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Training to improve temporal processing of letters benefits reading speed for people with central vision loss

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Reading is slow and difficult for many people with central vision loss. A previous study showed that the temporal threshold for letter recognition is a major factor limiting reading speed for people with central vision loss. Here, we asked whether the temporal threshold for letter recognition for people with central vision loss could be improved through training and, if so, whether that would benefit reading. Training consisted of six sessions (3000 trials) of recognizing letter trigrams presented at fixation. Trigrams were initially presented at a baseline temporal threshold that was decreased by 0.1 log step when observers' letter recognition accuracies reached 80% or higher for four consecutive blocks. Before and after training, we measured observers' visual acuity, preferred retinal locus for fixation, fixation stability, reading speeds using the rapid serial visual presentation (RSVP) paradigm, the MNREAD Acuity Chart and 100-word passages, the baseline temporal threshold for letter recognition at 80% accuracy, and a visual-span profile. After training, the temporal threshold was decreased by 68%. This improvement was accompanied by a higher RSVP maximum reading speed (but no change in MNREAD and passage reading speeds) and a larger visual span. A mediation analysis showed that the relationship between the temporal threshold and RSVP maximum reading speed was mainly mediated by the information transfer rate (size of visual span/temporal duration). Our results showed that the temporal threshold for letter recognition is amenable to training and can improve RSVP reading speeds, offering a practical means to improve reading speed for people with central vision loss.

Introduction

People with impaired vision often experience difficulty with reading. The difficulty is exacerbated when the central vision is compromised owing to eye diseases or disorders that affect the macular region of the retina, the area with the highest cone photoreceptors and the lowest convergence of photoreceptors to ganglion cells, which offers the most acute vision in normal vision. Because reading is an essential activity of daily living, and is often identified as the primary goal for patients with low vision seeking visual rehabilitation (Bullimore & Bailey, 1995; Elliott et al., 1997), the development of methods or technologies to improve reading performance is of utmost importance in low vision research.

The conventional method used in the clinic to address the reading difficulty of patients with low vision is magnification, or the enlargement of print. Although magnification does offer help, a lot of patients with low vision, especially those with central vision loss, still struggle with reading. Other common recommendations offered by rehabilitation specialists, including contrast enhancement of text, contrast reversal (changing the text from black-on-white to white-on-black), adjusting the characteristics of typography such as the use of serifs versus nonserifs, the use of boldface type, and so on, often lead to a very modest, if any, improvement (Chung, 2020). To date, the most promising method to improve reading performance for people with central vision loss, in addition to magnification, is perceptual learning, defined as "any relatively permanent and consistent change in the perceptions of a stimulus array, after practice or experience with this array" (Gibson, 1963).

Although perceptual learning has been used to improve functional vision for people with amblyopia for more than two decades (e.g., Levi, 2005; Levi & Polat 1996), its application in improving functional vision for people with visual impairment only began about a decade ago. Chung (2011) trained her observers with central vision loss using a reading task with words presented one at a time in quick succession (the rapid serial visual presentation [RSVP] paradigm). Her observers were asked to read aloud words presented in each trial (each trial comprised a sentence of 8–14 words) as quickly and as accurately as possible. After six sessions of training (a total of 300 sentences read), the reading speed of her observers improved by an average of 53%. Tarita-Nistor et al. (2014) used a similar paradigm as that of Chung (2011), with the exception that the print size used was smaller than that used by Chung, and observed an improvement in reading speed

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of 11%. Nguyen et al. (2011), also using the RSVP paradigm to train their observers with Stargardt's disease, reported an average improvement in reading speed of 25%. Besides using a reading task, there have been several attempts to boost reading speed for individuals with central vision loss by expanding their visual-span profiles through training (e.g., Thayaparan et al., 2010; Liu, Wagoner, & Legge, 2011). The premise was based on findings that, in normal peripheral vision, the expansion of visual-span profiles led to higher reading speed (Chung, Legge, & Cheung, 2004; Lee et al., 2010), and that there was a correlation between the size of visual span and reading speed (Legge, 2007; Legge et al., 2007). Unfortunately, attempts to expand visual-span profiles for individuals with central vision loss through training failed to expand their visual-span profiles and, hence, their reading speeds (Thayaparan et al., 2010).

The failure to increase the size of visual span through training for people with central vision loss was both disappointing and puzzling, because such training was effective in improving reading speed in normal peripheral vision. However, Cheong et al. (2008) showed that the size of visual span did not correlate with reading speed for their group of observers with macular degeneration, unlike what has been observed in the normal periphery (Legge et al., 2001, 2007). Instead, they observed a correlation between reading speed and the threshold duration for recognizing letters (see also Cheong et al., 2007), as well as a correlation between reading speed and information transfer rate (size of visual span/threshold duration). These authors took their findings as evidence for a strong temporal limitation on reading speed.

The findings of Cheong et al. (2007, 2008) imply that training to speed up the temporal processing of letter recognition could be an effective alternative to training to expand the visual span, as a means to improve reading speed for people with central vision loss. Yu et al. (2018) tested this idea in normal peripheral vision by training a group of seven young adults with normal vision to recognize letters at 10° in the lower visual field. The letter exposure duration was adjusted for a targeted 80% letter recognition accuracy. After four sessions of training, the averaged letter threshold duration decreased from 217 ms to 142 ms. This improvement in letter threshold duration was accompanied by an improvement in reading duration (the word exposure duration for an 80% reading accuracy) from 278 ms/word to 196 ms/word, corresponding to an increase in reading speed from 216 words per minute (wpm) to 306 wpm. The 41% increase in reading speed means that the temporal duration training task was effective in improving reading speed, but it was no more effective than the visual span training (Chung et al., 2004), at least in normal peripheral vision. However, recall that the results of visual span training were different in normal peripheral vision and for people with central vision loss; thus, it remains possible that we could observe a different effect of temporal duration training for people with central vision loss, in comparison with normal peripheral vision. Therefore, the primary goal of this study was to evaluate the effectiveness of temporal duration training for people with central vision loss. The secondary goal was to determine whether the improvement in temporal duration training for these individuals, if any, would transfer to improved reading performance.

To address the goals of this study, we adopted a temporal duration training paradigm similar to that of Yu et al. (2018) to test whether we could boost letter processing speed for people with central vision loss through an intensive period of training. Essentially, we used an adaptive method to track the threshold duration that allowed our participants to recognize letters at an accuracy of 80%. Participants' reading performance were compared before and after training. Previously, most perceptual learning studies that aimed at improving reading speed in normal peripheral vision or for people with central vision loss have invariably used the RSVP paradigm to present text. The RSVP paradigm presents words one at a time at the same location on a display in quick succession. The main advantages of using RSVP to measure reading performance in peripheral vision are that 1) it minimizes the need to make saccadic eye movements between words, thus allowing us to tease apart (at least to a certain extent) the oculomotor limitations on reading from other factors; and 2) that there is less variability in the eccentricity of words that are presented one at a time, when compared with an entire passage. However, RSVP has been criticized as unconventional and thus reading performance measured using RSVP may not truly represent how someone reads in his or her daily life. Because of this concern, and our desire to investigate whether an improvement in RSVP (if any) would generalize to more natural reading tasks that require eye movements,[1] in this study, we evaluated reading performance using three different formats: RSVP, MNREAD, and passage reading. The RSVP paradigm allows us to compare our findings with those of previous studies. MNREAD, standing for the Minnesota Reading Acuity Chart, is a popular reading test that presents short sentences at different sizes. All sentences are printed in three lines and must satisfy a set of stringent criteria, including the number of characters per line and the total number of words in the sentence (Mansfield et al., 1993; Mansfield & Legge, 2007). Although MNREAD seems more conventional as a reading task when compared with the RSVP format, MNREAD sentences are short and thus cannot evaluate sustained reading performance. Consequently, we included a passage reading task. All passages were formatted like a printed article in a

Observer ID	M/F	Age	Diagnosis	Acuity (logMAR) Right eye	Acuity (logMAR) Left eye	Eccentricity of fPRL (°)	Years Since Onset
A	F	76	AMD	0.36	0.90	3.16	4
B	M	72	AMD	0.80	0.80	3.52	2
C	F	86	AMD	0.56	0.58	4.72	9
D	M	84	AMD	0.84	0.82	6.67	10
E	M	83	AMD	1.10	0.56	6.56	3
F	F	80	AMD	0.95	0.56	8.56	11
G	F	73	AMD	1.10	1.40	10.57	3.5
H	M	50	Toxoplasmic chorioretinitis	0.98	0.86	10.12	36
I	F	43	Stargardt	1.08	0.86	6.36	29

Table 1. Visual characteristics of our observers. Acuities of the better and worse eyes are shown in red and green, respectively. The eccentricity of the fPRL referred to measurement obtained using the better eye. AMD = age-related macular degeneration; logMAR = logarithm of the minimum angle of resolution.

newspaper column and contained exactly 100 words. These three reading measurements were part of a larger battery of tests that were performed on our participants before and after training. Also included in the battery were measurements of visual acuity, the preferred retinal locus for fixation (fPRL), fixation stability, and visual-span profile.

To preview our results, after six sessions (a total of 3000 trials) of training, our participants' threshold duration for letter recognition was decreased to 31.8% of the duration before training. This improvement was accompanied by an average increase in the RSVP reading speed of 44% and an average increase in the size of visual span of 7.09 bits. Interestingly, despite an increase in RSVP reading speed, there was no significant change in reading speeds measured using the MNREAD and the passage format. In addition, although participants could read faster when text was presented using the RSVP format, they were not able to read smaller print. Last, the improvement in threshold duration was largely retained for at least a few weeks after the training ceased.

