Jonides, 1984). In the RSVP paradigm, the two flanker words are indeed flashing in synchrony with the target and may thus constitute conspicuous exogenous attractors which prevent attention from properly focusing on the target word. The ability to oppose this capture effect in order to focus attention on the target word should logically increase with the distance between target and flankers (Gobell, Tseng, & Sperling, 2004). In keeping with these two interpretations, a critical involvement of spatial attention as a limiting factor of eccentric reading has recently been suggested (Falkenberg, Rubin, & Bex, 2007).

Another alternative involves the different levels of gaze stability in the two reading modes. Gaze is quite stable in the RSVP mode because observers have an intact fovea allowing them to accurately fixate. In Chung's (2004) experiments, an eyetracker was used to control that gaze position did not deviate by more than 1° toward the target words. Trials with a deviation larger than 1° (only 3.7% of trials) were discarded. Despite some controversy (Parish & Legge, 1989), there is growing evidence that fixation instability is an important limiting factor of page mode reading with central visual loss (McMahon, Hansen, & Viana, 1991). It has been shown for instance that a linear relationship exists between reading speed and fixation stability for patients with central scotomas (Crossland, Culham, & Rubin, 2004). There is also recent evidence that simulating fixation instability by jittering words in an RSVP paradigm decreases reading speed in the periphery even though the visibility of the component letters is unaffected (Falkenberg et al., 2007). It seems therefore reasonable to assume that the relative weight of fixation instability effects relative to crowding effects should be larger in page mode reading than in RSVP mode (as fixation is almost perfect in the latter case). This difference would thus account for the much larger effect of interline spacing in the RSVP mode.

Finally, another alternative should be considered as meaningful sentences were used in our work whereas unrelated words were used in the RSVP study. It is thus possible that observers relied extensively on contextual predictability in our study and were thus able to efficiently counteract detrimental crowding effects. In contrast, low-level effects such as crowding might have been much more powerful in the RSVP study where each individual word had to be read without being influenced by previously read words.

Insofar as our results can be generalized to patients, the modest effects of interline spacing we report might be fruitfully used to guide the design of text layout for patients with central visual loss reading in page mode. Especially if patients find it more important to navigate within a text—for instance in skimming mode (Carver, 1990)—than to read at maximum speed, it seems unnecessary to display texts with an interline spacing larger than the standard one (1*X*). Interestingly, this observation is reminiscent of the conclusion of previous work concerning the horizontal distance between characters (Chung, 2002): it was shown that eccentric reading did not significantly benefit from increasing horizontal distance beyond the commonly used standard spacing. More generally, the benefit gained from keeping interline spacing as small as possible is to increase the number of lines displayed within a given area (for instance a monitor) and thus to partly reduce the page navigation problem (Beckmann & Legge, 1996). Concerning interline spacings smaller than the standard one (1*X*), the 0.85*X* value commonly used in newspapers has no measurable detrimental effect (as assessed for two scotoma sizes in experiments 1 and 2), so that simply magnifying text, without increasing interline spacing, seems to be the most parsimonious choice.

In summary, our work helps understand why two recent studies found discrepant results concerning the effect of interline spacing on eccentric reading speed. On the one hand, using a RSVP paradigm, it was shown that increasing interline spacing induced a dramatic improvement in reading speed (Chung, 2004). On the other hand, in a clinical study involving AMD patients who had to read in page mode, reading speed was found to be virtually unaffected by interline spacing (Jarvis et al., 2003). The similarity of our results with those of the latter study suggests that it is the type of reading (RSVP vs. page mode reading) which is responsible for this discrepancy. It is likely that attentional factors are differentially involved in both reading modes thus inducing different types of interactions between attention and low-level factors such as crowding.

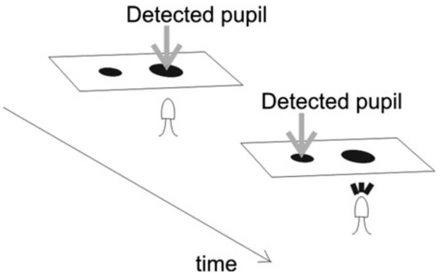

Fig. 8. Schematic description of the artificial eye used to measure the total delay of our gaze-contingent display.

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Appendix A. Artificial eye (see Fig. 8)

Two black dots are drawn on a sheet of paper (center-to-center distance: 7 mm). One dot is larger (Ø: 5 mm) than the other (Ø: 2 mm). When both dots are seen by the EL II camera, the pupil tracking algorithm selects the larger of the two dots as the pupil and reports its position. The larger dot has an infrared LED (peak at 880 nm) behind it that, when turned on, is bright enough to make the larger dot go below pupil threshold, so that the camera (sensitive only to infrared light) selects the smaller dot as the pupil and reports its position. This way we can make the “pupil” position jump instantly when the LED is turned on or off. The LED is controlled by a manual switch which also sends a TTL trigger to an oscilloscope thus proving an accurate temporal marker of the jump.

A photocell (whose output is also sent to the oscilloscope) is placed on the CRT screen at the position corresponding to one of the two “gaze locations”. We can thus measure the total delay between the physical jump of the “pupil” and the time at which the corresponding artificial scotoma actually appears on the CRT screen: this is the total delay of our gaze-contingent display.

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