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Training peripheral vision to read: Reducing crowding through an adaptive training method

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Abstract

Reading is slow and difficult for people with central vision loss who must rely on their peripheral vision. It has been shown that practicing on a letter-recognition task can increase peripheral reading speed (Yu, Legge et al., 2010), and that the training-related improvement is attributable mainly to reduced crowding (He et al., 2013). Since there is a high degree of variability in the vision conditions across people with central vision loss, a one-size-fits-all training protocol may not be adequate or appropriate for these patients. In this study, we target two aspects of training—training task and individual customization, and propose a training paradigm that focuses on reducing crowding and tailors training for each individual using an adaptive method. Seven normally-sighted adults were trained with four daily sessions of identifying crowded letters presented at various positions 10° below fixation in a pre/post design. During the training, a dynamic cue (jitter motion) was applied to target letters to modulate crowding. Amplitude of motion was varied on a block by block basis according to individual performance to maintain task difficulty near a pre-defined level (80% accuracy in letter recognition). We found that motion amplitude gradually reduced as training progressed, indicating a reduction in crowding. Following training, reading speed (measured using RSVP method) showed a significant improvement in both the trained (49%) and untrained (50%) visual fields. Despite showing similar improvement as observed in the previous training studies, our adaptive training method demands less effort and, most importantly, offers customization for each individual trainee.

Keywords

peripheral vision; reading speed; perceptual learning; adaptive method; crowding

1. Introduction

Central vision loss imposes severe impact on daily reading. People with central vision loss often learn to adopt a relative healthy region of the eccentric retina, the preferred retinal locus or PRL, as a new oculomotor reference and for fixation during reading (Cheung & Legge, 2005). However, reading is still difficult and slow for these patients (Faye, 1984; Fine & Peli, 1995; Fletcher, Schuchard, & Watson, 1999; Legge, Rubin, Pelli, & Schleske, 1985).

Since reading difficulty is the most common reason for people with central vision loss to seek out vision rehabilitation (Owsley, McGwin, Lee, Wasserman, & Searcey, 2009), developing suitable reading rehabilitation is vital to these patients.

Conventional low-vision rehabilitation typically includes prescribing assistive devices such as magnifiers to help with reading (e.g., Cheong, Lovie-Kitchin, Bowers, & Brown, 2005). Recently, a lot of research effort has been focusing on developing various training methods to improve reading performance in people with central vision loss, such as training on eccentric viewing (Nilsson, Frennesson, & Nilsson, 2003), fixation stability (Tarita-Nistor, González, Markowitz, & Steinbach, 2009), oculomotor control (Seiple, Grant, & Szlyk, 2011; Seiple, Szlyk, McMahon, Pulido, & Fishman, 2005), and sensory processing (i.e. perceptual learning; Chung, 2011; Yu, Legge, Park, Gage, & Chung, 2010). Since the immediate consequences of central vision loss are sensory deficits, many studies have been conducted to develop perceptual learning paradigm aiming to improve sensory processing and reading performance in the periphery (e.g. Yu, Legge et al., 2010; Yu, Legge, Wagnor, & Chung, 2017).

Perceptual learning, the relatively long lasting modification of the perceptual system following practice of a sensory task (Gibson, 1963; Goldstone, 1998), can enhance reading speed in both normal periphery and in people with central vision loss (e.g., Chung, 2011; Nguyen, Stockum, Hahn, & Trauzettel-Klosinski, 2011; Yu, Legge et al., 2010; Yu, Cheung et al., 2010). For reading, the training protocol typically involves extensive practice on a character-based task such as identifying strings of three random letters (trigram) for about an hour on several consecutive days (i.e., trigram training). Since visual span (the number of neighboring characters that can be reliably recognized without moving the eyes) imposes a sensory limit on reading speed (Legge et al., 2007), several training studies have been focusing on enlarging peripheral visual span using the trigram training paradigm which is expected to lead to an improvement in peripheral reading speed (Chung, Legge, & Cheung, 2004; He, Legge, & Yu, 2013; Lee, Kwon, Legge, & Gefroh, 2010; Yu, Cheung et al., 2010; Yu, Legge, et al., 2010). Although perceptual learning has been proven useful in improving peripheral reading speeds, further development of training protocols is still needed for optimizing learning on an individual level. Here, we are examining two aspects of training—training task and individual customization.