Methods

Nine observers with bilateral central vision loss participated in this study. Seven of them had vision loss owing to age-related macular degeneration. All of them had been diagnosed for at least 2 years. Table 1 summarizes their visual characteristics. Each observer gave oral and written consent before the commencement of data collection. The experimental procedures were approved by the Institutional Review Board at the University of California, Berkeley, and the study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Basic experimental design

The basic experimental design comprised a pretest, a training phase of six sessions, and a post-test. All observers also attended a follow-up visit 1 week after the post-test to evaluate whether or not the training effect was retained. Figure 1 shows a schematic summary of the experimental design. Pretests consisted of measurements of 1) high-contrast visual acuity, 2) the fPRL location and fixation stability, 3) reading speed as a function of print size using the RSVP paradigm (to establish the critical print size [CPS], the smallest print size at which observers read at their maximum reading speed [MRS]), 4) MNREAD performance, 5) reading speed for a 100-word passage, 6) threshold duration for letter recognition, and 7) visual-span profile. The order of testing of the various tasks was the same as listed above. Post-tests were identical to pretests. Pretests and post-tests were each completed in two sessions, with the first session devoted to the measurement of visual acuity, fPRL location, fixation stability, and RSVP reading performance. At the follow-up visit (1 week after the post-test), letter recognition performance was measured using the same task as that for training (the training task is described below), but only for five blocks (10 blocks were tested at each training session). In other words, each observer attended a total of 11 sessions. With the exception of observer B who attended the first ten sessions on a daily basis (his follow-up visit was still 1 week after the post-test), all observers attended these

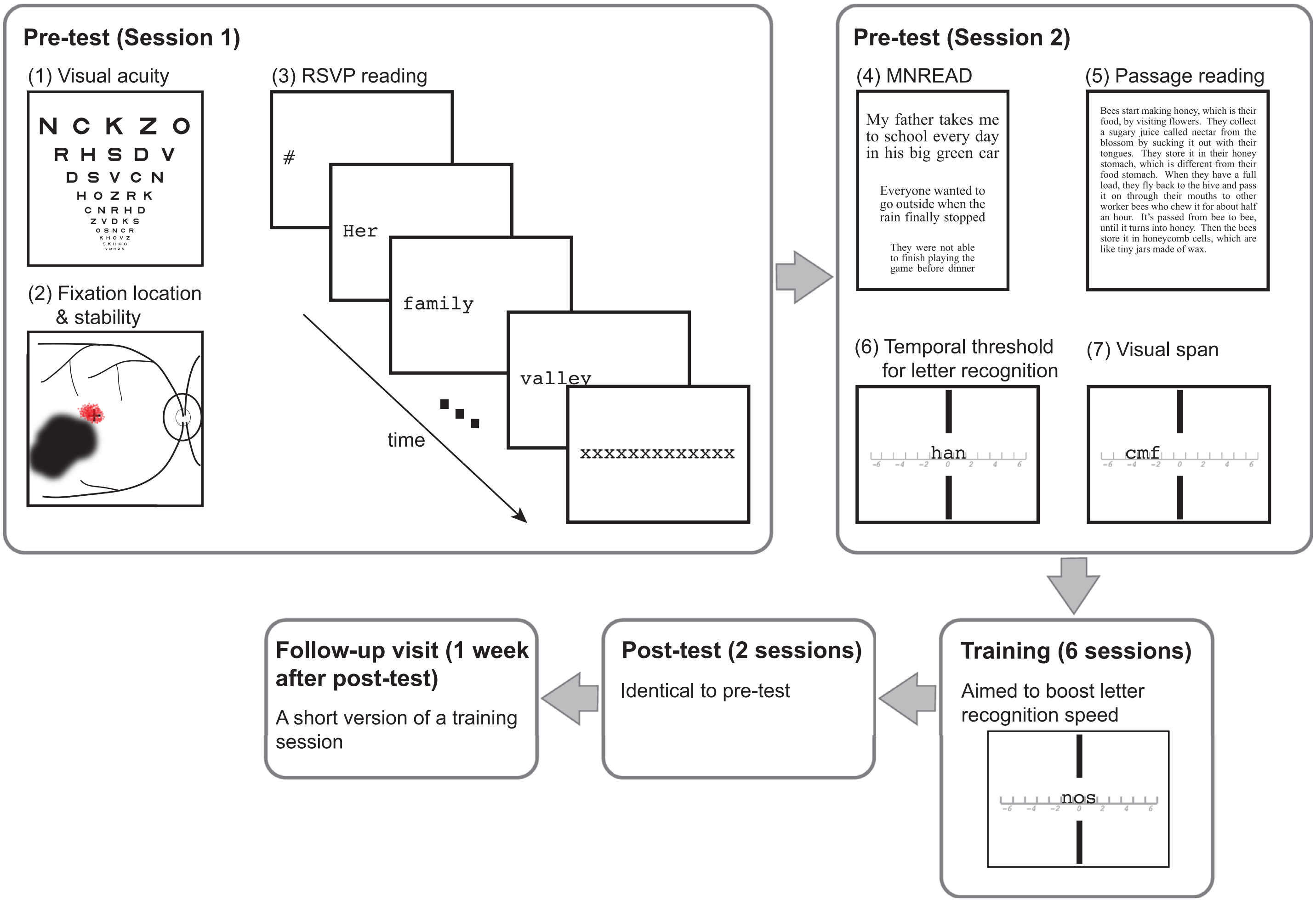

Figure 1. A schematic of the experimental design. A pretest, completed in two sessions, consisted of measurements of (1) visual acuity, (2) fPRL location and fixation stability, (3) RSVP reading performance, (4) MNREAD performance, (5) passage reading, (6) temporal threshold for letter recognition, and (7) visual-span profile. Training comprised six sessions and aimed at boosting letter recognition speed. A post-test, identical to the pretest, followed the last training session. One week after the post-test, observers returned for a follow-up visit to evaluate whether the improvements owing to training could be retained for several weeks after training ceased. For the measurements of temporal threshold, visual span and the training task, the light gray lines with numbers represent letter positions and they were not shown to the observers.

sessions on a weekly basis, completing the study in 11 weeks. Previously, Chung and Truong (2013) showed that the magnitudes of task improvement after training were similar between a daily and a weekly training schedule; thus, we were not concerned that observer B's training schedule was different from that of the others. All observers wore their best-corrected prescriptions, with the appropriate additions for the testing distances, during testing. Except for the measurements of visual acuity, the location of the fPRL and fixation stability, which were taken monocularly, all other testings, including training, were performed binocularly under normal office illumination.

Visual acuity measurement

Best-corrected visual acuity was measured monocularly for the right and left eye of each observer using the Bailey–Lovie Visual Acuity Chart. Values are given in Table 1 and are color coded for the eye with better or worse acuity (except for observer B, who had equal acuity in his two eyes, we designated his preferred eye [the left eye] as his "better" eye). Observers wore their best-corrected distance prescription during testing, with the nontested eye covered with a black plastic occluder. Observers read the letter chart at a distance of 10 feet, with the exception of observer G for whom we had to decrease the testing distance to 5 feet when testing her left eye. Observers were allowed to view letters on the chart eccentrically if necessary. Acuity was recorded in logarithm of the minimum angle of resolution (logMAR) notation, with each letter having a score of 0.02 log units.

Location of fPRL and fixation stability measurements

The retinal location corresponding to the fPRL and fixation stability were determined using a custom-built tracking scanning laser ophthalmoscope. Details of the hardware of the tracking scanning laser ophthalmoscope were reported in Sheehy et al. (2012). Measurements were performed only on the preferred eye of the observers, which also happened to be the eye with the better acuity for all observers, except observer B. Observer B had equal acuity in both eyes, but he preferred using his left eye; thus, fixation measurements were performed on his left eye. A 1° (observers A, C, E, and F) or 2° (observers B, D, G, H, and I) cross (stroke-width subtended one-fifth of the height/width of the cross) was presented at the center of the 10° × 10° imaging field, and observers were asked to keep the fixation cross visible at all times. This instruction was to encourage observers to place the fixation cross on their fPRLs instead of placing the cross at their nonfunctioning fovea. Fundus images, with the cross superimposed, were captured continuously for 10 seconds at a video frame rate of 30 Hz. Videos were analyzed offline according to the brute force cross-correlation procedures described by Stevenson and Roorda (2005) and Agaoglu et al. (2018), which allowed us to recover changes in eye positions during the 10-second recording period at a sampling rate of 540 Hz. A probability density function was then computed for the set of eye positions (Agaoglu et al., 2018; Castet & Crossland, 2012). The location corresponding to the peak density of the function was taken to represent the fPRL (shown in Table 1). The area enclosed by the iso-probability line corresponding to a probability of 0.68 was used to represent the fixation stability. The more unsteady the fixation is, the larger would be the area enclosed by the iso-probability line.

RSVP reading performance

Oral reading speed was measured for five print sizes spanning a range of four times (e.g., 0.35° to 1.41°, or 2° to 8°) so that we could construct a reading speed versus print size function. Stimuli and procedures were identical to those described previously (e.g., Chung, 2002, 2011; Chung, Mansfield, & Legge, 1998). In brief, observers read aloud words of single sentences presented using RSVP. On each trial, a sentence of 8 to 14 words in length, was chosen randomly from a pool of 2630 sentences (none of the sentences were shown more than once). All the words contained in our sentence set were among the 5000 most frequently used words in written English, according to word frequency tables based on the British National Corpus (Kilgarriff, 1997). Words were presented one at a time, each for a fixed exposure duration, at the same location on the display monitor. Observers were instructed to read as quickly and as accurately as possible. The number of words read correctly was entered after each trial. For a given print size, each word exposure duration was tested using six sentences, yielding a total of 53 to 78 word presentation (averaged across conditions and observers; mean, 66.6 ± 4.2 words). A cumulative Gaussian function was used to fit each set of data relating performance accuracy and word exposure duration, from which we derived the duration that yielded 80% of the words read correctly, as in our previous studies (e.g., Chung, 2002, 2011; Chung et al., 1998). This duration was subsequently converted to the criterion reading speed (at 80% correct) expressed in words per minute (wpm).

For each observer, the reading speed was then plotted as a function of print size. As described previously (Chung et al., 1998), reading speed improved with print size until the CPS, beyond which reading speed plateaued at the MRS. We used a bilinear fit, in which the slope (on log–log axes) of the first line was free to vary and the slope of the second line was fixed at zero, to fit each set of data. The CPS was then derived from the intersection of the two fitted lines and the MRS was derived based on the y-value of the second fitted line.

