Published in final edited form as:

Optom Vis Sci. 2016 June ; 93(6): 579–587. doi:10.1097/OPX.0000000000000848.

Effects of Temporal Modulation on Crowding, Visual Span, and Reading

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Abstract

Purpose—Crowding, the increased difficulty in recognizing a target due to the proximity of adjacent objects, is identified as the main sensory constraint for the size of the visual span (the number of letters recognized without moving the eyes) and reading speed in peripheral vision. The goal of the present study is to assess the impact of temporal modulation on crowding, visual span, and reading in the periphery.

Methods—Six normally sighted young adults participated the study. Four temporal modulation patterns were examined: 1) moving scotoma (sequentially masking the component letters in a letter string or word), 2) moving window (sequentially presenting the component letters), 3) flashing (repeatedly masking and presenting all letters simultaneously), and 4) static (the control condition; no temporal changes during the presentation). For each condition, we obtained the spatial extent of crowding, the size of the visual span, and reading speeds measured by the rapid serial visual presentation method.

Results—Compared to the static condition, the spatial extent of crowding was reduced in the moving window condition. Both the moving window and moving scotoma conditions led to faster reading speed for print sizes smaller than critical print size (the smallest print size that allows for maximum reading speed). However, none of the temporal modulations increased the size of the visual span and reading speed for print sizes larger than critical print size.

Conclusions—The results suggest that the temporal modulation patterns are of limited benefit for peripheral reading despite the substantial improvement for slow reading when print size is close to acuity threshold.

Keywords

peripheral vision; crowding; visual span; reading; temporal modulation; macular degeneration

Age-related macular degeneration, characterized by the progressive loss of central vision and relatively preserved peripheral vision, is one of the leading causes of blindness amongst older adults in US.¹ Patients with macular degeneration are forced to use their peripheral vision for everyday tasks. Reading, a critical task of daily living, relies heavily on central vision in normally-sighted people and becomes difficult and slow for patients with macular

degeneration.²⁻⁴ Developing suitable reading rehabilitation to enhance reading speed in peripheral vision is, therefore, crucial for these patients.

Fixation duration and saccade length are among the primary determinants of reading speed.⁵ Patients with central vision loss do not necessarily spend longer duration on each fixation^{6, 7} but the length of their saccades is consistently shorter which leads to slower reading.⁵⁻¹⁰ It has been suggested that saccade length is tightly connected with the size of the visual span, the number of letters that can be recognized without moving the eyes.^{10, 11} A large body of empirical data has confirmed that the size of the visual span imposes a sensory bottleneck on reading speed in both normal and low vision.¹²⁻¹⁵ There are three possible sensory factors determining the size of the visual span and reading speed: resolution (visual acuity), mislocation (position uncertainty), and crowding.¹² Crowding refers to the increased difficulty in identifying a target due to the proximity of adjacent objects (flankers). It reflects a failure of correct integration of target and flanker features¹⁶, and is especially problematic in peripheral vision (see Figure 1 for a demonstration).¹⁶⁻¹⁸ Among the three sensory components, crowding has been identified as the most important factor accounting for compromised performance in peripheral reading.^{16, 17, 19, 20}

In the clinical setting, text magnification is a simple and popular choice for aiding reading. However, text magnification can only assist with problems of reduced resolution in the periphery, and does not address the additional constraints imposed by crowding. Even with larger text, reading remains slower in the periphery compared to the fovea.²¹ There has been a lot of interest in research investigating possible means of reducing crowding and in turn increasing peripheral reading speed. According to Bouma's rule,¹⁸ crowding occurs in the periphery when target-flanker spacing is within roughly half the eccentricity. One intuitive way to reduce crowding is to increase the spacing between letters.^{14, 22} Unfortunately, despite the dependence of crowding on spacing, increasing letter spacing beyond the standard size did not lead to faster peripheral reading.²² Yu and colleagues¹⁴ found no enlargement in the size of the visual span (determined by resolution, mislocation, and crowding) for wider letter spacing, which explains the lack of improvement in reading speed. Since crowding is also modulated by target-flanker similarity,²³⁻²⁵ alterations of the spatial feature resemblance between target and flanking letters have been studied as well. For instance, crowding can be reduced when the target and flanking letters are of opposite contrast polarity.^{24, 26} Nonetheless, the mixed contrast polarity approach did not succeed in improving the size of visual span and reading speed in the periphery.²⁶

