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Development of a training protocol to improve reading performance in peripheral vision

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Abstract

People with central-field loss must use peripheral vision for reading. Previous studies have shown that reading performance in peripheral vision can improve with extensive practice on a trigram letter-recognition task. The present study compared training on this task with training on two other character-based tasks (lexical decision and RSVP (Rapid Serial Visual Presentation) reading) which might plausibly produce more improvement in peripheral reading speed. Twenty-eight normally sighted young adults were trained at 10° in the lower visual field in a pre/post design. All three training methods produced significant improvements in reading speed, with average gains of 39% for lexical-decision, 54% for trigram letter-recognition, and 72% for RSVP training. Although the RSVP training was most effective, the lexical-decision task has the advantage of easy self administration making it more practical for home-based training.

Keywords

visual span; reading speed; perceptual learning; peripheral vision; visual training

1. Introduction

Age-related macular degeneration (AMD) is the leading cause of visual impairment in developed countries. Since AMD frequently causes scotomas in central vision, afflicted patients must rely on their peripheral vision to read, making reading slow and difficult (Faye, 1984; Fine & Peli, 1995; Fletcher, Schuchard & Watson, 1999; Legge, Ross, Isenberg & LaMay, 1992; Legge, Rubin, Pelli & Schleske, 1985). Reading difficulty is the most common complaint in low vision clinics (Elliott, Trukolo-Ilic, Strong, Pace, Plotkin & Bevers, 1997). Thus, developing suitable low-vision rehabilitation to enhance reading is vital for these low vision individuals (Goodrich, Mehr, Quillman, Shaw & Wiley, 1977; Nilsson, 1990; Markowitz, 2006).

To improve reading performance, patients with AMD can be trained to use assistive devices such as a magnifier (Cheong, Lovie-kitchin, Bowers, & Brown, 2005), to improve eye-

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movement control (Seiple, Szlyk, McMahon, Pulido, & Fishman, 2005), and to read with an optimal retinal location outside of their scotoma (Nilsson, Frennesson, & Nilsson, 1998; 2003). In addition, perceptual learning tasks may have potential for improving the reading performance of AMD patients (Chung, Legge & Cheung, 2004; Cheung, Yu, Legge & Chung, submitted; Sommerhalder, Oueghlani, Bagnoud, Leonards, Safran & Pelizzone, 2003). Perceptual learning is defined as the long-term modification of perception and behavior following practice or sensory experience (Gibson, 1963; Fahle & Poggio, 2002). It takes advantage of brain plasticity, which is the lifelong modifiability of functional and anatomical organization in the brain (Fahle & Poggio, 2002; Mahncke, Bronstone, & Merzenich, 2006).

Chung et al.'s (2004) demonstration of the potential value of perceptual learning involved enlargement of the visual span for reading. Empirical evidence has suggested that the size of the visual span, the number of adjacent letters that can be recognized reliably without moving the eyes, imposes a bottom-up sensory limitation on reading speed (Legge, Cheung, Yu, Chung, Lee & Owens, 2007; Legge, Mansfield & Chung, 2001). Legge and colleagues (2001) found that the slower average reading speed observed in peripheral vision was associated with a smaller peripheral visual span. A prediction based on these results is that expanding the peripheral visual span may improve reading performance in peripheral vision. This prediction was tested and confirmed by Chung et al. (2004), who extensively trained normally-sighted young adults on a trigram letter-recognition task in peripheral vision. In this task, each trial consisted of the brief presentation of a random string of three letters along a horizontal line in the peripheral visual field. Letter-recognition accuracy as a function of distance left and right of the midline was plotted and referred to as a visual-span profile. The size of the visual span was quantified by measuring the area under the visual-span profile. After training on this task for four daily sessions, participants showed an average improvement of 41% in peripheral reading speed. This study also demonstrated that training at one retinal location can be transferred to an untrained retinal location, and from a trained print size to untrained print sizes.

Although training with the trigram letter-recognition task was successful in improving reading in peripheral vision, it is possible that other training tasks might be more practical in rehabilitation and/or more effective for improving reading speed. In this paper, we report on the benefits for reading speed of two additional training tasks—lexical decision and RSVP (Rapid Serial Visual Presentation) reading. Our version of the lexical-decision task, like the trigram letter-recognition task, uses strings of three letters. Subjects indicate with a button press whether the string is a word or a non-word. Like the trigram-recognition task, the strings are presented at a range of positions left and right of the midline. Compared to the trigram letter-recognition task, the lexical-decision task may be more engaging for participants because it is easier (a simple two-choice response), and involves recognition of words, rather than meaningless letter strings. Moreover, the two-choice response can be implemented with two keys or buttons, making it a more practical task for self testing by participants (e.g. with a computer at home).

We also assessed RSVP reading as a training task. It seems plausible, a priori, that training on a reading task may yield benefits that are equivalent to or greater than training on trigram letter recognition or lexical-decision tasks. On the other hand, it is possible that RSVP reading might be less effective as a training task. This is because most words in sentences are short, so most of the stimuli are concentrated in a smaller range of letter positions during training, compared with the more even distribution of stimuli across letter positions for the trigram letter-recognition and lexical-decision tasks. Our goal was to assess the improvements associated with the three training methods. The results can be considered in conjunction with practical considerations to determine which training method is likely to be most effective for rehabilitation.

One consideration is that the advantages of training will be reduced if the benefits are specific to print size and retinal location. The more general the transfer, the more useful the training for real-world applications. We assessed the transfer of training effects from the trained task to other character-based tasks by measuring RSVP reading speed, visual-span profiles and lexical-decision performance before and after training. Training was conducted at only one retinal location (lower visual field) for one print size (3.5°). Transfer of training was evaluated across retinal locations and print sizes by measuring the three tasks at two retinal locations (upper and lower visual fields) and testing RSVP reading speed for two print sizes (2.5° and 3.5°) in both the pre-test and the post-test.

To summarize, the present study investigated the extent to which each of the three character-based tasks (lexical-decision, trigram and RSVP) can improve reading speed in peripheral vision with extensive training. It explored whether these training effects can be transferred to other untrained tasks, to an untrained retinal location and to an untrained print size. The study's aim was to determine which training task is likely to be most effective for improving reading speed.

2. Methods

2.1. Subjects

Twenty-eight native-English-speaking, normally sighted young adults from the University of Minnesota were randomly assigned to four groups with 7 subjects in each group: a control group, a lexical-decision training group, a trigram letter-recognition training group, and an RSVP training group. Each subject participated in only one group. Table 1 shows the summary statistics for age, gender ratio, binocular distance visual acuity measured with the Lighthouse Distance Visual Acuity chart, log contrast sensitivity measured with the Pelli-Robson Contrast Sensitivity chart, and three measures from the MNREAD reading acuity chart. The MNREAD data were analyzed with the method described by Cheung, Kallie, Legge & Cheong (2008). None of the group differences are significant. Subjects signed an IRB-approved consent form before beginning testing. None had prior experience with the testing used in this study.

2.2. Apparatus, stimuli, experimental design and data analysis

MATLAB (version 5.2.1) and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) were used to generate the stimuli and control our experiments. The stimuli were displayed on a SONY Trinitron colour graphic display (model: GDM-FW900; refresh rate: 76 Hz; resolution: 1,600 × 1,024), controlled by a Power Mac G4 computer (model: M8570).

Figure 1 shows a schematic of the experimental design. A task battery consisting of the RSVP reading, trigram letter recognition, and lexical-decision tasks, each measured at 10° in the upper and lower visual fields, served as the pre-test and post-test for both experimental and control groups. Pre- and post-testing each consisted of 144 RSVP trials, 440 trigram trials, and 1080 lexical-decision trials[1]. The testing sequence for the pre-test was RSVP reading task (8 blocks), trigram letter-recognition task (8 blocks), and lexical-decision task (8 blocks). In the post-test, the testing sequence was reversed. Within each task, the block sequence was pseudo-randomized to minimize any sequence effects. Subjects completed practice trials before beginning each task, and these trials were excluded from the data analysis.

Training occurred in four daily one-hour sessions, with task performance measured at 10° in the lower visual field with a print size of 3.5°. It has been suggested that the consolidation of

[1]Each trigram letter-recognition trial generates three responses, where each response is one of 26 letters. The lexical-decision task is a sparser measure (yes or no) and requires more trials to produce accurate performance data. This explains the large disparity between the number of trigram letter-recognition trials and lexical-decision trials.