MNREAD performance

Oral reading speed was measured using the MNREAD Acuity Chart (Precision Vision, Woodstock, IL), according to the manufacturer's instructions (Mansfield et al., 1993; Mansfield & Legge, 2007), with the exception that we used a testing distance closer than 40 cm (the distance for which the MNREAD Chart was calibrated) for many of the observers. This action was to ensure that our observers could read several "large" print sizes before their reading speeds decreased for smaller print sizes. The print sizes of the sentences were adjusted for the shorter distances, for example, all print sizes were 0.1 log units larger than the nominal values printed on the chart when the testing distance was decreased from 40 to 32 cm (a 0.1 log unit change). We measured the time for our observers to read each sentence, starting with the largest size. The number of words read incorrectly was recorded. The measurement continued until the observers could only read a few words. The duration taken to read a sentence, adjusted for the number of reading errors, was used to calculate reading speed in words per minute. Following the more contemporary approach in fitting the reading speed versus print size data for MNREAD data (Cheong et al., 2007, 2008; Cheung, Kallie, Legge, & Cheong, 2008; Chung, Jarvis, & Cheung, 2007), we fit each set of data using an exponential function of the form:

$$\text{Log reading speed} = a \times (1 - e(-e^{b} \times (\text{print size} - c)))$$

where a represents the log reading speed when the exponential function reaches saturation, or, the MRS, b the log rate of change of reading speed with print size, and c the x-intercept of the function (i.e., when log reading speed is 0). Because an exponential function does not offer a clear break point of print size when it transits from limiting reading speed to having no effect on reading speed, a threshold print size (TPS) was adopted in lieu of the CPS. In this work, we defined the TPS as the print size that yielded a reading speed equivalent to 80% of the observer's MRS.

Passage reading speed

Oral reading speed was measured for a 100-word passage of newspaper article. More than 30 newspaper articles, each exactly 100 words in length, were obtained from electronic sources and had been standardized and used in a previous study (Chung et al., 2008). Passages used in this study were printed in newspaper column format. All passages were printed in single-line spacing format and contained 13 or 14 lines of text, with an average of 44 character spaces per line. For each observer, the print size used was 1.4 times the CPS as determined in the first pretest session, based on the RSVP reading performance. Before testing, observers were required to read aloud a practice passage, placed in a reading stand, as in the actual testing, until he or she was comfortable with the task. To minimize fatigue, observers were not required to finish reading the practice passage. A test passage (different between pretest and post-test for each observer) covered with a piece of white paper, was then placed in the reading stand. Observers were asked to read aloud each word of the passage as quickly as possible upon the removal of the cover paper. The time taken to complete the task and the number of words read incorrectly were recorded. The passage reading speed (wpm) was then calculated based on these two measurements.

Threshold duration for letter recognition

A trigram, consisting of three lowercase letters randomly chosen (with replacement) from the 26 letters of the alphabet, was presented at fixation. To facilitate fixation, a pair of thick black lines (1 × 10 cm) were placed, one above and one below the letter position 0 (see Figure 1). Given that all our observers had long-standing central vision loss, we expected that they would fixate using their fPRLs. The observers' task was to name the three letters, from left to right, guessing if necessary. The letter size was set at 1.4 times the CPS as determined in the first pretest session. Depending on individual observers, between five and eight exposure durations were tested. The durations varied in steps of 0.1 log unit. At least 10 trigrams were presented at each duration. Although observers were asked to recognize all three letters of each trigram, we only counted the accuracy for recognizing the middle letter. Based on the data relating recognition accuracy and presentation duration, the threshold duration was defined as the duration that yielded 80% of accuracy of recognizing the middle letter of trigrams, following the definition of Cheong et al. (2007).

Visual-span profile

Stimuli and procedures used to measure visual-span profiles were identical to those described previously (e.g., Cheong et al., 2008; Chung & Truong, 2013; Chung et al., 2004; Legge et al., 2001). In brief, a trigram consisting of three lowercase letters randomly chosen from the 26 letters of the alphabet, indexed by the position of the middle letter, was presented between six letter positions left and right of fixation (designated as letter position 0). In other words, the stimulus configuration was similar to that for measuring the temporal threshold for letter recognition, with the exception that trigrams were presented at various letter positions left and right of fixation. The observers' task was to name the three letters, from left to right, guessing if necessary. Responses were scored as correct only if the letters were also identified in the correct relative position within a trigram. The letter size was set at 1.4 times the CPS as determined in the first pretest session, and the exposure duration of the trigrams was set at the pretest threshold duration for letter recognition (details given above). To facilitate fixation, a pair of thick black lines (1 × 10 cm) were placed, one above and one below the letter position 0, and we assumed that observers fixated using their fPRLs. Although their fPRL was not explicitly monitored during testing (the experimenter constantly reminded the observers to fixate at the center of the gap between the two thick black lines), as we shall see later, there were hints about the location of their

PRLs from their visual-span profiles. A visual-span profile, relating letter recognition accuracy with letter position (combining trials in which the left, middle, and right component of trigrams were presented at a given letter position), was then constructed based on two blocks of trials, with 130 trigram presentations in each block (13 letter positions × 10 presentations). The second block followed the first block after a short break (approximately 5 minutes).

In previous studies, when we reported the visual-span profiles in central and peripheral vision of people with normal vision, we conventionally fit each profile using a split Gaussian function. In this study, as we shall describe later, the visual-span profiles of several observers showed a sharp reduction in letter recognition accuracy at certain letter positions, followed by a steep rise in letter recognition accuracy at several letter positions away — a result that resembled the visual-span profiles of several participants in the study of Cheong et al. (2008). Because of the irregular shapes of these visual-span profiles, we will not be fitting any mathematical functions to describe the shape of the profiles. Nevertheless, to facilitate a quantitative comparison of the size of the visual span before and after training, we adopted the method used previously (e.g., Cheong et al., 2008; Chung et al., 2004; Chung & Truong, 2013; Legge et al., 2001, 2007) to convert letter recognition accuracy at each letter position to bits of information transmitted according to the following equation, which was derived based on confusion matrices for single letter recognition measured empirically by Beckmann (1998):

$$\text{Bits of information} = -0.037 + 4.676 \times \text{proportion-correct of letter recognition}$$

The size of the visual span was then represented by the sum of the bits of information transmitted across all letter positions (from letter position –5 [left of fixation] to letter position +5 [right of fixation]).

Training task

The training consisted of six sessions, scheduled on six different days. There were 10 training blocks per session, with 50 trials per block. Observers were encouraged to take a short break between blocks. Each session took on average approximately 1.5 hours. The training task was similar to the task for measuring threshold duration for letter recognition. On each trial, a trigram was presented at the fixation location and observers were asked to recognize all three letters, from left to right. Print size used was equivalent to 1.4 times the CPS. At the beginning of training, the trigram exposure duration was set at each observer's own pretest threshold duration (discussed earlier). Accuracy for recognizing the middle letters of trigrams was summarized at the end of each block. As soon as the recognition accuracy reached 80% or higher for four consecutive blocks, the exposure duration was shortened by 0.1 log unit (e.g., decrease from 320 ms to 250 ms).

One-week follow-up visit

To evaluate if the improvements during training, if any, could be retained after training ceased, all observers returned for a follow-up visit a week after the post-test (for most observers, that means 3 weeks after the last training session). Testing comprised five blocks of trials, the same as those used for training, with the trigram exposure duration fixed at the duration used for the last training block.

Apparatus

Measurements of RSVP reading, threshold duration for letter recognition, visual-span profile, and for the training task, were performed using the same set up. Stimuli were generated and experimental procedures were controlled using a Macintosh G4 computer, with software custom-written in MATLAB 7.7.0 (The MathWorks, MA) using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). A Sony color graphics monitor (model#GDM-17E21) was used to display the letter or word stimuli at a refresh rate of 85 Hz and a resolution of 1280 × 1024 pixels (36.75 × 29.60 cm). All stimuli were rendered in Courier font, as black (2.6 cd/m^2) letters on a white background (153.8 cd/m^2).

Results

Training effect

Accuracy for recognizing the middle letter of trigrams is plotted as a function of training block (blue unfilled circles, left axes) in Figure 2. Individual panels summarize the training performance for individual observers. Each circle represents the recognition accuracy for a block of 50 trials (trigrams were presented for the same duration within a block). Because of our experimental design and the criterion adopted for determining the trigram exposure duration to be used, the performance for all observers hovered around an accuracy of 80%. Also plotted in each panel, in red, is the exposure duration used for the specific training blocks (values shown on the right axes). As training progressed, all observers were able