In more recent years, there has been increasing research on exploring the effect of temporal manipulation on crowding. Husk and Yu²⁷ found that moderate dynamic cues such as forward zooming of one or more letters can alleviate the effect of crowding. The crowding reduction is possibly a result of more accurate feature tagging to individual letters, assisted by motion trajectory cues and/or potentially enhanced local attention.²⁷ Varying the temporal properties of target and flankers while all spatial properties remain unchanged has also been found to be effective in altering crowding.²⁸⁻³⁰ Greenwood and colleagues²⁸ found that crowding can be reduced when the target is switched briefly off and on in the middle of a presentation (i.e., blink) but not when the flankers or all elements simultaneously blink. The authors also reported a substantial improvement in performance when the target onset is

simply delayed relative to the flanker onsets without any transient blink. Previously, the effect of stimulus onset asynchrony between target and flankers on crowding has been systematically examined by Huckauf and Heller²⁹ who found that crowding can be lessened with sufficient temporal separation of target and flankers especially when the flanker onsets are prior to the target onset.

In the present study, we aimed to assess whether temporal modulation can improve peripheral reading performance via a reduction in crowding. In typical reading, almost every letter is flanked immediately by one or two letters, and serves two concomitant yet independent roles—target and flanker to its adjacent letters. Since fluent reading requires accurately recognizing multiple adjacent letters simultaneously within one fixation, here we investigate the effect of temporal modulation applied to each individual letter in the reading stimulus. In this study, temporal modulation refers to altering the temporal pattern of letter onsets and offsets during presentation. We examined four temporal modulation patterns: moving scotoma, moving window, flashing, and static. As shown in Figure 2, the four temporal modulations differed with respect to the number of letters presented or masked at a given moment. In the moving scotoma condition, transient off-and-on manipulation was applied to letters one at a time from left to right. In the moving window condition, transient on-and-off manipulation was applied to letters one at a time from left to right. In the flashing condition, transient onsets and offsets were introduced to the entire letter array by repeatedly masking and presenting all letters simultaneously. The static condition served as control and no temporal changes were made during the presentation. Three measurements, the spatial extent of crowding (i.e. size of crowding zone), the size of the visual span, and reading speeds measured by the rapid serial visual presentation (RSVP) method³¹, were obtained for each condition. Based on the previous finding that transient target onset reduces crowding whereas simultaneous onset of all elements does not, we hypothesize that the moving scotoma and moving window conditions, but not the flashing condition, may outperform the static condition on spatial extent of crowding. Since crowding is identified as the main sensory constraint for the size of the visual span and reading speed,^{17, 19, 20} we expected to find consistent changes in the spatial extent of crowding, the size of visual span, and RSVP reading performance.

METHODS

Six native English-speaking young adults (age 21-25 years) with normal or corrected-to-normal vision were recruited. None of the subjects reported difficulties in reading. The research was conducted according to the tenets of the Declaration of Helsinki. The experimental procedures were approved by the Ohio State University Institutional Review Board. The experiments were undertaken with the understanding and written consent of each subject.

The experiments were programmed and controlled using MATLAB (MathWorks, Ltd.) and PsychToolbox^{32, 33} on a MacBook Pro. The display was a ViewSonic Graphics Series G220fb CRT monitor (size of the screen: 34.5 cm × 27.7 cm) with 1280 × 1024 pixel resolution and 85 Hz refresh rate. Stimuli were presented in Courier font (a fixed-width font) at 10° below fixation. All stimuli were composed of lowercase English letters and were

presented as black letters on white background (149 cd/m^2) at $\sim 99\%$ Weber contrast. Viewing was binocular at 40 cm distance in a dark room.