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perceptual learning can be triggered only when the amount of training per day reaches some critical value which is task and stimulus dependent (Wright & Sabin, 2007). Chung et al. (2004) showed that one hour training of the trigram letter-recognition task was adequate so that the learning obtained in each training day was retained on the following day. In this study, we matched the total training time (one hour per day) across the three groups. Because the time per trial differs for the three tasks, the number of training trials differed for the three training groups: the lexical-decision training group completed a total of 5400 trials (1350 trials per day), the trigram letterre-cognition training group completed 3520 trials (880 trials per day), and the RSVP training group completed 864 trials (216 trials per day). Control subjects completed only the pre- and post-tests and had no training trials.

All testing was conducted binocularly in a dimly lit room at a viewing distance of 40 cm. Stimuli consisted of black letters on a white background (luminance of 89 cd/m^2) with Weber contrast higher than 99%. Letters were rendered in lowercase Courier, a serif font with fixed width. A print size (defined as x-height in lowercase) of 3.5° was chosen because this value exceeds the critical print size for reading at 10° retinal eccentricity (Chung, Mansfield & Legge, 1998; Chung et al., 2004). In addition, pre- and post-testing of RSVP reading speed was measured for 2.5° characters to examine possible transfer of training to a different print size.

Measuring reading speed with the RSVP reading task—The RSVP reading task involved sequential presentation of the words of a sentence at a fixed location (left justified) on a display screen. Subjects were instructed to fixate on a horizontal line while reading aloud a sentence presented in the peripheral visual field. They were allowed to complete their report after the sentence disappeared from the display. Only horizontal eye movements along the fixation line were permitted during testing. A second experimenter monitored the eye movements of the subjects. A trial was cancelled when vertical eye movements were detected. Across all the subjects, about 10% of trials were cancelled due to vertical eye movements. We used a pool of 2658 sentences developed by Chung et al. (1998). In each trial, a sentence was selected randomly from the pool without replacement. In other words, no sentence was presented more than once to each subject. Sentence length ranged from 7 to 17 words and averaged 11 words per sentence. Word length was between 1 and 14 characters, with a mean length of 4 letters per word. Before the first word of each sentence, a pre-mask "xxxxxxxxxxxxxx" was presented to indicate the location of the upcoming words (as shown in Figure 2). This row of x's was also shown after the last word of each sentence as a post-mask.

For a given condition (combination of a visual-field location and a print size), the proportion of words read correctly was measured at six different exposure durations using the method of constant stimuli. Depending on the subject's performance on the practice trials, the six durations were 26, 53, 92, 158, 289, and 526 ms per word or 53, 92, 158, 289, 526, and 947 ms per word. The exposure durations were selected so that subjects could read less than 30% of words correctly at the shortest duration and more than 80% of words correctly at the longest duration. Six sentences were tested at each exposure duration. The resulting data were fitted with a Weibull function, and reading speed was computed from the exposure duration yielding 80% of words read correctly.

For the RSVP training group, the RSVP task in the training sessions was identical to the RSVP task in the pre- and post-tests, except that testing was confined to the lower visual field and a print size of 3.5°. RSVP reading speed was measured six times during each training day. Each measurement consisted of 36 sentences, with 6 trials for each of the six durations.

Measuring visual-span profiles with the trigram letter-recognition task—Visual-span profiles were obtained with a letter-recognition task as described previously (Chung et al., 2004; Legge et al., 2001; Legge et al., 2007; Yu, Cheung, Legge & Chung, 2007). The stimuli were trigrams, random strings of three letters, each randomly drawn from the 26 lowercase letters of the English alphabet. The exposure duration for each trigram was 105 ms. Subjects were asked to fixate a dot and identify all three letters of each trigram in order, from left to right. Trigrams were presented at different letter distances left and right of the midline at 10° above or below fixation. A visual-span profile was constructed for each condition from multiple trigram trials by plotting proportion correct letter recognition as a function of letter position.

Figure 3 shows trigrams presented in the two conditions (upper and lower visual fields) and an example of a visual-span profile. For both conditions, letter slots along a horizontal line were labelled by negative or positive numbers to indicate positions to the left or right of the midline, respectively. The location of the middle letter was used to indicate the position of the trigram. In Figure 3, trigram “upr” is presented at letter position −4 in the upper visual field, which means that the three letters are at positions −5, −4, and −3, respectively. The position of trigram “lwe” is 2 in the lower visual field, indicating that letter “l” is at position 1 and letter “w” is at position 3. The position of the trigram, which is also the location of the middle letter, ranged from −5 to 5.

Data at each letter position were accumulated from the inner, middle, and outer letters of the trigrams centered on that position, or centered one letter position to the left or right. A visual-span profile is a plot of letter recognition accuracy as a function of letter position. In the present study, each visual-span profile was based on four blocks (a total of 220 trials). In each block, five trials were completed at each of the 11 letter positions (ranging from −5 to 5). Since only the outer letters of the trigrams were presented in positions −6 and 6, and no inner letters were presented at position −5 and 5, less data were collected at these four letter slots. Therefore, the visual-span data were only analyzed for letter positions −4 to 4, where data from all three letter positions were available.

An asymmetric 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 (Legge et al., 2001). The size of the visual span was quantified by calculating the total amount of information in bits transmitted by it. For each letter position, 100% accuracy in letter recognition corresponded to 4.7 bits of information transmitted and 3.8% accuracy (chance accuracy) to 0 bits transmitted. Proportion correct letter recognition was converted to bits of information transmitted (the right vertical scale in Figure 3) using letter-confusion matrices (mutual information = −0.036996 + 4.6761 × proportion correct letter recognition; Beckmann & Legge, 2002). The size of the visual span was calculated by summing the amount of information transmitted by the 9 slots of the profile, similar to computing the area under the profile as shown in Figure 3.

For training, the trigram letter-recognition task in the training sessions was identical to the trigram letter-recognition task in the pre- and post-tests, except that the testing in the training was confined to the lower visual field. During each training day, a visual-span profile was measured four times (220 trials for each visual-span measurement).

Measuring word-recognition accuracy with the lexical-decision task—The lexical-decision task also involves trigrams presented at varying distances left and right of the midline in peripheral vision. A post-mask “###” was presented after each trigram. Instead of reporting the identities of the three letters, subjects reported whether the trigram was a word or a non-word. Trigrams were words 50% of the time.

The pool of trigrams for the lexical-decision task included the 350 most frequently used three-letter words in English and 350 non-words. The word list was originally developed by Lee, Gefroh, Legge and Kwon (2003). Appendix 1 describes how the 350 non-words were selected from the pool of possible trigrams. The term “non-word” was broadly defined in the present study to include words with very low usage frequency, abbreviations, and three-letter words in languages other than English. Prior to testing, subjects were asked to review the word and non-word lists. On average, subjects identified 2 trigrams out of the 350 on the word list as non-words and 6 trigrams out of the 350 on the non-word list as words. The identified words remained on the lists. During testing, subjects were instructed to classify the trigrams exactly as they appeared on the word and non-word lists.

The word and non-word lists were each divided in half. Word frequency was equally distributed between the two newly-created word lists. Each of the two new word lists was combined with half of the non-word list to form trigram set A and set B. Trigram set A was used in the pre- and post-tests for the control group, the RSVP training group, and the trigram letter-recognition training group. For the lexical-decision training group, we used both sets in the pre- and post-tests, but only one set was used in the training sessions (four subjects were trained with set A and three with set B). This enabled us to examine whether learning would transfer from the trained word and non-word set to the untrained set (see Appendix 2 for a more detailed discussion).

Multiple forms of visual feedback were used in the lexical-decision training (see Appendix 2 for a more detailed discussion). Since subjects might differ in their bias toward “yes” (word) or “no” (non-word) answers, we computed accuracy as d’ (calculated from the data accumulated across all nine target positions) to separate discriminability from response bias. d’ was computed as the difference between the z-transforms of hit rate (proportion of word trials to which subject responded “word”) and false alarm rate (proportion of non-word trials to which subject responded “word”). A higher value of d’ indicates better discrimination between words and non-words.

The verbal responses for the trigram letter-recognition and RSVP reading tasks are more complicated than the simple two-choice response for the lexical-decision task, which makes it more difficult to devise straightforward and informative feedback for the trigram letter-recognition and RSVP reading tasks. Therefore, feedback was not provided to the groups trained on these tasks.