The main sensory factor determining the size of the visual span is crowding—the increased difficulty in recognizing a target object due to the interference from flanking objects (Yu, Legge, Wagoner, & Chung, 2014). The investigation on how sensory factors contribute to learning following the trigram training confirmed that improvements in visual-span size and reading speed can be primarily accounted for by the reduction in crowding (He et al., 2013). However, another study (Chung, 2007) found that practicing crowded letter identification at a fixed peripheral location can reduce crowding, but that the reduced crowding was not accompanied by an improvement in peripheral reading speed. The reason for the lack of improvement in reading may be that only one letter position was used in the training. Since reading typically involves processing multiple letters in parallel, it is likely that improving peripheral reading speed requires training multiple rather than a single position. The present study places the emphasis of training on reducing crowding and evaluates whether learning to identify crowded letters across multiple positions can improve reading speed in the periphery. Since the middle letter is the most crowded letter in a trigram, we adopt the trigram training paradigm with the modification that subjects report only the middle letter instead of all three letters.

In perceptual learning, difficulty of the training task can affect the magnitude (Green & Bavelier, 2006) and the generalization of learning (Ahissar & Hochstein, 2004). Learning tends to be specific to the trained context when the training task is difficult (Ahissar & Hochstein, 2004), while a task that is too easy tends to result in a limited amount of learning. To maximize the magnitude and generalization of learning, maintaining task difficulty at an intermediate level is a rational choice. Training at an intermediate level is also recommended for the purpose of keeping high motivation and engagement in trainees (Chermak & Musiek, 2002). Adaptive method can provide a simple solution for such need. Here, we use adaptive method to maintain task difficulty (i.e. performance) at a constant, intermediate level throughout the training. Specifically, we adaptively adjust a stimulus parameter that controls task difficulty in response to individual performance as training progresses. Such adaptive adjustment simultaneously provides customization for each individual. In the normal periphery, the initial reading performance, and the speed and magnitude of learning can be quite variable across subjects (e.g., Yu, Legge, et al., 2010). The individual variability is even greater in people with central vision loss (e.g., Chung, 2011). Patients' scotoma(s) can be of different shape, size, density, and location (Fletcher & Schuchard, 1997). For these patients, an individualized training program may be more beneficial than a one-size-fits-all training protocol. Employing adaptive method in training is not new. Although, to our knowledge, only one study (Yu, Legge, Wagoner & Chung, 2017) has incorporated adaptive procedure in training to improve peripheral reading, adaptive method is a viable option for achieving customization in the present and future studies given its potential benefits.

In the present study, we aim to develop a perceptual learning paradigm that focuses on reducing crowding in reading and utilizes adaptive method to customize the training process on an individual basis. Specifically, we monitor subject's training performance on a crowded letter- recognition task and adaptively adjust a stimulus parameter (the amplitude of a dynamic cue applied on the target letter) block by block to maintain the training-task difficulty close to a pre- determined level. By targeting training on crowded letters and adopting adaptive method, we hope to reduce task demand during the training and offer customization for each individual trainee while maintaining effectiveness of learning.

2. Methods

2.1. Subjects

Fourteen normally-sighted adults (aged 20-35 years) participated the study and were randomly assigned to a training group and a no-training control group. Another seven subjects participated in a supplementary experiment. All subjects were native English speakers, and had no history of ocular pathology nor difficulties with reading. The study protocol followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of The Ohio State University. Written informed consent was obtained from each subject prior to the experiment.