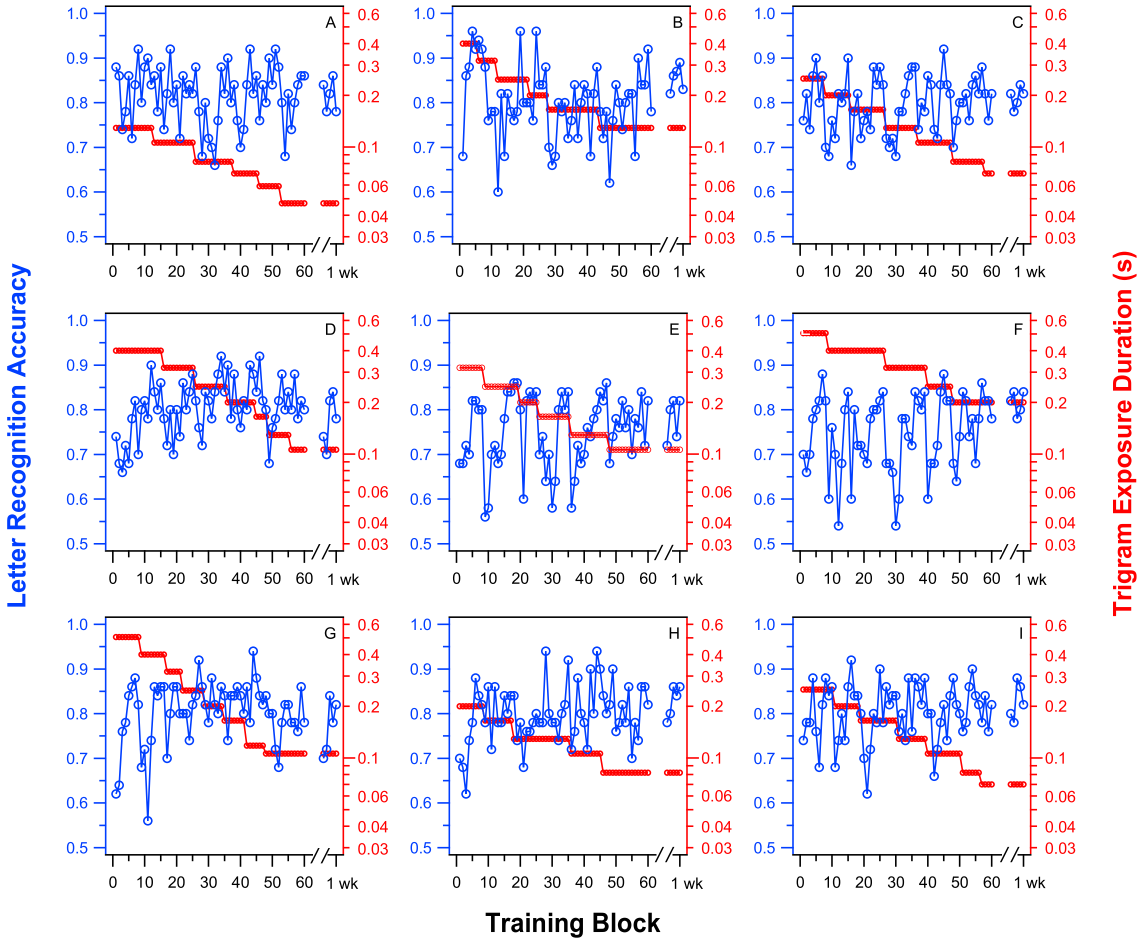

Figure 2. The accuracy for recognizing the middle letter of trigrams (*left axis*) is plotted as a function of training block in *blue*. Each panel presents data for an individual observer (observer ID is given in each panel). Each blue circle represents the proportion-accuracy for a block of 50 trials. The trigram exposure duration used for any given block is plotted in *red* (*right axis*).

to perform the training task at successively shorter durations, accounting for the step-like changes of the red symbols and lines. After 60 blocks of training, the mean exposure duration was shortened to 31.8 ± 6.5% of the baseline value, representing a significant training effect on speeding up temporal processing of letters, two-tailed paired *t*-test comparing the first and the last block: $t_{df=8} = 6.80$, $p < 0.0001$. This amount of improvement was highly comparable with that of Yu et al. (2018) who investigated the effect of training on temporal processing of letters in normal peripheral vision. In that study, after 4 days of training with a paradigm similar to the present study, temporal processing of letters (based on the letter exposure duration) improved by 25 ms per day (decreasing from an average of 217 ms on day 1 to 142 ms on day 4). If we extrapolate the improvement to 6 days of training, the average letter exposure duration would have been 67 ms on day 6, equivalent to 30.9% of the baseline value.

Transfer effects

The secondary goal of this study was to test whether or not training to improve temporal processing of letters leads to faster reading speed. To ensure that our results are not specific to a particular way of evaluating reading performance, we evaluated reading speed using three different methods: the RSVP paradigm, the MNREAD Acuity Chart and passages of newspaper articles.

Figure 3 summarizes the pretest and post-test reading performance measured using the RSVP paradigm for the nine observers. Each panel shows the results for one observer. As shown previously (e.g., Chung, 2002, 2011; Chung et al., 1998, 2004), reading speed increases with print size until the CPS and then plateaus at the MRS. When fitted using the bilinear fit (see Methods for details), the x-value of the intersection of the two lines represents the CPS and the y-value of the intersection yields the MRS. If training leads to an improvement in

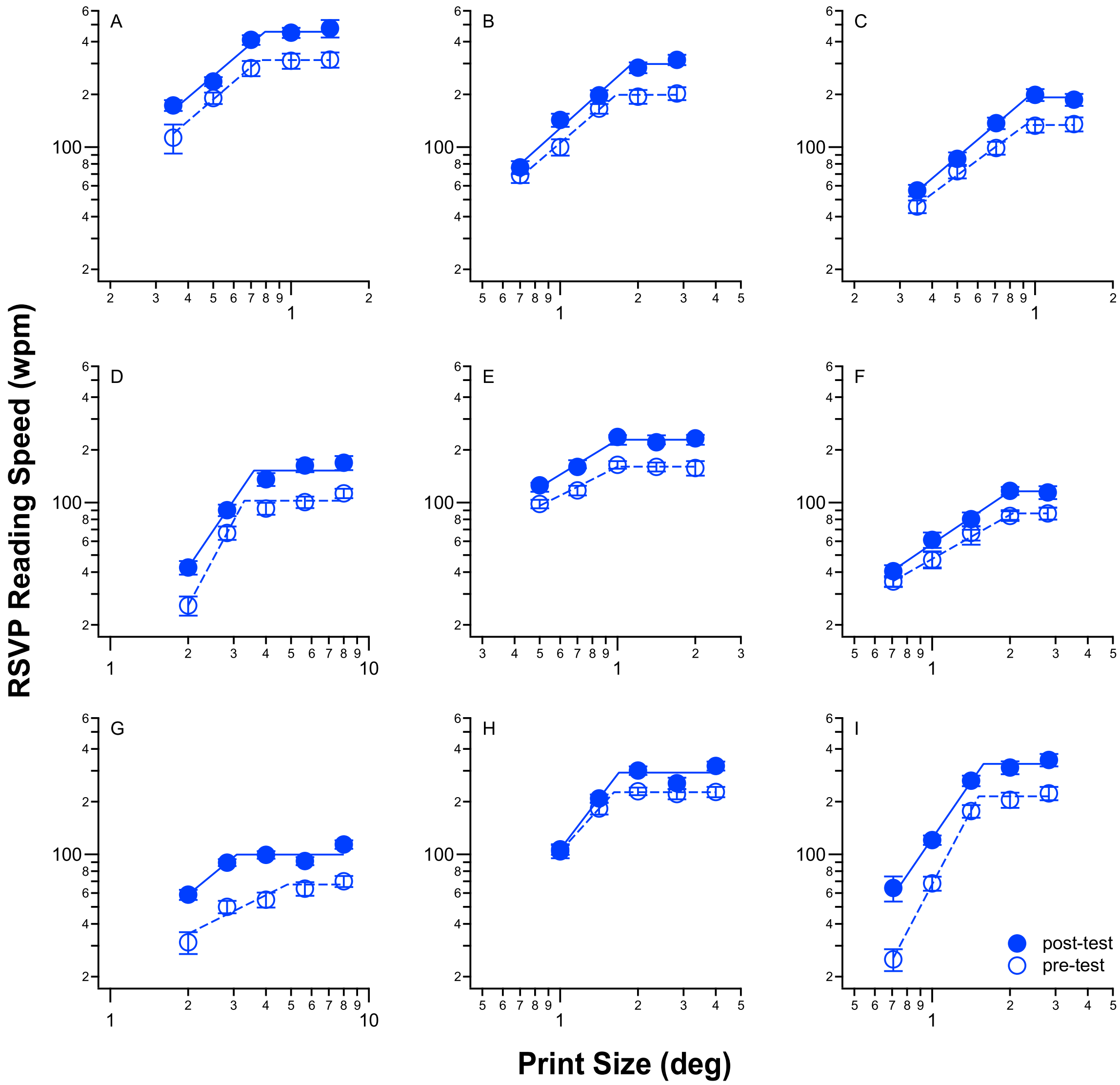

Figure 3. Reading speed (wpm) measured using the RSVP paradigm is plotted as a function of print size (degrees) for the nine observers. A bilinear fit in which the slope of the second line was constrained at zero was used to fit each set of data (*dashed line*, pretest; *solid line*, post-test). Unfilled symbols represent pretest results and filled symbols represent post-test results. Error bars represent ±1 SEM.

MRS, we expect to see an upward shift of the two-line function for the post-test measurement, when compared with the pretest. As for CPS, a leftward shift (shifts toward smaller print sizes) of the post-test, compared with the pretest function, signifies that observers were able to read smaller print sizes after training. Here, the post-test functions relating RSVP reading speed with print size are shifted vertically above the pretest functions for all observers, implying that the MRS measured using the RSVP paradigm (MRS_{RSVP}) was higher after than before training, two-tailed paired t-test on log MRS_{RSVP}: $t_{df=8} = -19.4$, $p < 0.0001$. Across observers, the MRS_{RSVP} improved by an average of 44.00 ± 0.08%. However, there was no change in CPS after training, two-tailed paired t-test: $t_{df=8} = 0.57$, $p = 0.58$. The ratio of CPS after and before training (post–pre ratio) averaged 1.00 ± 0.14.

The second measurement of reading performance was obtained using the MNREAD Acuity Chart. Figure 4 compares the pretest and post-test performance for the nine observers. Like the measurement using RSVP, reading speed measured using the MNREAD Acuity Chart shows a drastic improvement with small print sizes, with the rate of improvement slowing down after the print size reaches a certain level, beyond which reading speed seems to reach a plateau. However, unlike what we observed for the results for RSVP reading (Figure 3), there is no sizeable upward shift of the post-test reading speed versus print size function, when compared with the pretest one. In other words,