The lexical-decision task in the training sessions was identical to the lexical-decision task in the pre- and post-tests, except that the testing in the training was confined to the lower visual field and one set of trigrams (set A or set B). Difficulty level in the training sessions was adjusted by varying the exposure duration. When pre-test performance was better than 70% accuracy, the exposure duration used in the training sessions was reduced from 105 msec to 92 msec. Two of the subjects (L2 and L7) were trained at 92 msec. During each training day, d’ was repeatedly measured five times (270 trials for each d’ measurement).

3. Results

3.1. Pre-post difference comparison among the four groups

A repeated measures ANOVA was used to analyze the ratio of post-test RSVP reading speed to pre-test RSVP reading speed. The two within-subject factors were visual field (lower visual field and upper visual field) and print size (2.5° and 3.5°). The single between-subject factor was group (control group, lexical-decision training group, trigram letter-recognition training group and RSVP training group). A repeated measures ANOVA was used to analyze the pre-post difference in visual-span size (bits). The one within-subject factor was visual field. The one between-subject factor was group. A repeated measures ANOVA was used to analyze the pre-post difference in discriminability d' in the lexical-decision task with one within-subject factor (visual field) and one between-subject factor (group).

As shown in Figure 4A and Table 2, the post/pre ratios in RSVP reading speed differed significantly between the four groups ($F(3,24) = 12.95$, $p < .0005$). Post-hoc pairwise comparisons revealed that the subjects in all the three training groups showed larger post/pre ratios in RSVP reading speed than those in the control group (no training). Among the three training groups, the RSVP training group showed a significantly larger post/pre ratio than the lexical-decision training group. The rank ordering of training effects on reading speed is consistent across field location and print size. Collapsing across visual field and print size variables, the average post/pre ratio of reading speeds was 1.64 (95% confidence interval [1.52, 1.76]) for the RSVP training group, 1.47 ([1.39 1.55]) for the trigram letter-recognition training group, 1.36 ([1.27 1.45]) for the lexical-decision training group and 1.10 ([1.03 1.17]) for the control group.

In comparing the pre-post improvements in visual-span size among the four groups (shown in Figure 4B), the ANOVA revealed a significant main effect of group ($F(3,24) = 5.25$, $p = .006$). Post-hoc pairwise comparisons indicated that both the trigram letter-recognition training group (average pre-post improvement across visual fields equals 4.24 bits) and the RSVP training group (improved 3.64 bits) showed significant growth in the size of the visual span compared with the control group (improved 1.41 bits).

Figure 4C plots pre-post differences in d' (the differences were computed as post-test d' minus pre-test d') for the lexical-decision task. The group effect ($F(3,24) = 5.44$, $p = .005$) and the corresponding post-hoc tests showed that the lexical-decision training group (average pre-post improvement across visual fields of 0.85) showed significant pre-post improvement in d' compared to the control group (0.12).

We also found a significant main effect of visual field (upper versus lower) on the pre-post changes in RSVP reading speed ($F(1,24) = 4.86$, $p = .037$), visual-span size ($F(1,24) = 4.40$, $p = .047$), and lexical-decision d' ($F(1,24) = 4.39$, $p = .047$). Averaged across the three training groups, there was a larger pre-post increase in performance in the trained lower visual field (1.55 for RSVP reading speed, 4.05 bits for visual-span size, and 0.72 for lexical-decision performance) than in the untrained upper visual field (1.43 for RSVP reading speed, 2.96 bits for visual-span size, and 0.52 for lexical-decision performance; see Figure 4 and Table 2). Even so, training effects were qualitatively consistent across field location, suggesting that there is substantial, but not complete, transfer of training to an untrained field location. A consistent difference between upper and lower visual field was also found in pre-test. The performance in the lower visual field was always better than the performance in the upper visual field (RSVP reading speed: $F(1,24) = 16.32$, $p < .0005$; visual-span size: $F(1,24) = 28.59$, $p < .0005$; lexical-decision d': $F(1,24) = 46.21$, $p < .0005$).

When comparing the pre-post difference between groups for the lexical-decision task, we found that there was also an interaction effect between visual field and group ($F(3,24) = 4.64$, $p = .011$). The difference between groups was larger at the trained retinal location than at the untrained retinal location.

No significant effect of print size on the pre-post improvements in RSVP reading speed was found, indicating that training transfers across print size. Overall, for each training method, the largest improvement typically occurred under the trained conditions (e.g., the lower visual field and 3.5° print size for the RSVP training).

3.2. Block-by-block changes across training

Figure 5, Figure 6 and Figure 7 show block-by-block changes in performance across training days for individual subjects and the group average in the RSVP, lexical-decision and trigram letter-recognition training groups respectively. Pre- and post-test data are also displayed in the figures.

Data from each of the three training groups consistently showed that within-day improvement (the difference in performance between the last block and the first block of the training day) was significant and largest in the first training day (RSVP reading training group: $t(6) = 2.56$, $p = .04$; lexical-decision training group: $t(6) = 3.78$, $p = .01$; trigram letter-recognition training group: $t(6) = 8.00$, $p < .0005$). Little improvement was associated with the last training day (training day 4). The number of days that performance continues to improve depends on the training task. Averaged across subjects, it was three days for trigram letter-recognition training, two days for RSVP reading training, and one day for lexical-decision training.

3.3. Correlations

Table 3 shows the correlations (collapsed across the four groups) between the pre-post changes in visual-span size, lexical-decision d’ (combining data from both the trained and untrained trigram sets) and RSVP reading speed. Both the change in lexical-decision d’ and the change in RSVP reading speed are strongly correlated with the change in visual-span size. The correlation between d’ and visual-span size is unsurprising because the trigram letter-recognition task and the lexical-decision task share many similarities. A significant positive correlation was also found between the change in lexical-decision d’ and the change in RSVP reading speed for the trained print size (3.5°) in the upper visual field.

Is the pre-test performance level a predictor of the size of the training effect? If so, pre-test performance should be correlated with the pre-post improvement for each of the three training groups. Training effects might be larger for subjects with low pre-test levels because poor pre-test performance should leave more room for improvement. Individual variability in pre-test performance covered a range large enough to examine this correlation. For example, under the trained conditions (lower visual field and 3.5° print size), pre-test performance ranged from 28 bits to 35 bits for visual-span size, 162 to 270 wpm for reading speed, and 0.7 to 1.9 for lexical-decision d’. However, none of the correlations between pre-test performance levels and post-pre improvements were significant. This finding indicates that the potential for training benefits cannot be predicted by pre-training performance.

4. Discussion and conclusions

The present study showed that all three training methods were effective in improving reading speed, but the RSVP training method was the most beneficial. Overall, we found that perceptual learning results in increased performance on the trained task at the trained retinal location and print size, and that this training benefit can be generalized to an untrained task, an untrained retinal location, and an untrained print size. Our results also indicated that the pre-post improvement on a given task was greater for training with that task than for training with other tasks. The important consequence of this result is that RSVP training produces the largest benefit for RSVP reading. Using RSVP training, we obtained a mean improvement in reading speed of 72% at the trained retinal location. With trigram letter-recognition training, our subjects showed a mean improvement in reading speed of 54%. Using the lexical-decision training method, subjects improved by 39%, which is significantly lower than the improvement in the RSVP training group. From these results, RSVP training appears to be more effective at increasing reading speed than either trigram letter-recognition or lexical-decision training.

The RSVP training advantage is also found when the effects of training are tested at an untrained visual-field location and print size.

For trigram letter-recognition training, the mean improvement in reading speed of 54% exceeds the 41% improvement due to training reported by Chung and colleagues (2004). We used a very similar testing procedure to Chung et al. (2004). The only differences were that our trigram letter-recognition training group completed 4 blocks of trials per training day instead of 5 blocks, and that we measured lexical-decision performance in both the pre- and post-tests while Chung et al. (2004) did not include a lexical-decision task in their protocol.