Four temporal modulation patterns were examined: moving scotoma, moving window, flashing, and static. Each stimulus consisted of five (for trigrams) or seven (for five-letter words; see Figure 2) sequential image frames. The first and last image frames contained all stimulus letters. Letter presentation in the intermediate frames was determined by the temporal modulation pattern. For the moving scotoma condition, as time elapsed, a one-letter-wide invisible blind spot moved one letter position per image frame from left to right across the stimulus (i.e., masking one letter at a time). For the moving window condition, a one-letter-wide window was used to reveal one letter per image frame in a left-to-right sequence. For the flashing condition, all letters were simultaneously masked and revealed in an alternating manner. The static presentation served as control and no temporal changes were introduced during the presentation (i.e., all letters are presented throughout all image frames). For each condition, we obtained the spatial extent of crowding, the size of the visual span, and RSVP reading performance.

A crowded letter recognition task was used to assess the spatial extent of crowding. In the crowding task, subjects fixated a small dot in the center of the display while recognizing the middle letter of a trigram (random strings of three letters selected from the 26 lowercase English letters with replacement) presented at 10° below fixation. Since the spatial extent of crowding is independent of stimulus size above acuity limit,³⁴⁻³⁶ a print size of 1.0° (defined as x-height in lowercase) was used. The print size was selected so that it is above the acuity threshold²⁷ and allows small non-overlapping letter-to-letter spacings. The exposure duration of each stimulus (sum of all five image frames) was 176 ms. For each of the four temporal modulation conditions, accuracy of letter recognition was measured as a function of letter spacing. Six letter spacings ($0.8, 1.0, 1.4, 1.8, 2.5, 3.4 \times \text{x-width}$) were tested. The standard spacing for Courier font is $1.16 \times \text{x-width}$. Subjects completed 40 trials per letter spacing with a total of 240 trials for each temporal modulation condition. The data were fitted with a Weibull function. A criterion of 75% letter-recognition accuracy was used to derive the spatial extent of crowding.

Visual-span profiles, plots of letter-recognition accuracy as a function of letter position left or right of the midline (see an example in Figure 3), were measured using a letter-recognition task.³⁷ As in the crowding task, the stimuli were trigrams presented with an exposure duration of 176 ms. Unlike the crowding task, letter spacing was kept constant at the standard spacing ($1.16 \times \text{x-width}$). We used a print size of 2.5° that exceeds the critical print size (CPS), the smallest print size that allows for maximum reading speed (MRS), at 10° eccentricity.²¹ Trigrams were tested at various positions left and right of the midline at 10° eccentricity in the lower visual field. The position of the middle letter was used to indicate the trigram position. There are a total of eleven trigram positions ranging from -5 to 5 . As shown in Figure 3, the position 0 marks the location directly below the fixation dot. Negative values refer to the letter slots left to the midline; positive values refer to the positions right to the midline. Subjects were instructed to report the identity of the three letters from left to right. Letter identification was scored as correct only if the letter was reported at the correct location within the trigram. Each subject completed a total of 880

trials (20 trials per letter position, 220 trials for each of the four temporal modulation conditions). Proportion correct at each letter slot was accumulated from all letters presented at that location. Although we presented trigrams at eleven positions (from -5 to 5), only data from the central nine letter slots (-4 to 4) were analyzed because only these positions contained trials from all three component letters (left, middle and right letters) of trigrams. A split-Gaussian function was used to fit the visual-span profile with three parameters: the peak amplitude, the left-side standard deviation, and the right-side standard deviation.³⁷ To quantify the size of the visual span, we converted proportion correct letter recognition into bits of information transmitted and calculated the total amount of information transmitted by the nine slots of the visual-span profile.¹³⁻¹⁵ Information transmitted at any given letter position ranges from 0 bits corresponding to a chance accuracy of 3.8% to 4.7 bits for 100% accuracy.