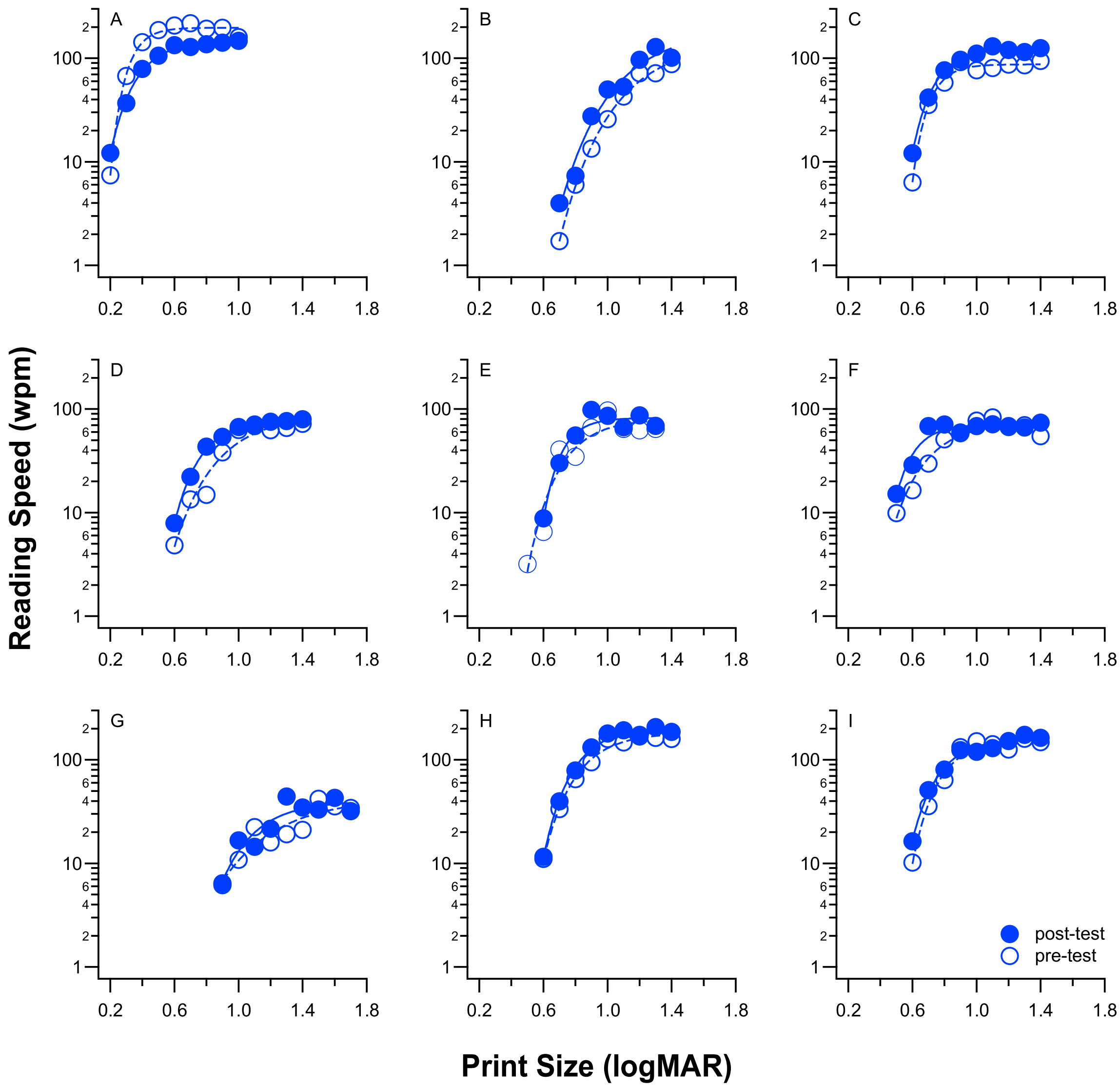

Figure 4. Reading speed (wpm) measured with the MNREAD Acuity Chart is plotted as a function of print size (logMAR) for the nine observers. An exponential function was used to fit each set of data (*dashed line*, pretest; *solid line*, post-test). *Unfilled symbols* represent pretest results and *filled symbols* represent post-test results.

the improvement in the temporal processing of letter recognition owing to training does not transfer to a higher MRS when measured using MNREAD, two-tailed paired t-test on log MRS_{MNREAD}: $t_{df=8} = -0.42$, $p = 0.69$, or a change in TPS, two-tailed paired t-test: $t_{df=8} = 1.88$, $p = 0.10$. The post–pre ratios for MRS_{MNREAD} and TPS averaged 1.05 ± 0.21 and 0.94 ± 0.18, respectively.

The third measurement of reading speed was obtained using passages of newspaper articles that contained 100 words each. Across observers, passage reading speed was 1.82 ± 0.24 log-wpm (corresponding to a geometric mean reading speed of 65.7 wpm) before training, and 1.87 ± 0.21 log-wpm (corresponding to a geometric mean reading speed of 74.6 wpm) after training. There was no difference between the pretest and post-test passage reading speed (two-tailed paired t-test on log reading speed: $t_{df=8} = -1.48$, $p = 0.18$). A comparison of the pretest and post-test passage reading speed for the nine observers is shown in Figure 6h.

In addition to reading speed measurements, we also obtained measurements for visual acuity, location of the fPRL, fixation stability, visual span and the threshold duration for letter recognition. Averaged across observers, there was no change in visual acuity after training (0.84 ± 0.25 logMAR (before) versus 0.85 ± 0.23 logMAR (after), two-tailed paired t-test: $t_{df=17} = -0.99$, $p = 0.33$, Figure 6a)[2]. Fixation stability also did not change after training, 3.90 ± 2.36 log-deg^2 (before) versus 3.81 ± 2.24 log-deg^2 (after), two-tailed paired t-test: $t_{df=8} = 0.89$, $p = 0.40$ (Figure 6b.) As for the location of the fPRL, because it is difficult to use

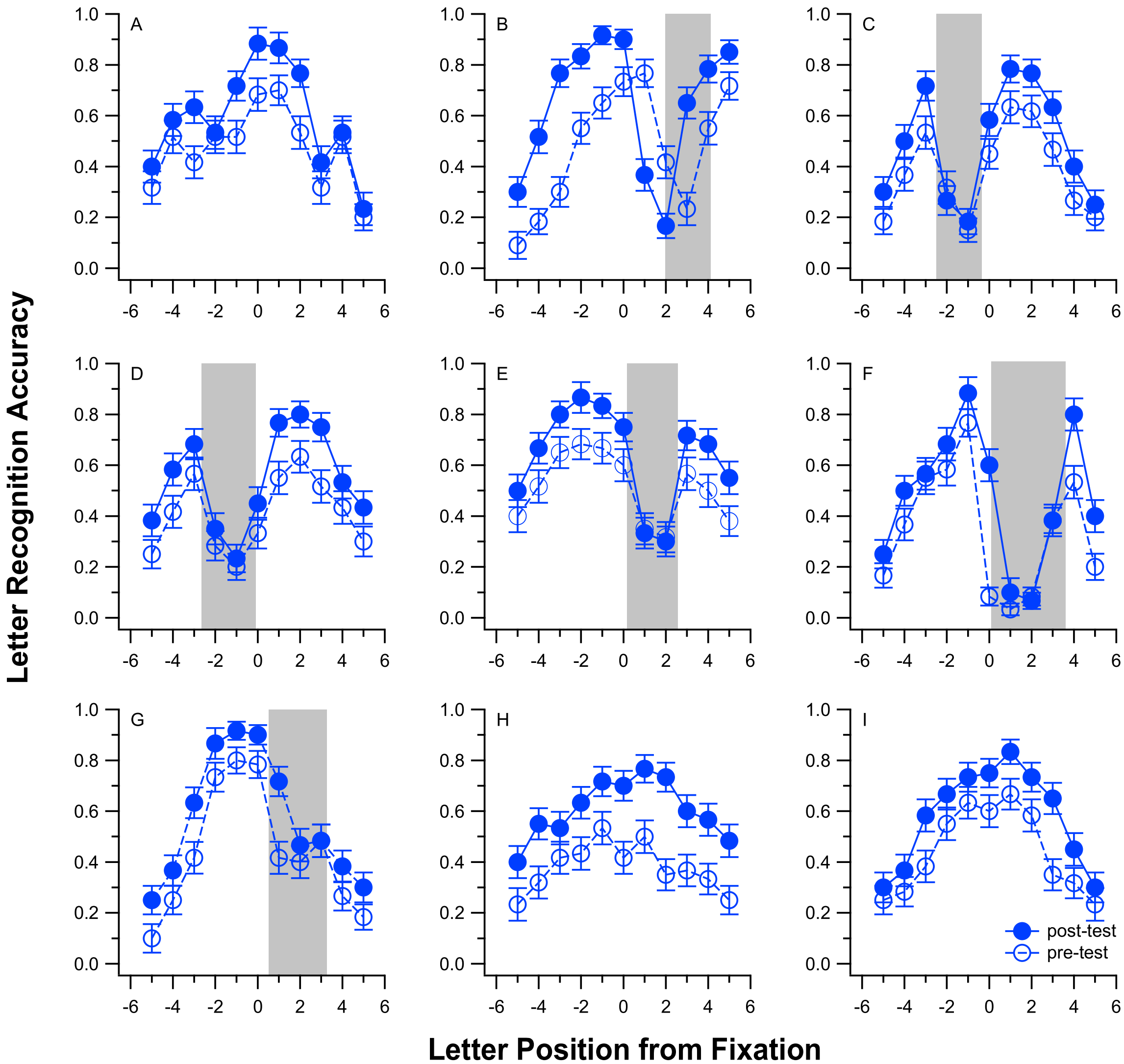

Figure 5. Visual-span profiles, plots of accuracy of letter recognition as a function of letter position from fixation, are shown here for the nine observers. The *shaded region* in each plot, if present, represents the horizontal extent (because trigrams were presented along the horizontal meridian) of the scotoma of the observer. Note that there was a shift in the visual-span profile for observer B, which was most likely owing to a shift of his PRL for fixation for this task (see Supplementary Figure S1). Unfilled symbols connected by dashed lines represent pretest results and filled symbols connected by solid lines represent post-test results. Error bars represent the standard errors of proportion. The size of a visual-span profile is defined as the sum of the bits of information transmitted across letter positions from −5 to +5 (refer to the main text for details of the conversion from letter recognition accuracy at each letter position to bits of information transmitted).

a single number to represent it, we summarized the location of the fPRL for all observers in Supplementary Figure S1 (Supplementary Information). Across observers, the location of the fPRL did not vary substantially after training.