Studies investigating the specificity of perceptual learning suggest that generalization to an untrained task or untrained retinal location depends on the site in the visual pathway altered by the training (Fahle & Poggio, 2002). Information processing in the brain is thought to be hierarchical. At early stages in visual processing, neurons are specialized along basic dimensions such as position and size. Neurons in high-level areas have receptive fields that generalize across these basic dimensions. Where learning occurs in the brain depends on which neurons are activated by the stimulus and also relates to task performance (Ahissar & Hochstein, 1993). Many perceptual-learning effects are retinotopically specific (Karni & Sagi, 1991; Poggio, Fahle & Edelman, 1992; Ahissar & Hochstein, 1996). This specificity implies that the neural changes are occurring in early visual areas which are retinotopically organized. Training effects only generalize when changes occur in higher-level cortical processing areas (Ahissar & Hochstein, 1997). When perceptual training alters low-level processing areas, the training effect is specific to the trained target, retinal location or size. In the current study, the observed transfer of learning from the trained retinal location to an untrained retinal location, from the trained print size to an untrained print size, and from the trained task to an untrained task imply that the neural basis of the training occurs at least partially at a nonretinotopic level of the visual pathway. On the other hand, since the transfer of learning was not complete from the lower to the upper visual field, there must be some retinotopic-specific learning. The learning effect found in the current study could be a combination of early sensory improvements and higher level influences.

Where in the high-level processing hierarchy did the learning occur? Although this question cannot be answered directly from the current study, we can rule out some possibilities. Lee, Legge and Ortiz (2003) found similar word-frequency effects in central and peripheral vision, despite differences in the speed of processing, suggesting that the speed limitation for peripheral reading is in a perceptual rather than a language area.

Can attention explain the training benefit observed in the current study? It has been shown that attention can improve with training (Anderson, 1980; Baron & Mattila, 1989; McDowd, 1986; Richards, Bennett, & Sekuler, 2006). It is possible that subjects became better at decoupling attention from fixation so that they were more able to attend to objects in peripheral vision after training. However, Lee et al. (2003) provided evidence that improvement in deploying attention to peripheral vision was not correlated with training-related improvement in trigram recognition. Our results further argue against an explanation based on attention because of the lack of transfer of learning for some tasks (e.g. no transfer of learning from RSVP task to lexical-decision task). Transfer would have been expected if learning was due to an improvement in the ability to deploy attention to peripheral vision.

The block-by-block learning curves from the three training groups indicated that three days of training are adequate for subjects to reach an asymptotic level in their learning, which is consistent with Chung et al.'s (2004) finding. These authors found a similar pattern of results, suggesting that two to three days of training are sufficient.

Although the lexical-decision training had less benefit for reading than the trigram or RSVP training tasks, it may have some practical advantages for training. From the subject's point of view, the response is simpler and faster i.e., pressing one of two keys rather than reading sentences aloud or reciting strings of random letters. From the experimenter's point of view, collecting and scoring the two-choice response may be preferable if it is desirable to have a protocol in which the subjects test themselves. It would be hard to automate the scoring of trials in the RSVP and trigram procedures because the subject gives verbal responses of words or letters. It is easier to automate data collection in the lexical-decision task in which the responses are key presses. What makes the lexical-decision training less effective? As shown in Figure 6 and Appendix 2, the increased improvement for the trained trigram set over the untrained trigram set indicates that the lexical-decision training effect was more specific to the trained trigram set. This may be a consequence of the small size of the trigram set used for training. There were 350 trigrams (175 words and 175 non-words) in the trained set. Each training session included 1350 lexical-decision trials, which means that each of the 350 trigrams appeared four times per day (on average) and sixteen times during the four training days. The high frequency of repetition could make learning more specific to the trained stimuli. To improve the transfer of the lexical-decision training, one possible approach might be to expand the pool of words and non-words by using four-letter strings.

The results of the present study showed that practice on any one of three perceptual learning tasks (RSVP reading, trigram letter recognition, or lexical decision) improved reading speed in the peripheral vision of normally-sighted young adults. Given these findings, the RSVP training method is likely to yield the greatest improvement in reading speed for low-vision subjects with central-field loss.

This study has improved our understanding of the range of tasks that might be used to train peripheral vision to read, the magnitude of improvement to be expected, and the extent of training required. Next steps in translating these findings into a useful form of low-vision reading rehabilitation are to conduct similar measurements on people with central-field loss and to evaluate the training effects on page reading.

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Appendix 1: Construction of the non-word list in the lexical-decision task

Our goal in selecting 350 non-words was to pair them with the 350 words so subjects could not easily discriminate a word from a non-word by recognizing only one or two of the letters of the trigram. To create the non-word list, we first divided the 26 letters into four groups as follows. Group 1 included the five vowels. Group 2 included all the consonants with ascenders. Group 3 included all the consonants with descenders. Group 4 contained the consonants with no ascenders or descenders.

For each of the 350 words, we created a non-word as follows. Starting with the left letter, we shuffled the 350 letters in each slot independently within each of the four letter groups until the resulting 350 trigrams were all non-words. For example, to find the non-word corresponding to "far": the "f" was categorized into Group 2, and was then shuffled with all of the other Group 2 letters presented in the left slot on the word list. As a result of the first shuffling, the "f" was replaced with a "b", producing the word "bar". Next, "a" was shuffled with all of the other Group 1 letters presented in the middle slot on the word list, and successfully produced the non-word "bir". We also constrained the distribution of letter frequencies in the three letter positions (left, middle and right) to be the same for words and non-words.

Appendix 2: Preliminary testing with variants of the lexical-decision training

During preliminary testing, we made several modifications to the lexical-decision training protocol. Some of the results of these modifications are discussed in this appendix.

The word and non-word lists were each divided in half. Half of the word list was combined with half of the non-word list to form trigram set A. The rest formed set B. When trigram set A was used in pre- and post-tests and set B was used in training sessions, we found that lexical-decision performance dropped significantly in the post-test compared to performance on the last training day. It appeared that the training effect was at least partially specific to the trained set (in particular, set B). To confirm this specificity, we included both set A and B in the pre- and post-testing for the main experiment. We conducted a two-factor (visual field and trigram set) repeated measures ANOVA for the lexical-decision training group to test for a difference between the trained trigram set and the untrained trigram set. As shown in Figure 6, we found that performance on the trained trigram set improved more than performance on the untrained set ($F(1,6) = 6.61$, $p = .042$).

Although learning without feedback is possible (Chung et al., 2004; Fahle & Edelman, 1993; Karni & Sagi, 1991), many studies have shown that feedback can enhance perceptual learning (Herzog & Fahle, 1997, 1998; Fahle, 2004). To test how visual and/or auditory feedback facilitated learning in our lexical-decision task, we compared three feedback conditions—both visual and auditory feedback, visual feedback only, and no feedback. Trial-by-trial auditory feedback utilized two sounds. One sound indicated correct responses and the other indicated incorrect responses. Visual feedback was provided after every 35 trials and after each block, showing a numerical representation of cumulative percent correct in the current block (averaged across letter positions). Images of “winning” and “losing” turtles above bar plots showing the number of correct trials and the number of incorrect trials were also provided. Our pilot investigation of different types of feedback suggested that the visual feedback alone was superior to combined auditory and visual feedback, and better than no feedback. Therefore, only visual feedback was used in the main experiment.

References

Ahissar M, Hochstein S. Attentional control of early perceptual learning. Proc. Natl. Acad. Sci. USA 1993;90(12):5718–5722. [PubMed: 8516322]

Ahissar M, Hochstein S. Learning pop-out detection: specificities to stimulus characteristics. Vision Res 1996;36:3487–3500. [PubMed: 8977015]

Ahissar M, Hochstein S. Task difficulty and the specificity of perceptual learning. Nature 1997;487:401–406. [PubMed: 9163425]

Anderson, JR. Cognitive psychology and its implications. San Francisco: W. H. Freeman; 1980. p. 30

Baron A, Mattila WR. Response slowing of older adults: effects of time-limit contingencies on single- and dual-task performances. Psychol Aging 1989;4(1):66–72. [PubMed: 2803613]

Beckmann PJ, Legge GE. Preneural limitations on letter identification in central and peripheral vision. Journal of the Optical Society of America A: Optics, Image Sciences, and Vision 2002;19:2349–2362.

Brainard DH. The psychophysics toolbox. Spatial Vision 1997;10:433–436. [PubMed: 9176952]

Cheong AMY, Lovie-Kitchin JE, Bowers AR, Brown B. Short-term in-office practice improves reading performance with stand magnifiers for people with AMD. Optometry and Vision Science 2005;82:114–127. [PubMed: 15711458]

Cheung SH, Kallie CS, Legge GE, Cheong AMY. Nonlinear mixed-effects modeling of MNREAD data. Investigative Ophthalmology and Visual Science 2008;49:828–835. [PubMed: 18235034]

Cheung SH, Yu D, Legge GE, Chung STL. Reading speed in the peripheral vision of older adults: Does it benefit from perceptual learning? Vision Research. (submitted).