Reading speed was measured using the RSVP paradigm.⁴⁸ In each trial, six five-letter words were randomly selected from a word list and presented one at a time in succession at 10° below a horizontal fixation line (the length is the same as the width of a five-letter word). We constructed the word list by compiling the most frequently used five-letter English words (difficulty level is at or below 8th grade level) from multiple online sources. The list included 1483 words. Prior to the start of the experiment, we asked each subject to review the word list. None of the words were identified as unfamiliar by any of the subjects. As demonstrated in Figure 2, presentation of each word consisted of seven image frames. During each trial, subjects were instructed to read the words aloud. Only horizontal eye movements along the fixation line were permitted. We measured the proportion of words read correctly at five exposure durations (increased in constant log steps) using the method of constant stimuli with eight trials per exposure duration. For each temporal modulation condition, reading speed was measured at six print sizes, 0.8°, 1.0°, 1.4°, 1.8°, 2.5°, and 3.4°. For print sizes equal or smaller than 1.4°, the exposure durations were 247, 494, 988, 1894, and 3459 ms/word. For print sizes larger than 1.4°, the exposure durations were 165, 247, 494, 988, and 1894 ms/word. When subject's performance did not reach 80% accuracy at the longest exposure duration tested, eight additional trials at a longer duration were added at the end of the last session. The total number of trials per subject was 960 plus a few additional trials at longer exposure durations for some subjects. To derive reading speed, we plotted the proportion of words read correctly as a function of exposure duration. We fitted the data with a Weibull function and used 80% as criterion to derive the threshold duration from which reading speed was computed (see Figure 4A). As shown in Figure 4B, reading speed data were plotted as a function of print size on log-log axes. We fitted the data with a two-line function. The slopes of the two lines were constrained to 2.32 and zero, respectively.²¹ MRS and the CPS were given by the intersection of the two lines.

Each subject took part in one practice session and four testing sessions. The trials obtained in the practice session were not included in the data analysis. The orders of task, temporal modulation pattern, and values of other parameters were randomized across testing sessions and subjects. Subject's eye movements were monitored during all testing trials by the experimenter. A trial was discarded and replaced when eye movements away from the fixation were detected. We used repeated measures analysis of variance (ANOVA) to assess the effect of temporal modulation condition. Post-hoc tests were conducted when needed.

For most comparisons, there is no clear hypothesis about the direction of the effect. Therefore, all tests are two-tailed.

RESULTS

As shown in Figure 5, there was a significant effect of temporal modulation on the spatial extent of crowding ($F(3,15) = 7.832$, $p = 0.002$). Post-hoc pairwise comparisons were performed to further evaluate the differences between temporal modulation patterns. Among the four temporal modulation conditions, the moving window condition had the smallest spatial extent of crowding (1.43 ± 0.07 (SE) $\times$ x-width; $p < 0.05$) at 10° eccentricity below fixation. The static condition yielded a spatial extent of crowding of $1.65 \pm 0.12 \times$ x-width. The spatial extents of crowding for the flashing ($1.57 \pm 0.10 \times$ x-width; $p > 0.05$) and the moving scotoma conditions ($1.64 \pm 0.09 \times$ x-width; $p > 0.05$) were similar to that observed in the static condition.

Visual-span profiles for the four temporal modulation conditions were plotted in Figure 6. Consistent with previous reports^{14, 15, 38}, the peaks of all the profiles occurred near letter position 0, and the right sides of the profiles were slightly broader than the left (paired t-test: $t(23) = 5.31$, $p < 0.0005$). There was no significant effect of temporal modulation on the size of the visual span. In other words, the size of the visual span was similar across all temporal modulation condition at 10° eccentricity in the lower visual field. It was 32.52 ± 0.31 bits for the moving scotoma condition, 32.28 ± 1.20 bits for the moving window condition, 32.45 ± 0.86 bits for the flashing condition, and 31.78 ± 1.09 bits for the static condition, respectively.