Pretest and post-test visual-span profiles for the nine observers are plotted in Figure 5. In normal central and peripheral vision, visual-span profiles usually peak around letter position 0, which represents the fixation point, and falls off as letter positions increase from the fixation point. Conventionally, visual-span profiles are fitted using a split-Gaussian function. For people with macular disease, Cheong et al. (2008) reported that visual-span profiles sometimes show a sharp decrease in letter recognition accuracy at some letter positions, with the decrease reaching an accuracy close to zero in some cases. The positions at which the sharp decreases occurred were thought to correspond to the central scotomas. Similar to the report of Cheong et al., six of our nine observers showed a sharp decrease in letter recognition accuracy at some locations away from fixation. The letter positions at which these sharp decreases occurred were consistent with the location and size of the observer's central scotoma (as measured

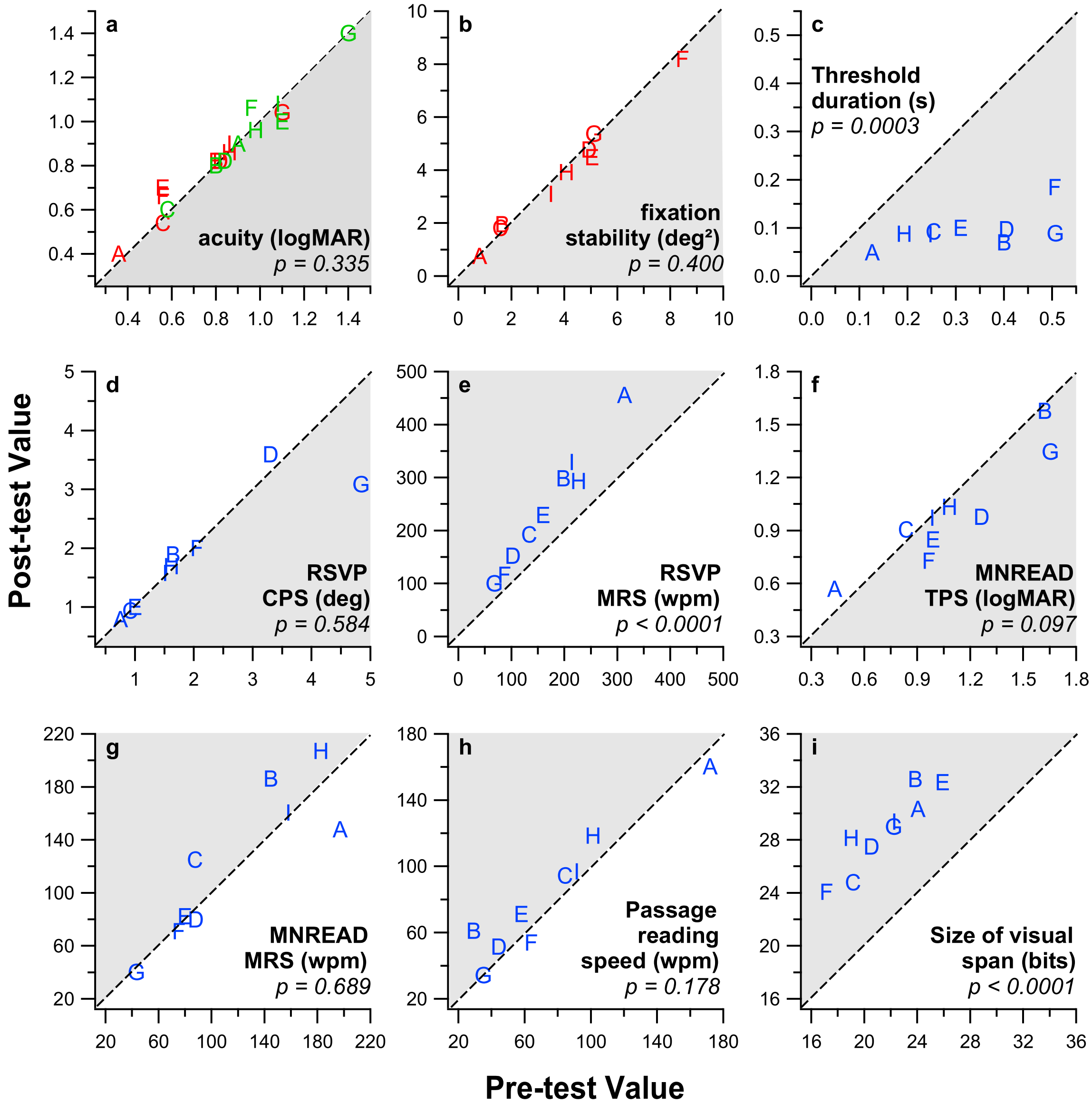

Figure 6. Post-test values are plotted as a function of pretest values for the nine observers (denoted by their observer IDs) and for each of the measurements: (a) visual acuity, (b) fixation stability, (c) threshold duration, (d) CPS estimated using the RSVP method, (e) MRS estimated using the RSVP method, (f) TPS estimated using the MNREAD chart, (g) MRS estimated using the MNREAD chart, (h) passage reading speed, and (i) size of the visual span. (a) *Red* and *green symbols* represent acuities for the better and worse eyes, respectively. (b) Results plotted were obtained from the better eye. For the rest of the panels, results plotted were obtained binocularly (shown in *blue*). In each panel, the dashed line represents the unity line (no change in values before and after training) and the shaded region represents the region of improvement. The *p*-value given in each panel was based on a *t*-test. Among all the measurements, improvements were observed only for threshold duration (c), MRS estimated using the RSVP method (e) and size of the visual span (i).

using the tracking scanning laser ophthalmoscope). Regardless of whether the visual-span profiles were smooth curves or showed idiosyncratic decreases in letter accuracy at some letter positions, we were more interested in whether or not there was an improvement in the visual-span profiles after training. An improvement in the visual-span profile is defined as one that is larger in size, and thus transmits more information. This could be manifested as a broader profile, or a profile that shifts upward. Figure 5 shows that all observers' post-test visual-span profiles are generally higher than their pretest profiles. To quantify the size of the visual span, we expressed the size of the visual span in terms of bits of information transmitted. Averaged across observers, the size of the visual span profiles was 21.57 ± 2.84 bits before training and 28.66 ± 2.96 bits after training, representing a significant improvement and a transfer of the training effect, two-tailed paired *t*-test: $t_{df=8} = -18.85$, $p < 0.0001$ (see also Figure 6i).

Figure 6 compares the pretest and post-test values for each of our measurements. In each panel, post-test measurements are plotted on the *y*-axis and pretest measurements are plotted on the *x*-axis. Each observer is represented by his or her observer ID (Table 1). The dashed line represents the unity line (no change between pretest and post-test). Observers who showed an improvement following training would fall within the shaded region, and the *p*-value given was based on a paired *t*-test. Note that these *p*-values have not been corrected for multiple comparisons. If we apply the conservative Bonferroni corrections, taking into account a total of nine comparisons were made, we could compare our *p*-values against a significance level of 0.0056 to determine if the *p*-values are significant or not, which does not change our pattern of results. Across all measurements, the only three that show a significant change of post-test values from pretest values are the threshold duration, size of the visual span and MRS_{RSVP}.

Given that our training task was designed to boost temporal processing of letters, and that all observers exhibited an improvement on the task, it came as no surprise that the threshold duration improved after training. The improvement in the size of the visual span was likely a consequence of the improved temporal processing of letters, because the method for measuring visual span relied on the recognition of letters of the presented trigrams. As for the improvement in MRS_{RSVP}, the improvement could be due to its association with the temporal threshold for letter recognition (Cheong et al., 2007), or its association with the size of the visual span (Legge et al., 2001, 2007) although this association has been shown to be weak for people with macular disease (Cheong et al., 2008).

Retention of improvements

All observers attended a follow-up visit 1 week after the post-test (i.e., 3 weeks after the last training session, except for observer B, as stated earlier in this article), during which their letter recognition performance was measured for five blocks, using identical stimulus parameters as their respective last training block. These results are plotted in Figure 2 above the label "1 wk" on the *x*-axis. Averaged across observers, the average recognition accuracies of these five blocks of trials were not different from those of the last five training blocks, two-tailed paired *t*-test: $t_{df=8} = 0.60$, $p = 0.56$,[3] implying that observers were able to retain their improvements owing to training, at least for several weeks.

What governs the improvement in RSVP MRS?

The improvement in MRS_{RSVP} after perceptual learning to boost temporal processing of letters is encouraging (the lack of improvements in reading speed measured using MNREAD and passages are discussed in the Discussion). To explore the factors that led to the improved reading speed, we examined the correlations of the magnitude of improvement (post–pre ratio) in MRS_{RSVP} with the magnitudes of improvement in the training duration and the size of the visual span. We chose to examine the changes in training duration instead of the threshold duration measured in the pretest and post-tests because they were derived directly from training and thus they represented a more direct transfer effect. We also examined an additional factor, information transfer rate, defined as bits of information transmitted by the visual span per unit time (unit: bits/s). According to Cheong et al. (2008), the information transfer rate demonstrated a higher correlation with reading speed than the size of the visual span per se. These relationships are summarized in Figure 7. Despite the significant correlations reported previously between MRS_{RSVP} and the size of the visual span (Legge et al., 2001, 2007), and between MRS_{RSVP} and information transfer rate (Cheong et al., 2008), none of these relationships shown in Figure 7 yield a significant correlation.

The lack of a significant correlation between the magnitude of improvement of MRS_{RSVP} and that of training duration, size of visual span or information transfer rate seems puzzling, given the results from previous studies. A potential explanation is that what we examined were the correlations of the *magnitudes of improvement* of the variables of interest, instead of the values of the variables, as in previous studies (Cheong et al., 2008; Legge et al., 2001, 2007). Therefore, in Figure 8, we evaluated the correlations of the values of these variables, and we did so for the pretest and post-test values separately. These correlations were performed on the log values of the variables (except for the size of the visual span, which is already a logarithmic quantity; Yu, Cheung, Legge, & Chung, 2007), given that reading speed and duration data are conventionally analyzed in their log values (because the variance is proportional to the value). The results show that log MRS_{RSVP} exhibits a significant correlation with log training duration and log information transfer rate, but not with the size of the visual span, for both the pretest and post-tests.