Chung STL, Legge GE, Cheung SH. Letter-recognition and reading speed in peripheral vision benefit from perceptual learning. Vision Research 2004;44(7):695–709. [PubMed: 14751554]

Chung STL, Mansfield JS, Legge GE. Psychophysics of reading: XVIII. The effect of print size on reading speed in normal peripheral vision. Vision Research 1998;38:2949–2962. [PubMed: 9797990]

Elliott DB, Trukolo-Ilic M, Strong JG, Pace R, Plotkin A, Bevers P. Demographic characteristics of the vision-disabled elderly. Investigative Ophthalmology & Visual Science 1997;38(12):2566–2575. [PubMed: 9375576]

Fahle M. Perceptual learning: A case for early selection. Journal of Vision 2004;4:879–890. [PubMed: 15595892]

Fahle M, Edelman S. Long-term learning in vernier acuity: effects of stimulus orientation, range and of feedback. Vision Research 1993;33(3):397–412. [PubMed: 8447110]

Fahle, M.; Poggio, T. Perceptual learning. Cambridge, MA: MIT Press; 2002.

Faye, EE. Clinical low vision. Vol. 2nd ed.. Boston: Little Brown & Co.; 1984.

Fine EM, Peli E. Scrolled and rapid serial visual presentation texts are read at similar rates by the visually impaired. Journal of the Optical Society of America A: Optics, Image Sciences, and Vision 1995;12:2286–2292.

Fletcher DC, Schuchard RA, Watson G. Relative locations of macular scotomas near the PRL: Effect on low vision reading. Journal of Rehabilitation Research and Development 1999;36:356–364. [PubMed: 10678458]

Gibson EJ. Perceptual learning. Annual Review of Psychology 1963;14:29–56.

Goodrich GL, Mehr EB, Quillman RD, Shaw HK, Wiley JK. Training and practice effects in performance with low-vision aids: a preliminary study. American Journal of Optometry & Physiological Optics 1977;54(5):312–318. [PubMed: 900251]

Herzog MH, Fahle M. The role of feedback in learning a vernier discrimination task. Vision Research 1997;37(15):2133–2141. [PubMed: 9327060]

Herzog MH, Fahle M. Modeling perceputal learning: difficulties and how they can be overcome. Biol. Cybern 1998;78:107–117. [PubMed: 9525037]

Karni A, Sagi D. Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. Proc. Natl. Acad. Sci. USA 1991;88:4966–4970. [PubMed: 2052578]

Lee, HW.; Gefroh, J.; Legge, GE.; Kwon, MY. Training improves reading speed in peripheral vision: Is it due to attention?; Paper presented at the 44th Annual Meeting of the Psychonomic Society; November 2003; Vancouver, BC. 2003.

Lee H-W, Legge GE, Ortiz A. Is word recognition different in central and peripheral vision? Vision Research 2003;43:2837–2846. [PubMed: 14568099]

Legge GE, Cheung S-H, Yu D, Chung STL, Lee H-W, Owens DP. The case for the visual span as a sensory bottleneck in reading. Journal of Vision 2007;7(2):1–15. http://journalofvision.org/7/2/9/, doi:10.1167/7.2.9.

Legge GE, Mansfield JS, Chung STL. Psychophysics of reading: XX. Linking letter recognition to reading speed in central and peripheral vision. Vision Research 2001;41:725–734. [PubMed: 11248262]

Legge GE, Ross JA, Isenberg LM, LaMay JM. Psychophysics of reading. XII. Clinical predictors of low-vision reading speed. Investigative Ophthalmology and Visual Science 1992;33:677–687. [PubMed: 1544792]

Legge GE, Rubin GS, Pelli DG, Schleske MM. Psychophysics of reading. II. Low vision. Vision Research 1985;25:253–265. [PubMed: 4013092]

Mahncke HW, Bronstone A, Merzenich MM. Brain plasticity and functional losses in the aged: scientific bases for a novel intervention. Progress in Brain Research 2006;157:81–109. Chapter 6. [PubMed: 17046669]

Markowitz SN. Principles of modern low vision rehabilitation. Can J Ophthalmol 2006;41:289–312. [PubMed: 16767184]

McDowd JM. The effects of age and extended practice on divided attention performance. J Gerontol 1986;41(6):764–769. [PubMed: 3772053]

Nilsson UL. Visual rehabilitation with and without educational training in the use of optical aids and residual vision. A prospective study of patients with advanced age-related macular degeneration. Clinical Vision Science 1990;6(1):3–10.

Nilsson UL, Frennesson C, Nilsson SEG. Location and stability of a newly established eccentric retinal locus suitable for reading, achieved through training of patients with a dense central scotoma. Optom Vis Sci 1998;75:873–878. [PubMed: 9875992]

Nilsson UL, Frennesson C, Nilsson SEG. Patients with AMD and a large absolute central scotoma can be trained successfully to use eccentric viewing, as demonstrated in a scanning laser ophthalmoscope. Vision Research 2003;43:1777–1787. [PubMed: 12818347]

Pelli DG. The VideoToolbox software for visual psychophysics: Transforming numbers into movies. Spatial Vision 1997;10:437–442. [PubMed: 9176953]

Poggio T, Fahle M, Edelman S. Fast perceptual learning in visual hyperacuity. Science 1992;256:1018–1021. [PubMed: 1589770]

Richards E, Bennett PJ, Sekuler AB. Age related differences in learning with the useful field of view. Vision Research 2006;46:4217–4231. [PubMed: 17027061]

Seiple W, Szlyk JP, McMahon T, Pulido J, Fishman GA. Eye-movement training for reading in patients with age-related macular degeneration. Invest Ophthalmol Vis Sci 2005;46:2886–2896. [PubMed: 16043863]

Sommerhalder J, Oueghlani E, Bagnoud M, Leonards U, Safran AB, Pelizzone M. Simulation of artificial vision: I. Eccentric reading of isolated words, and perceptual learning. Vision Research 2003;43:269–283. [PubMed: 12535986]

Wright BA, Sabin AT. Perceptual learning: how much daily training is enough? Experimental Brain Research 2007;180(4):727–736.

Yu D, Cheung S-H, Legge GE, Chung STL. Effect of letter spacing on visual span and reading speed. Journal of Vision 2007;7(2):1–10. 2, http://journalofvision.org/7/2/2/, doi:10.1167/7.2.2.