In Figure 7, RSVP reading speed in words per minute is plotted as a function of print size for the four temporal modulation conditions. As the figure shows, the print size used to measure the size of the visual span, 2.5° , is above the CPS for all testing conditions. Given that the size of the visual span imposes a sensory bottleneck on reading speed,¹²⁻¹⁵ we expected the reading speed at or above CPS (i.e. MRS) to have the same dependence on temporal modulation as the visual-span size measured at the print size of 2.5° . Specifically, we hypothesize that the MRS remains at the same level across the four temporal modulation patterns. Alternatively, it is possible that MRS is not constant for different conditions if factors other than visual span also play a significant role in determining peripheral reading speed and if the effect of the factors varies according to temporal modulation. The statistical analyses revealed a significant effect of temporal modulation on MRS ($F(3,15) = 14.36$, $p < 0.0005$), as well as on CPS ($F(3,15) = 5.81$, $p = 0.008$). These analyses were then followed by post-hoc pairwise comparisons to identify which pairs of the temporal modulation patterns are significantly different from each other. We found that among the four temporal modulation conditions, the moving window condition yielded the slowest MRS (102 ± 12 wpm, $ps < 0.05$) and also the smallest CPS ($1.65^\circ \pm 0.05^\circ$, $ps < 0.05$). For the static condition, the MRS averaged across the subjects was 130 ± 14 wpm and the CPS was $2.04^\circ \pm 0.10^\circ$. When compared with the static condition, both MRS and CPS did not differ significantly for the moving scotoma (CPS = $1.85^\circ \pm 0.10^\circ$, MRS = 127 ± 12 wpm; $p > 0.05$) and flashing (CPS = $1.95^\circ \pm 0.10^\circ$, MRS = 138 ± 16 wpm; $p > 0.05$) conditions.

Across all conditions and subjects, the CPS ranged between 1.46° and 2.37°. To examine the effect of temporal modulation on print sizes smaller than the CPS, we took a focus on the performance measured at the two smallest print sizes, 0.8° and 1.0°. We found significant effects of temporal modulation on reading speeds ($F(3,15) = 5.49$, $p = 0.01$ for 0.8° and $F(3,15) = 6.19$, $p = 0.006$ for 1.0°). Post-hoc tests revealed that reading speeds increased significantly in both the moving window condition (28 ± 4 wpm, $t(5) = 3.49$, $p = 0.018$ for 0.8°; 43 ± 7 wpm, $t(5) = 3.76$, $p = 0.013$ for 1.0°) and the moving scotoma condition (27 ± 7 wpm, $t(5) = 2.88$, $p = 0.035$ for 0.8°; 42 ± 9 wpm, $t(5) = 3.77$, $p = 0.013$ for 1.0°), compared to the static condition (16 ± 5 wpm for 0.8°; 28 ± 6 wpm for 1.0°). No significant improvement was found for the flashing condition for both 0.8° and 1.0° print sizes ($ps > 0.05$).

DISCUSSION

Temporal modulation has been shown to mitigate crowding for pattern recognition in the periphery.²⁸⁻³⁰ The goal of our study was to investigate the impact of temporal modulation on the spatial extent of crowding, the size of the visual span, and reading performance in peripheral vision. Specifically, we compared four temporal modulation patterns (moving scotoma, moving window, flashing and static) and evaluated which is the most beneficial. We found that compared to the static condition, the spatial extent of crowding was reduced in the moving window condition by a significant but modest amount. Both the moving window and moving scotoma conditions led to faster reading speed for print sizes smaller than CPS. However, none of the temporal modulations improved the size of the visual span and reading speed when print size was larger than CPS. Moreover, a slower MRS was even found at the moving window condition. The results suggested that the temporal modulation patterns are of limited benefit for peripheral reading, despite the substantial improvement for slow reading when print size is close to acuity threshold.