The significant correlations between log MRS_{RSVP} and log training duration are consistent with the proposition of Cheong et al. (2007) of a strong temporal limitation on reading speed, at least for RSVP reading, which was what Cheong et al. (2008) measured in their study. Cheong et al. (2008) further proposed that the information transfer rate was a better predictor of reading speed than the size of the visual span itself. Here, we showed that there was also a significant correlation between log MRS_{RSVP} and information transfer rate. However, Cheong et al. (2008) did not clarify the roles or contributions of temporal duration and information transfer rate on reading speed. Are

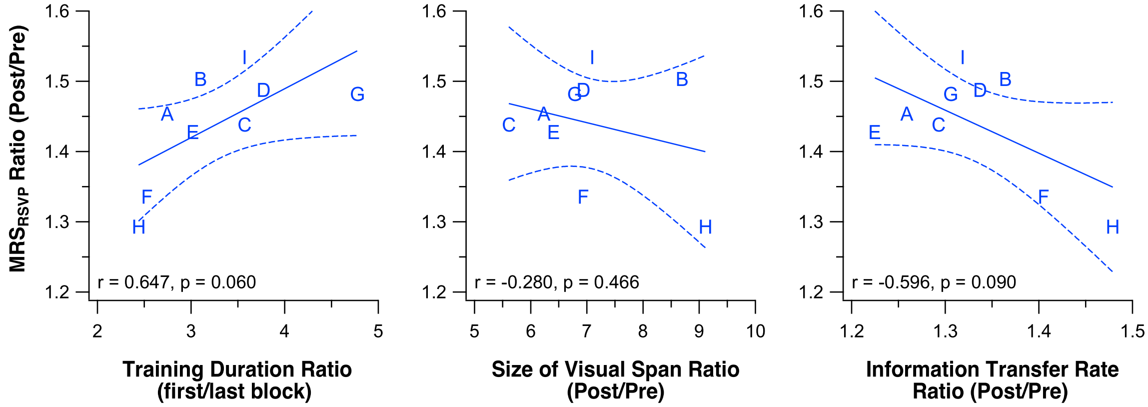

Figure 7. The magnitude of improvement of MRS_{RSVP} is plotted as a function of the magnitudes of improvement for training duration (*left*), size of visual span (*middle*), and information transfer rate (*right*). With the exception for training duration, the magnitude of improvement is calculated as the ratio of values between the post-test and the pretest. For training duration, the magnitude of improvement is defined as the ratio between the duration used in the first and the last training block. Data for individual observers are denoted by their observer IDs. *Solid lines* represent the best fit regression line to the data and the *dashed lines* represent the 95% confidence bands. The Pearson's correlation coefficients and whether or not they are statistically different from the null hypothesis of a correlation coefficient of zero are given as *p*-values in each panel.

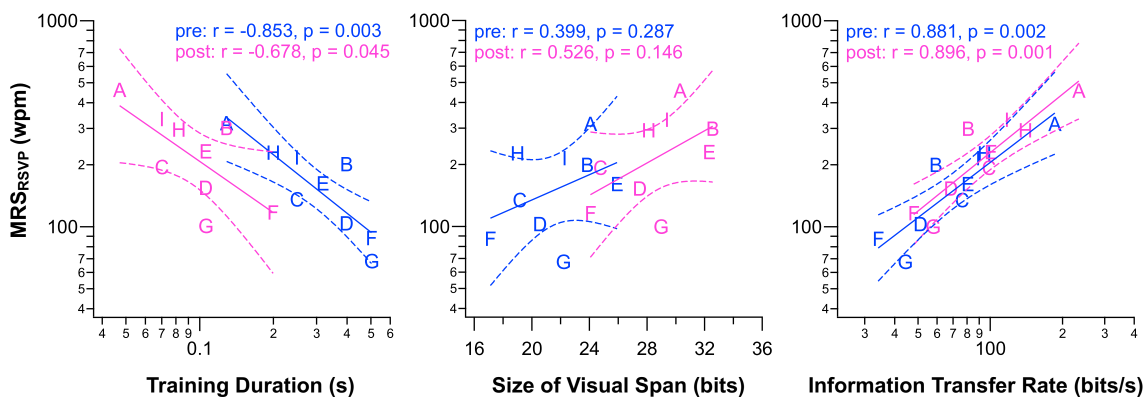

Figure 8. MRS_{RSVP} is plotted as a function of (*left*) training duration, (*middle*) size of visual span, and (*right*) information transfer rate for the nine observers (denoted by their observer IDs), before (*blue*) and after (*pink*) training. *Solid lines* represent the best fit regression line to the data and the *dashed lines* represent the 95% confidence bands. The Pearson's correlation coefficients and whether or not they are statistically different from the null hypothesis of a correlation coefficient of zero are given as *p*-values in each panel.

the effects of these two factors independent, or are they related? Considering that information transfer rate comprises two factors — size of the visual span and duration, and that there was a significant effect of training duration on information transfer rate, regression analysis performed on the log values of the two variables: $r = –0.966$, $p < 0.0001$, could the effect of training duration on reading speed simply reflect the combined effects of training duration on improving the information transfer rate, and the benefit of an improved information transfer rate on reading speed? To explore this possibility, we performed a mediation analysis (Baron & Kenny, 1986) to examine whether the effect of training duration on reading speed was mediated by the information transfer rate. Details of the procedures of the mediation analysis can be found in Calabrèse et al (2014), Chung, Kumar, Li, and Levi (2015) and Agaoglu and Chung (2020). The analyses were performed on the pretest and post-tests results separately.

In brief, we took reading speed as our dependent variable, training duration as the independent variable and information transfer rate as the mediator. We used the lavaan ("latent variable analysis": Rosseel, 2012) package in R (2017) to perform the mediation analysis. Bootstrapping, based on 10,000 resamples, was used to estimate the 95% confidence intervals. Table 2 summarizes the output of the mediation analysis. For the pretest results, the ratio of the indirect to total effect was 0.954, suggesting that the effect of training

	Point estimate	CI lower percentile	CI upper percentile
Pretest			
Indirect effect	−0.900	−2.854	0.584
Total effect	−0.943	−1.364	−0.486
Ratio of indirect to direct effect	0.954	−0.568	4.022
Post-test			
Indirect effect	−1.402	−2.245	−0.441
Total effect	−0.826	−1.566	−0.053
Ratio of indirect to direct effect	1.698	−0.003	5.384

Table 2. Results of the mediation analyses: Point estimates and 95% CIs for the indirect effect of training duration on reading speed through information transfer rate, the total effect and the ratio of the indirect to total effect (a common measure of the effect size).

duration on reading speed was almost completely explained by the combined effects of training duration on information transfer rate, and information transfer rate on reading speed. For the post-test results, the ratio of the indirect to total effect was 1.698, which seems difficult to interpret. According to Kenny and Judd (2014), a ratio greater than 1 implies inconsistent mediation and usually arises as a consequence of the indirect effect having a different sign than the direct effect (MacKinnon, Fairchild, & Fritz, 2007). The result may also suffer from a weaker (although still significant at the alpha = 0.05 level, see Figure 8 left panel) total effect of training duration on reading speed. In any case, we acknowledge that the confidence intervals were rather large for both the pretest and post-tests; thus, caution should be taken when interpreting the significance of these ratios.

Discussion

The main objectives of this work were to evaluate whether letter recognition could be sped up through perceptual learning for people with central vision loss, and if so, whether the improvement could lead to better reading performance. Our results clearly showed positive results for both objectives, but there was a major caveat. We only observed an improvement in reading speed when measured using RSVP (MRS improved by an average of 44%), but not when it was measured using MNREAD Acuity Chart or passages. Why?

Despite the surge in popularity of using RSVP to measure reading performance in research settings over the past decades, one lingering question is how relevant is RSVP reading to daily reading, that is, reading that requires eye movements. Direct comparisons between RSVP reading and reading requiring eye movements are scarce. Pioneering studies primarily focused on comparing comprehension, memory and linguistic limitations between the two modes of reading (e.g., Juola, Ward, & McNamara, 1982; Masson, 1983; Potter, Kroll, & Harris, 1980). In general, it has been found that, despite the faster rate at which text could be presented using RSVP (note that all these previous studies used "silent reading" in which participants did not need to orally read the words), a memory buffer was needed for participants to process the information and comprehend the text. Therefore, the benefit of RSVP over conventional reading was limited to single sentences, or, when a brief pause (e.g., 500 msec) was inserted after each sentence in the case of longer passages (Masson, 1983). Rubin and Turano (1992) were likely to be the first investigators to adopt RSVP reading speed itself as a performance measurement by measuring oral reading speed. They tested the dependence on print size of reading using the RSVP and PAGE (sentence or passage reading that required eye movements) format for a group of normally sighted observers and found that while RSVP reading speed exhibited a stronger dependence on print size than PAGE reading, the advantage (higher reading speed) of RSVP over PAGE reading persisted over the range of print sizes they tested (2× – 32× participant's single letter acuity), and for both oral and silent reading. Based on these results, Rubin and Turano (1994) hypothesized that the advantage of RSVP over PAGE reading would be greater for people with central vision loss, many of whom exhibit poor eye movement control. Contrary to their prediction, the benefit of RSVP over PAGE reading was smaller for their participants with central vision loss than for those with intact central vision. Yu et al. (2007) compared the effect of letter spacing on reading speed and the size of visual span for RSVP and "flashcard" reading for a group of normally sighted observers. Flashcard was a procedure in which MNREAD sentences were presented on a computer display one sentence at a time with a fixed exposure duration. These authors found that RSVP and flashcard reading demonstrated qualitatively similar dependence of reading speed and size of visual span on letter spacing. In short, there is no single established relationship between RSVP reading and reading that requires eye movements.