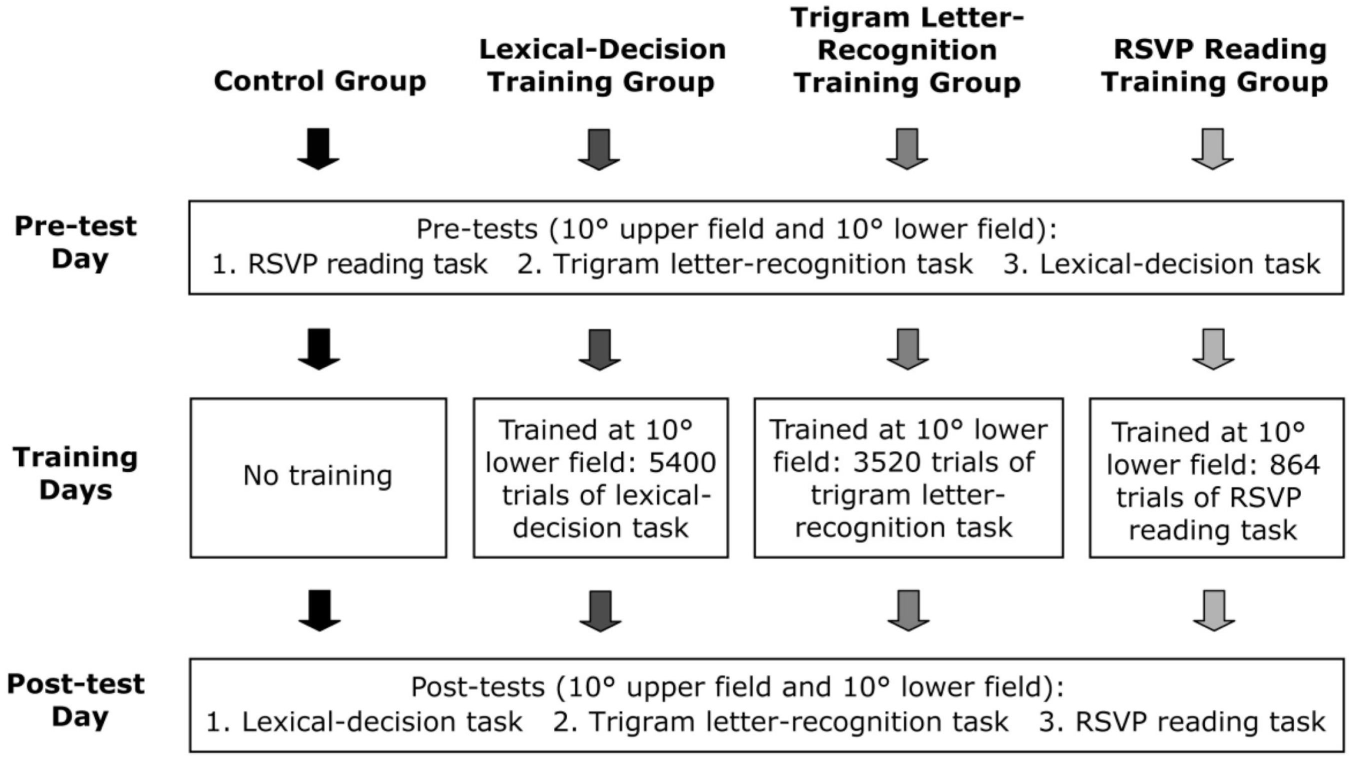

Figure 1.
Schematic diagram of the sequence of pre-test, training, and post-test for four groups.

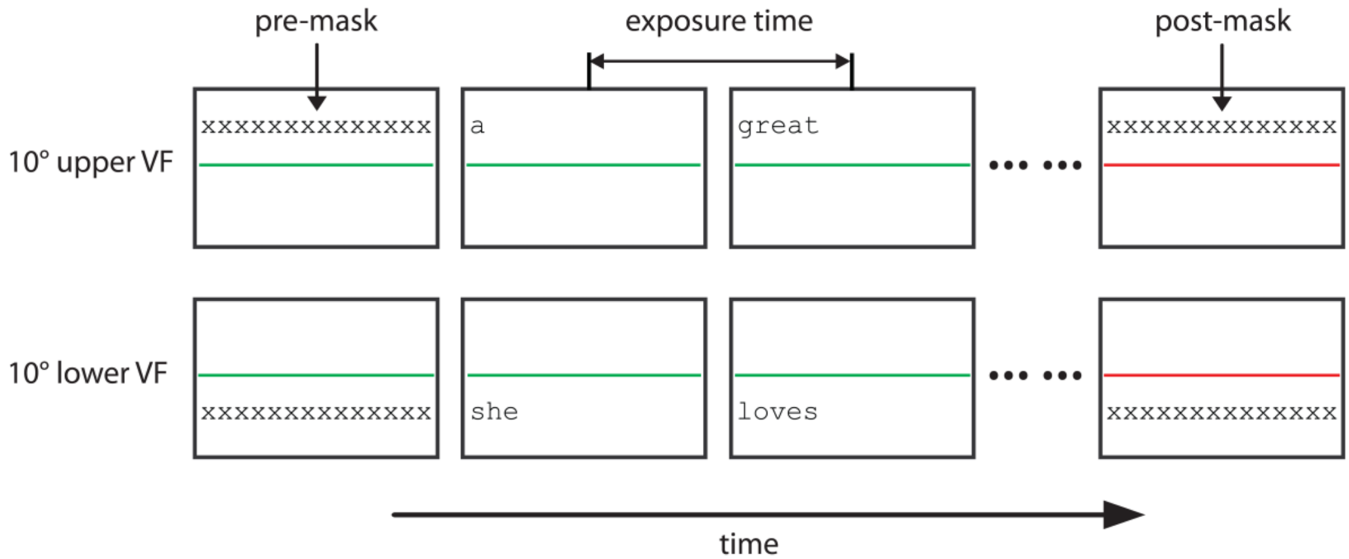

Figure 2.
Schematic diagram of the RSVP reading task.

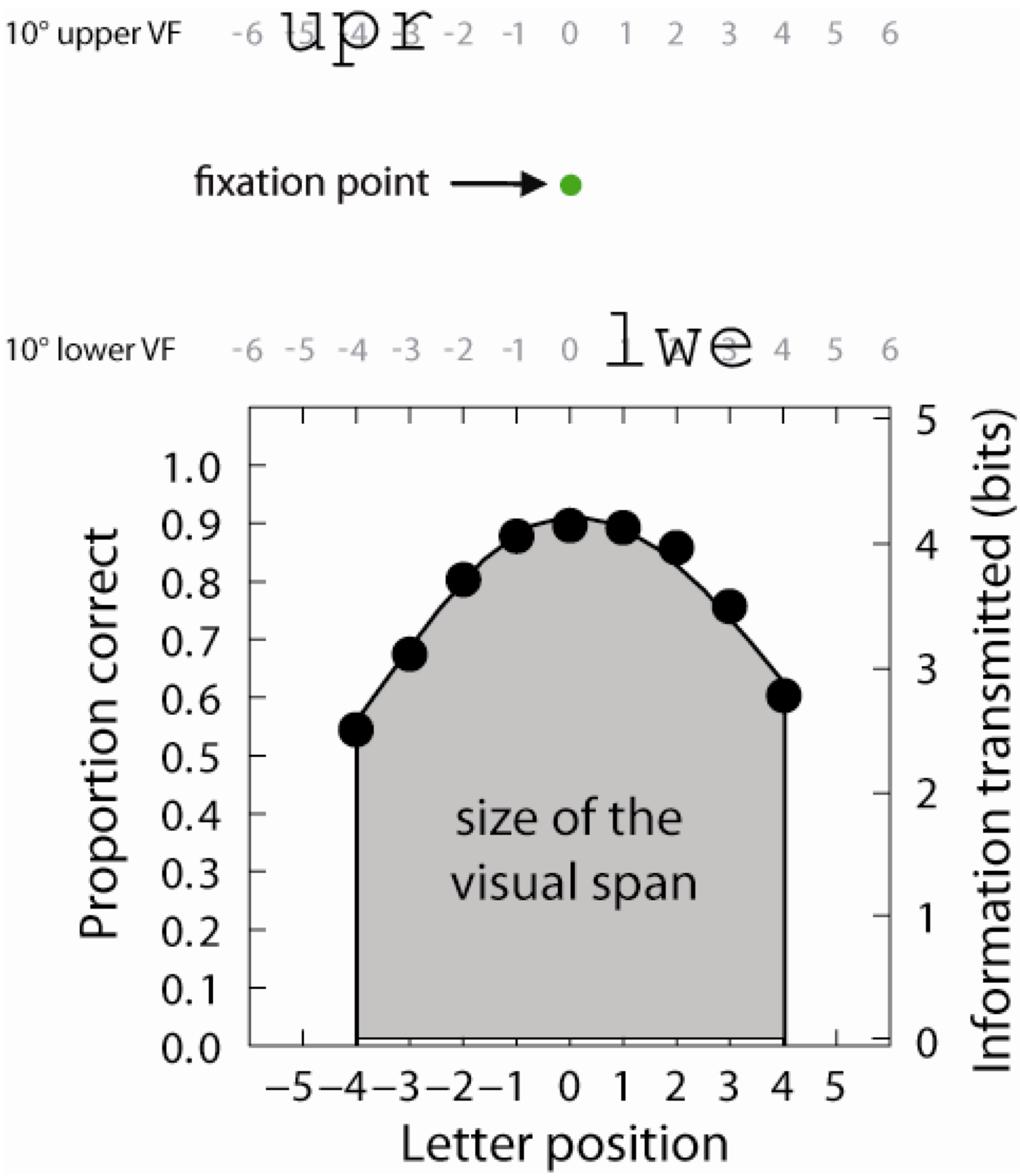

Figure 3.

Examples of trigrams presented in the upper and lower visual fields and a sample visual-span profile. Each trigram is presented at a letter position left or right of the midline 10° above or below the fixation dot. A visual-span profile is a plot of letter-recognition accuracy (proportion correct) as a function of letter position. The right vertical scale shows a conversion from proportion correct for letter recognition to information transmitted in bits. The area under the visual span indicates the visual-span size.