Consistent with previous observations,²⁸⁻³⁰ we found that crowding can be reduced by varying the stimulus onset asynchrony between target and flankers, but only when there are no temporal overlaps among letters (i.e. spatial isolation of letters in separate temporal windows). Among the three non-static temporal modulation patterns that we investigated, only the moving window pattern had letters isolated in separate intermediate image frames, and successfully reduced the spatial extent of crowding (by 13.3%) compared to the static condition. However, even for the moving window condition, there is still a substantial amount of crowding remained. The limited reduction of crowding may be due to short exposure duration (35 ms) of each image frame which may lead to insufficient within-frame processing and destructive cross-frame interference. It has been shown that recognition accuracy (indicating the amount of information processed) of both isolated and crowded letters at a non-foveal retinal location reduces with decreasing exposure duration following a non-linear form.^{37, 39} Target-flanker asynchrony, depending on its degree, may or may not facilitate crowded target recognition in the periphery.²⁹ Crowding is minimally reduced or even worsened within a temporal gap of 50 ms between the target and flanker onsets due to detrimental cross-frame interference. As a result, the total benefit of 35 ms onset asynchrony is small. In summary, three factors might be responsible for the effect of temporal modulation on crowded letter recognition: 1) spatial interference within each image frame, 2) exposure duration of each image frame, and 3) interference across image frames. The

three factors can also be used to account for the lack of crowding reduction for the moving scotoma condition. Compared to the moving window condition, the moving scotoma condition provided overall longer exposure for each component letter but involved more spatial interference within each intermediate image frame and subsequently more cross-frame interference. In consequence, the combined effect of the three factors for the moving scotoma condition led to little reduction in crowding. Crowding has been found to remain the same when onsets and offsets of target and flankers are in synchrony.²⁸ The present study showed consistent result of no mitigation of crowding in the flashing condition in which the target and flankers were flashed on and off concurrently.

As we know, crowding is the major factor limiting the size of the visual span.⁴⁰ Since crowding was alleviated for the moving window condition, we expected to observe a similar beneficial effect in visual span. However, we found that none of the temporal modulations changed the size of the visual span. There were two differences in stimulus properties between the crowding and visual-span tasks: stimulus position and print size. Stimulus positions were always directly below fixation (i.e., letter position 0) for the crowding task but ranged from -5 to 5 for the visual-span task. When only evaluating the performance at position 0, we still found no effect of temporal modulation on that part of the visual span. If we express the spatial extent of crowding in the unit of degree, it ranges from 1.30° to 2.42° across subjects and conditions. The visual-span task used a print size of 2.5°, of which the corresponding letter spacing was 3.49° ($1.16 \times x\text{-width}$), well beyond the spatial extent of crowding for all temporal modulation conditions. This explained the lack of changes in the visual-span measurement at position 0 where the average performance was consistently close to ceiling (94%) across conditions. For the other letter positions, a similar argument may be true; or it may be that the spatial extent of crowding does not vary significantly with different temporal modulations. The difference in task demand such as identifying one versus three letters also likely contributed to the different findings between the two measurements.

The visual-span hypothesis states that the size of the visual span, primarily limited by crowding, imposes a sensory bottleneck on reading speed.^{12, 13} The present study found that temporal modulations did not increase the size of the visual span at a print size larger than the CPS. For print sizes smaller than the CPS, only the moving window condition successfully reduced the spatial extent of crowding. According to the visual-span hypothesis, we expected to observe a similar pattern of effect of temporal modulation in RSVP reading speed. Indeed, we found a lack of improvement in reading performance at the print sizes near or larger than CPS and some beneficial effects of temporal modulation for reading performance at print sizes smaller than CPS. However, there were also two seeming inconsistencies. Firstly, for the moving window condition, there was a slight reduction of MRS but no concurrent change in the size of the visual span. Even when we examined only the central five letter slots of the visual span (presumably used for reading five-letter words), there was still no effect of temporal modulation. One possible explanation centers on the utilization of word shape information (the pattern of ascenders and descenders in the lowercase words) in reading. Word shape has been shown to have an effect on word recognition⁴¹⁻⁴⁴ possibly through providing the coarse spatial structure of words or playing a supplementary cue to letter identity. The review by Legge¹² nevertheless suggested that in