There are several potential reasons why we observed an improvement in RSVP reading speed after our training protocol, but not for MNREAD or passage reading. First, there was a font difference. The text was rendered in Courier font when presented using RSVP, and was printed in Times Roman on the MNREAD Acuity Chart and for the passages. Mansfield, Legge, and Bane (1996) reported a 10% higher reading speed with Courier than with Times font for participants with central vision loss, whereas subsequent studies reported similar reading speeds with Courier and Times fonts (Tarita-Nistor et al., 2013; Xiong et al., 2018). Hence, even if there was an advantage in using Courier for the RSVP format, it was likely to be small. Besides a font difference, there were also methodology differences. Our training task required observers to fixate well at a certain location on the display at which the stimulus trigrams were presented. This paradigm did not encourage observers to make saccadic eye movements from words to words (or more specifically, from a group of letters to another group of letters), which is essential in eye-movement–based reading, or in our case, MNREAD and passage reading. Therefore, even if our training task were beneficial in improving the temporal processing of letters, MNREAD and passage reading could still be limited by oculomotor demands, which the training task was not designed to address. Another characteristic of eye-movement-based reading is the availability of parafoveal information (words to the right of the fixated word), which is fundamental to the concept of perceptual span for reading (e.g., McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980). Perceptual span refers to the region around fixation in which useful information from the text is available to the reader during normal reading. Unlike the concept of visual span which is primarily limited by sensory factors, perceptual span is also influenced by cognitive factors and oculomotor control, and thus is larger than the visual span, extending to approximately 15 characters to the right and 4 characters to the left of fixation. Rayner and his colleagues have shown that parafoveal information is important because it facilitates subsequent lexical processing of words when they are fixated eventually (e.g., Rayner, 1978; Rayner, McConkie, & Zola, 1980; Schotter, Angele, & Rayner, 2012). Potentially, our training task might have encouraged observers to focus their attention over the fixation region, given that only three letters were presented in each trial. This focused attention could benefit RSVP reading but could hurt MNREAD and passage reading because observers were trained to focus their attention around the fixation region. When tested with the MNREAD and the passage reading task, observers would need to redistribute their attention over a larger area to benefit from parafoveal information. If observers could not readily readjust to deploying their attention over a larger area than during training, that might impact their performance on eye-movement–based reading. Further, with our RSVP procedure, even though the word exposure durations used were tailored to each individual observer, observers could not simply read at their own pace as for MNREAD and passage reading, because words presented via RSVP would disappear after the specified word exposure duration, whereas for MNREAD and passage reading, the reading materials were present until the participant finished reading the sentence/passage. Previously, Calabrèse et al. (2014) reported that reading speed of people with central vision loss was negatively correlated with fixation duration. Therefore, when the RSVP word exposure durations were short, observers' reading speed increased. Observers may also be under the pressure to read as quickly as possible before the words disappear, which could potentially explain why Yu et al. (2007) obtained qualitatively similar dependence of reading speed and size of visual span on letter spacing, because their flashcard procedure, like RSVP, only presented the reading materials for a fixed amount of time. Last, Calabrèse et al. (2016) showed that the locations of eye fixations of people with central vision loss were not uniformly distributed across a line of text, but rather fixations were clustered more around long, difficult, or low-frequency words. The nonuniformity of fixations was found to be a strong determinant of reading speed. The fixed duration used for all words in an RSVP sequence, regardless of the word length and word frequency, minimizes the nonuniformity of eye fixations, which theoretically would lead to improved reading speed. Of course, the lack of an improvement in MNREAD and passage reading is likely to be due to a combination of these factors.

Clinical implications

In addition to our main findings of an improvement in speed in letter recognition, and the associated improvement in MRS_{RSVP}, there are several auxiliary findings based on other task performance that are worth noting, especially in relation to the implications of using training to improve task performance for people with central vision loss.

First, Figure 5B shows that the depression in the post-test visual-span profile was shifted relative to that in the pretest. Most likely, this was due to a shift in this observer's fPRL (the depression represents the location of his dense scotoma) instead of an improvement in letter recognition at some locations that were previously within the scotoma, coupled with a decrease in performance at other locations that were previously outside the scotoma. In Supplementary Figure S1 (Supplementary Information), we show the retinal locations used for fixation during a 10-second fixation trial for each observer, before and after training. As mentioned earlier, by fitting the set of data with a probability density function, we used the location corresponding to the peak probability as a representation of the fPRL. Supplementary Figure S1B shows that the post-test fPRL is shifted horizontally by approximately 2.2° when compared with the location of the pretest fPRL, coinciding with the amount of shift in the position of the depression in his visual span. Although it was not our intention to train observers to adopt an alternate retinal location as the fPRL in this study, this finding confirms that sometimes it only takes a patient to shift his or her gaze by a small amount so that he or she could use an area adjacent to the dense central scotoma to see better. As for the other observers, we found no evidence that they adopted another retinal location as their fPRLs based on the consistency of the location of the depression in their visual-span profiles before and after training (Figure 5), as well as from the fundus images (Supplementary Figure S1). Of course, we acknowledge that, considering we did not formally monitor the retinal locations used by our observers during training, we do not know for certain whether the PRL used for letter recognition or for reading was the same as that for fixation (fPRL), and we also do not know whether the PRL used for letter recognition or for reading was indeed shifted during and after training. These questions could only be answered if the retinal locations for visual tasks are measured continuously throughout the training phase, for example, by using a scanning laser ophthalmoscope.

Second, although the training trigrams were presented only at a single fixed location on the display, there was a general improvement in letter recognition performance across all letter positions when we measured the visual-span profiles, consistent with that shown by Chung and Truong (2013) and He and Legge (2017). He and Legge (2017) suggests that this lack of a location-specific improvement might indicate a non–retinotopic-specific mechanism that underlies the enlargement of the visual span following training. One such mechanism could be a better template-matching process that results from perceptual learning (e.g., Dosher & Lu, 1999; Gold, Sekuler, & Bennett, 2004; Sun, Chung, & Tjan, 2010). The clinical implication of this lack of a location-specific improvement means that if our goal were to enlarge the visual span profile of patients through perceptual learning, we could simply present the training stimulus at a single location, instead of multiple locations, overcoming the main barrier of measuring visual span profiles for people with central vision loss (Thayaparan et al., 2010). Note however that even if the visual span profiles are enlarged for people with central vision loss, their reading speed may not improve correspondingly (Figure 8, also see Cheong et al., 2008).

Third, despite an improvement in $\mathrm{MRS_{RSVP}}$, there was no change in the CPS (note that there was also no change in the TPS for MNREAD reading), nor was there a change in the acuity of our observers. In other words, we were able to help observers read faster for print that exceeded their CPS, but we could not help them read smaller print or improve their resolution capability. This finding is reminiscent of that of Chung (2011), who trained her observers with macular disease using an RSVP reading task. Tarita-Nistor et al. (2014) also used RSVP to train observers with macular disease but with a print size closer to the acuity-limit of the observers, instead of 1.4 times the CPS used by Chung (2011). Like the results reported here and in Chung (2011), there was an improvement in MRS (by 11%) but no change in CPS. However, these authors observed an improvement in reading acuity as well as in visual acuity. Whether our training paradigm could have resulted in an improvement in visual acuity had we used a smaller print size would need to be tested in a future study.

Using our training paradigm that aimed at boosting the processing speed of letters, we observed an average improvement in $\mathrm{MRS_{RSVP}}$ of 44%. In a previous study, we observed an average improvement in $\mathrm{MRS_{RSVP}}$ of 53% when using RSVP reading as the training task (Chung, 2011). A two-tailed two-sample t-test assuming unequal variances showed that the magnitudes of improvement were not different between the two studies, $t_{\mathrm{df}=6} = 1.22$, $p = 0.27$, suggesting that the paradigm used in the present study was not more, or less effective in improving reading speed than what we have observed in the past. However, we should keep in mind the finding of Yu et al. (2010), who showed that the most effective training task to improve performance on a given task is the task itself. In other words, if the goal is to improve reading speed, then training on a reading task would be more effective than any other training tasks.

Coda

This study was not designed to be a clinical trial to evaluate the effectiveness of training to improve temporal processing of letters on reading for people with central vision loss. A proper clinical trial should have a larger sample size with participants randomly assigned to the intervention and a control group, and preferably with the experimenter(s) masked as to the group-assignment of the participants. This study was simply testing the feasibility of boosting the temporal processing of letters through training and to determine if that would lead to improved reading speed. Given our limited number of observers, and the substantial individual observer variability, we were still able to show an effect of the training paradigm. The information provided here would be useful for the design of, and the calculation of sample size for, future clinical trials designed to use perceptual learning paradigms to improve reading performance for patients with central vision loss. However, we suggest that the choice of a training task should consider several factors. Should the training task be focused on removing or minimizing some spatial bottleneck on reading (e.g., expanding the visual span), or should it focus on improving the temporal aspects of reading? Clearly, spatial and temporal factors are inseparable in relation to reading; therefore, future studies may wish to design a training task that could decrease both spatial and temporal limitations on reading. Perhaps that may produce a synergistic benefit on reading speed greater than what we observed in this study or in previous studies. Further, considerations should be given to designing a training task that could transfer any improvement to eye-movement–based reading.

In summary, despite the relatively small number of observers tested in this study, we observed a robust training effect after only six sessions of training to recognize letters, a task that is fairly simple for observers, especially older adults. The training effect, a shorter temporal duration for letter recognition, was associated with faster RSVP reading speeds and an enlarged visual span. A mediation analysis showed that the relationship between the temporal duration for letter recognition and RSVP reading speed was almost completely mediated by the information transfer rate — a combined effect of temporal duration and the size of the visual span. However, at least with respect to improving reading speed, the temporal duration training task was not more effective than training using RSVP reading (Chung, 2011). Further, the improvement in reading speed was observed only for an RSVP task and was absent when reading performance was evaluated using the MNREAD Acuity Chart or 100-word passages. Future studies need to design training tasks that are more effective in improving reading speed beyond what have been reported in the current and previous studies (approximately 50%) and more importantly, with improvement that could be transferred readily to daily reading tasks.

Keywords: training, macular degeneration, central vision loss, temporal processing, reading

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Footnotes

[1]In this paper, we refer to reading tasks that require observers to make eye movements to read lines of text as "natural reading" or "eye-movement based reading". Other synonymous expressions used in previous studies to refer to such tasks include "eye-mediated reading" (e.g. Calabrèse et al., 2016), "PAGE reading" (e.g. Rubin & Turano, 1992; 1994) or "page mode reading" (e.g. Bernard, Scherlen & Castet, 2007; Scherlen, Bernard, Calabrèse & Castet, 2008) although the latter two imply that the reading materials are longer than single sentences.

[2]The statistics reported here were based on analyzing the acuities for both eyes (a total of 18 eyes). Analyzing the acuities for only the better or the worse eyes led to the same result that there was no improvement in acuities after training (better eyes only: $p = 0.19$; worse eyes only: $p = 0.90$).

[3]The temporal duration used for the last five training blocks was constant for all except two observers. Therefore, we also compared the average letter recognition accuracies during the follow-up visit with those of the last three training blocks (all observers had the same temporal duration for the last three training blocks) or the very last training block. The results remain qualitatively the same (follow-up visit *vs.* the last three training blocks: $p = 0.29$; follow-up visit *vs.* the last training block: $p = 0.99$).

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