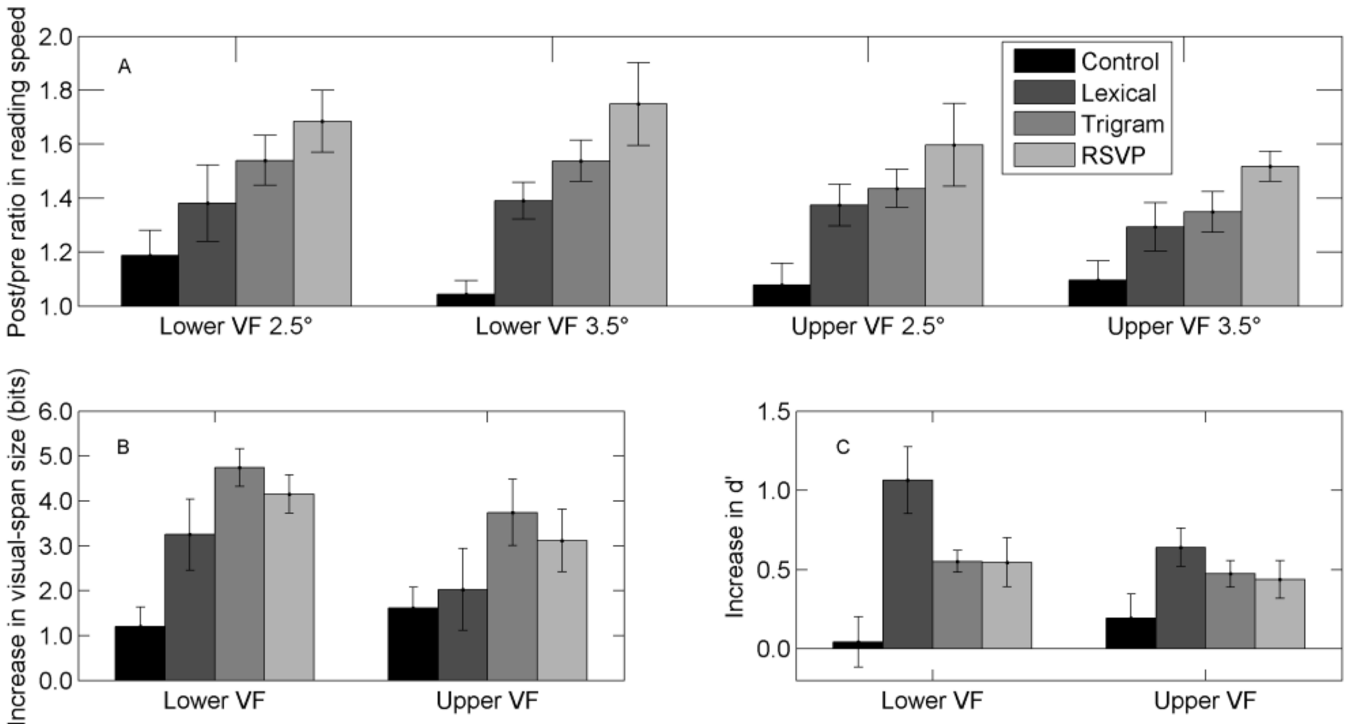

Figure 4.
Post/pre ratio in RSVP reading speed (panel A), post-pre difference in visual-span size (panel B) and post-pre difference in lexical decision accuracy d' (panel C) for the control, lexical-decision training, trigram letter-recognition training, and RSVP training groups in both lower and upper visual fields. Error bars indicate standard errors.

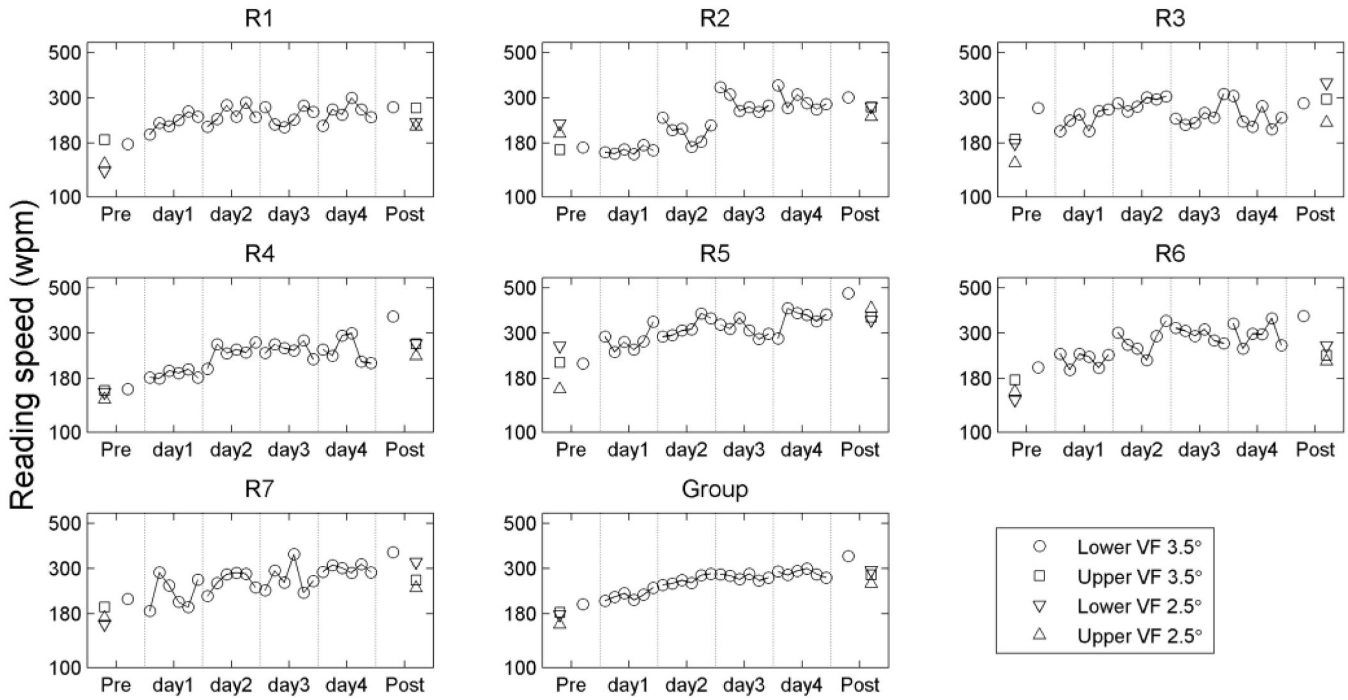

Figure 5.

Block-by-block RSVP reading speed (wpm) is shown for the seven trained subjects in the RSVP training group and the group average. Each panel shows pre- and post-test results, and also day-by-day training performance. Data are plotted as circles (lower visual field) and squares (upper visual field) for 3.5° print size, and upside-down triangles (lower visual field) and triangles (upper visual field) for 2.5° print size. Data from each of the four training days were divided into six training blocks, with 36 RSVP trials in each block. Boundaries between days are indicated by the vertical dashed lines.