comparison with letter recognition, word shape plays only a minor role in reading. When the visual span shrinks with shorter exposure duration³⁸, it is possible that factors concerning supra-letter features such as word shape start to contribute more in word recognition to compensate for the degraded letter-level information. For the moving window condition, word shape is, however, absent in the intermediate image frames, possibly accounting for the slower MRS. The moving window condition also resulted in a reduction in CPS, suggesting a smaller threshold size required for achieving MRS. As shown in the Figure 4B, CPS is partially determined by the level of MRS, and it is not surprising to obtain a smaller CPS with a reduced MRS. Although smaller CPS is considered as a form of improvement, the associated reduction in the MRS compromised the advantage gained in CPS.

For the print sizes below CPS (0.8° and 1.0°), two patterns of temporal modulation — moving window and moving scotoma—outperformed the static condition on reading speed. For the moving window condition, there was a shrink in the spatial extent of crowding, which was translated into improved reading performance. On average, this condition produced 61% and 127% faster reading speeds for 1.0° and 0.8° print sizes, respectively. For the moving scotoma condition, despite that crowding was not mitigated, the enhancement in reading speed was 53% for 1.0° print size and 97% for 0.8° print size. When considering only the spatial accounts (reading speed is limited by the size of the visual span which is determined primarily by crowding), we cannot explain this discrepancy. It is important to note that different exposure durations were used in the reading and crowding measurements, because of which our original assumption about the relationship between reading speed and crowding may become inaccurate. For RSVP reading, we can estimate the presentation duration allocated to each image frame for a given print size and performance level. For example, duration per image frame for the words presented with the MRS (i.e., print size CPS, reading accuracy = 80%) is 84 ms for the moving window condition and 66 ms for the static condition. To read with a similar high accuracy at 1.0° print size, duration of each image frame needs to be about 200 ms for the moving window and moving scotoma conditions, and about 300 ms for the static condition. For such a long stimulus exposure, letter recognition is mostly limited by spatial interference (within-frame crowding) rather than temporal processing and cross-frame interference. In other words, when exposure duration is long enough to allow thorough processing of each image frame and to substantially lessen the interference across frames, the net benefit would depend primarily on the reduction of spatial interference within each image frame. Both moving window and moving scotoma conditions offer reduced within-frame interference (spatial crowding) by turning off one or more letters. Accordingly, letter-level information becomes more reliable, leading to more accurate word recognition and faster reading speed. Albeit the benefit acquired from long exposure duration, the real-world application may be limited due to the inevitable slowness of the reading speed. For a short stimulus exposure, the additional limitations introduced by temporal changes may counteract their benefits to spatial interference. Specifically, the modulation of moving scotoma becomes ineffective when the duration falls below a certain level where interference across frames becomes prominent. Here we found no reduction of crowding for the moving scotoma condition at a presentation rate of 35 ms per image frame. Overall, it is plausible to obtain the result of enhanced reading speed but no crowding reduction given the difference in stimulus duration between

the measurements. To sum up, a proper balance in the temporal domain needs to be maintained for temporal modulation to be useful, and the application is restricted to improving slow reading with a limited amount of effectiveness.