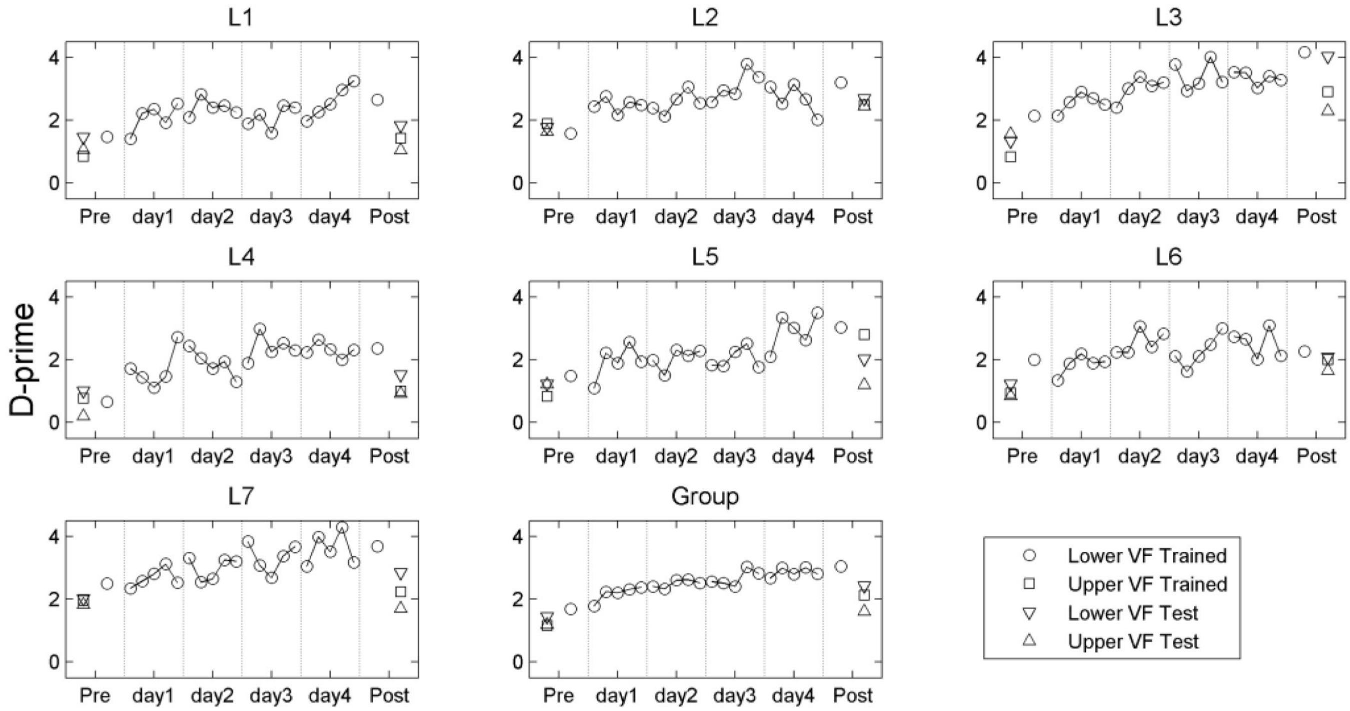

Figure 6.

Block-by-block lexical-decision performance (d’) is shown for the seven trained subjects in the lexical-decision training group and the group average. Each panel shows pre- and post-test results, and also day-by-day training performance. Data are plotted as circles (lower visual field) and squares (upper visual field) for the trained word and non-word set, and upside-down triangles (lower visual field) and triangles (upper visual field) for the testing (untrained) word and non-word set. Data from each of the four training days are divided into five training blocks, with 270 lexical-decision trials in each block. Boundaries between days are indicated by vertical dashed lines.

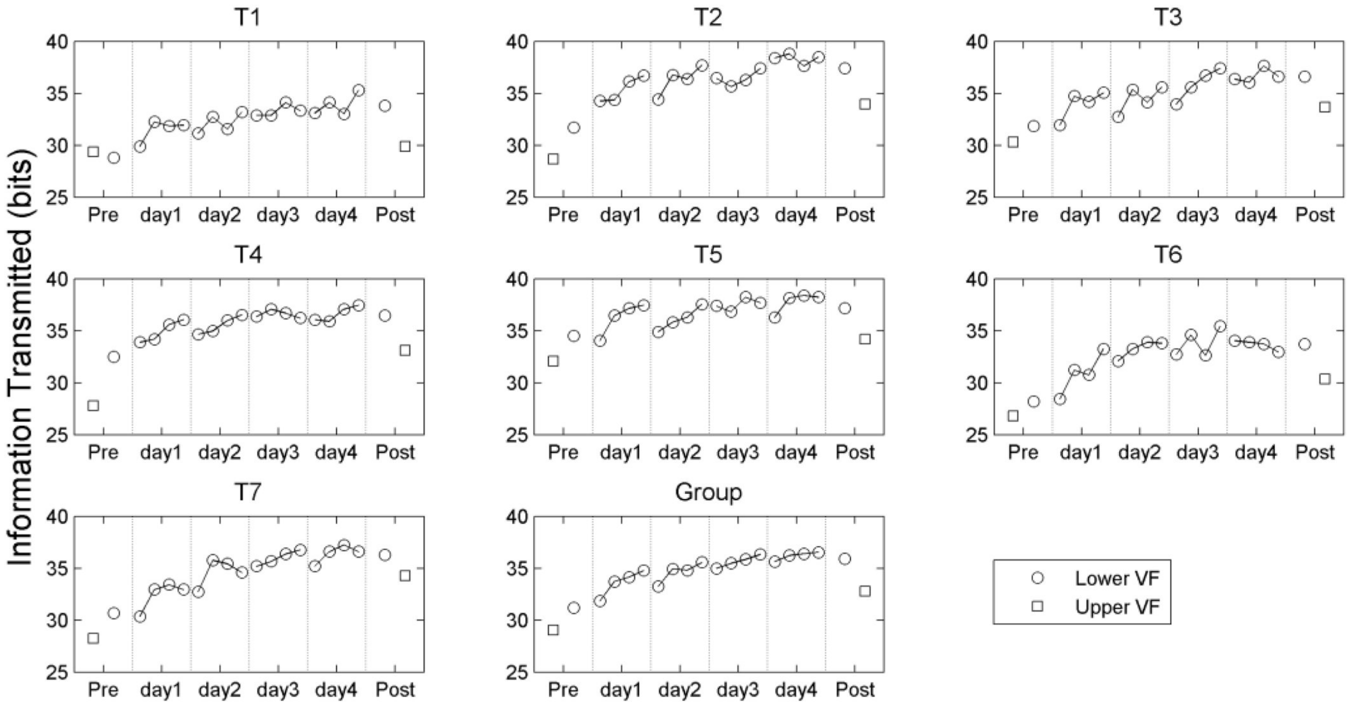

Figure 7.

Block-by-block visual-span size is shown for the seven trained subjects in the trigram letter-recognition training group and the group average. Each panel shows pre- and post-test results, and also day-by-day training performance. Data are plotted as circles for the lower visual field and squares for the upper visual field. Data from each of the four training days are divided into four training blocks, with 220 trigram trials in each block. Boundaries between days are indicated by the vertical dashed lines.

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Table 1

Summary of age, gender ratio, and clinical test results (mean ± standard deviation) for four groups of subjects.

	Control	Lexical	Trigram	RSVP
Age (year)	20.6 ± 2.1	19.1 ± 0.9	21.4 ± 1.5	19.6 ± 1.3
Gender ratio (M:F)	3:4	3:4	3:4	3:4
Visual acuity (logMAR)	−0.13 ± 0.05	−0.10 ± 0.05	−0.11 ± 0.07	−0.15 ± 0.06
Log contrast sensitivity	2.01 ± 0.04	2.00 ± 0.04	2.00 ± 0.04	1.96 ± 0.03
MNREAD reading acuity (logMAR)	−0.21 ± 0.06	−0.15 ± 0.06	−0.16 ± 0.12	−0.20 ± 0.08
MNREAD critical print size (logMAR)	−0.01 ± 0.10	−0.01 ± 0.06	0.03 ± 0.10	−0.01 ± 0.07
MNREAD maximum reading speed (wpm)	195 ± 24	225 ± 44	196 ±12	190 ± 18

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Table 2

Mean improvement ± standard error for the four groups.

	Visual Field	Print Size	Control	Lexical	Trigram	RSVP
RSVP Reading Speed (ratio)	Lower VF	2.5°	1.19 ± 0.09	1.38 ± 0.14	1.54 ± 0.09	1.68 ± 0.12
		3.5°	1.04 ± 0.05	1.39 ± 0.07	1.54 ± 0.08	1.75 ± 0.15
	Upper VF	2.5°	1.08 ± 0.08	1.37 ± 0.08	1.44 ± 0.07	1.60 ± 0.15
		3.5°	1.10 ± 0.07	1.29 ± 0.09	1.35 ± 0.08	1.52 ± 0.06
Visual-span Size (difference)	Lower VF		1.20 ± 0.43	3.25 ± 0.79	4.74 ± 0.42	4.15 ± 0.43
	Upper VF		1.61 ± 0.47	2.03 ± 0.91	3.74 ± 0.74	3.12 ± 0.70
Lexical-decision d’ difference)	Lower VF		0.04 ± 0.16	1.06 ± 0.21	0.55 ± 0.07	0.55 ± 0.15
	Upper VF		0.19 ± 0.15	0.64 ± 0.12	0.47 ± 0.08	0.44 ± 0.12

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Table 3

Correlations between the pre-post differences for the three measurements.

	Lower Visual Field		Upper Visual Field	
	r	***p***	***r***	***p***
Visual-span size and d'	.52	< .005*	.38	.04*
Visual-span size and reading speed at 2.5°	.49	.01*	.45	.02*
Visual-span size and reading speed at 3.5°	.61	< .005*	.39	.04*
Reading speed at 2.5° and d'	.26	.22	.18	.26
Reading speed at 3.5° and d'	.36	.06	.40	.03*

*two-tailed p-value < .05