In our daily life, we encounter a diversity of print sizes from those near or below recognition threshold to those well above CPS. Legge and Bigelow⁴⁵ examined the distribution of print sizes in contemporary published reading materials and found that the vast majority of printed texts fall in a range approximately from 1.4 mm to 14 mm (x-height). The corresponding degrees of visual angle are 0.2° and 2° assuming a reading distance of 40 cm, and 0.4° and 4° for a distance of 20 cm. For patients with central vision loss, small print sizes impose a particular difficulty because crowding increases quickly in the periphery and its amplitude depends on letter-to-letter spacing (proportional to letter size). Clinically, we can enlarge small print to or above CPS electronically or optically with magnifiers. Nonetheless, the enlarged text may run into scotoma(s), be pushed further into the periphery where acuity deterioration, mislocation errors and crowding are much worse, or result in greatly narrowed field size (few characters simultaneously present in the field of magnifier). Despite the limited benefits demonstrated in the present study, temporal modulation may be a potential alternative to improving slow reading speed for people with central vision loss when enlarging print size is not an option or is not sufficient to achieve the best possible reading performance. Given the nature of the presentation formats, the method investigated here may be more suitable for brief, momentary reading such as going through labels on medication and cooking instructions on food package. To translate these findings into a useful form of low-vision reading rehabilitation, questions such as whether the effect of temporal modulation is same for people with central vision loss and whether the effect generalizes to page reading need to be investigated.

ACKNOWLEDGMENTS

This research was supported by NIH training Grant T35-EY00715114 to CH.

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Figure 1.

Demonstration of crowding. Both targets (“s”) are equidistant from the fixation dot. When fixating the left dot, it is easy to discern the target “s” below. When fixating the right dot, it is more difficult to identify the same letter below because of the interference from flankers “o” and “u”. This phenomenon is referred to as “crowding”. In our study, stimuli were always presented at 10° below fixation.

Figure 2.

Samples of the word “music” as rendered in four temporal modulation conditions. Five-letter words were used to measure RSVP reading speed. Each temporal modulation was achieved by a seven-image frame sequence. Each column, illustrating the image frame sequence from top to bottom as time elapses, corresponds to one temporal modulation condition. We used trigrams (not shown in this figure), strings of three random letters, to measure the spatial extent of crowding and the size of the visual span. For trigram stimuli, each temporal modulation was achieved by a five-image frame sequence.

Figure 3.

Examples of trigrams and a sample visual-span profile. Each trigram is presented at a letter position left or right of the midline at 10° below fixation. Trigram positions are defined by the position of the middle letter. For instance, the trigram “vis” is presented at position 3. The trigram “osu” is located at position -5 with the three letters positioned at -6 (“o”), -5 (“s”), and -4 (“u”), respectively. Position 0 corresponds to the location directly below fixation on the midline. A visual-span profile is a plot of letter-recognition accuracy as a function of letter position. The right vertical scale shows the conversion from the proportion of correct responses to information transmitted in bits.

Figure 4. Example of RSVP data analysis. **(A)** Proportion correct of word recognition is plotted as a function of exposure duration for each print size. Threshold duration is determined using a criterion of 80% accuracy. **(B)** Reading speed computed from threshold duration is plotted as a function of print size. Data are fitted with a two-line function with one slope being 2.32 and the other being 0. The intersection of the two lines represents the estimated CPS and MRS.

Figure 5.

The spatial extents of crowding for four temporal modulation conditions. Proportion correct of letter recognition is plotted as a function of letter spacing (xX -width) for the group average and for the six individual subjects. Data from each condition are fitted with a Weibull function. The dashed line represents the 75% letter recognition from which the spatial extent of crowding was determined.

Figure 6.

Visual-span profiles for four temporal modulation conditions. Proportion correct of letter recognition is plotted as a function of letter position for the group average and for the six individual subjects. Data from each condition are fitted with split Gaussians.

Figure 7. RSVP reading speeds for four temporal modulation conditions. Reading speed in words per minute is plotted as a function of print size for the group average and the six individual subjects. Data from each condition are fitted with a two-line function on log-log axes. The slopes of the two lines are fixed to 2.32 and 0. The intersection of the linear functions marks the CPS and MRS for each temporal modulation condition.