2.2. Apparatus and Stimuli

MATLAB R2010a and Psychtoolbox 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) were used to generate the testing stimuli and to control the experiments. All stimuli were black text on a white background, displayed on a ViewSonic Graphics Series G225f CRT monitor (size: 38.1cm×30.2 cm; resolution: 1280×1024; refresh rate: 85 Hz) in a dark room. Luminance was 136 cd/m^2 for the white background and 0.5 cd/m^2 for the black letters. Letters were rendered in lowercase Courier font (a fixed-width, serif font). We used a print size of 2.5° (defined as *x*- height; equivalent to 20/600 in Snellen notation) which is larger than the critical print size for reading at 10° eccentricity (Chung, Mansfield, & Legge, 1998). Testing was performed binocularly. A chin and forehead rest was used to stabilize subject's head to maintain a viewing distance of 40 cm.

2.3. Experimental Design

The control and training groups completed the same pre- and post-tests one week apart. During the pre- and post-testing, reading speeds and visual span profiles were measured at 10° eccentricity in both the upper and lower visual fields. Subjects were given a few practice trials to begin each task. In the pre-test, we measured reading speeds first and then visual span profiles. The testing order was reversed for the post-test.

The training group completed four consecutive days of training beginning two days after the pre- test. In each training session, subjects identified crowded letters at 10° eccentricity for about an hour. While training only took place in the lower visual field, pre- and post-measurements were obtained in both the trained lower field and the untrained upper field. This design allowed us to assess the transfer of learning from the trained to the untrained retinal location. Subjects in the control group received no training.

Subjects' eye positions were monitored during the experiment by experimenter who was able to reliably detect an eye movement of 1.5° (Fogt, Baughman, & Good, 2000). Detection of any deviation away from fixation target led to cancelation and replacement of the trial. Deviation of the fixation was detected in 3% of the trials for the letter recognition tasks and in 5% of the trials for the reading task.

2.4. Visual-span profile

The size of the visual span can be derived from the visual-span profile. As shown in Figure 1, the visual-span profile, measured using a trigram task, refers to a plot of letter recognition accuracy as a function of letter position (Legge et al., 2001). In the trigram task, strings of three lowercase letters were randomly chosen from the 26 letters in the English alphabet, and presented at various positions to the left and right of midline, for an exposure duration of 188ms. Eleven trigram positions were tested, five positions to the left of the midline (positions −5 to −1), one position directly below or above the fixation at 10 eccentricity (position 0), and five positions to the right of the midline (positions 1 to 5). While fixating on a green dot at the center of the display, subjects identified all three letters of a trigram in the left-to-right order. To obtain a visual-span profile, each trigram position was tested 20 times, yielding a total of 220 trials for each visual field.

The visual-span profile was constructed by examining the accuracy of letter identification at each letter slot between positions −4 and 4 where the left, middle and right letters of trigrams were equally presented. The visual-span profile was fit with an asymmetric Gaussian function. As shown in Figure 1, proportion correct of letter identification can be converted to bits of information transmitted. An accuracy of 100% corresponds to 4.7 bits of information (i.e. $\log_2(26) = 4.7$). An accuracy of 3.8% or 1/26 corresponds to 0 bits of information. The total amount of information transmitted through the visual-span profile (i.e., area under the curve) indicates the size of the visual span expressed in bits.

2.5. RSVP reading speed

Reading speed was measure using the rapid serial visual presentation (RSVP) method. The RSVP method presents words one at a time at the same, left justified, position. Each trial started with a row of *x*'s to indicate where words would be presented and ended with a row of *x*'s to indicate the end of the sentence. Sentences were presented at various speeds. Six exposure durations of word presentation were used: (76ms, 159ms, 241ms, 406ms, 735ms, 1312ms). Each trial was initiated by the subject left-clicking a computer mouse. Subjects were instructed to fixate on a horizontal line while reading aloud a sentence. Only horizontal eye movements along the fixation line were allowed. For any vertical eye movement, the trial was cancelled and replaced. The number of words read correctly was recorded. For each testing location, there were a total of 36 sentences, six for each of the six exposure durations. Sentences were randomly selected, without replacement, from over 2000 sentences. We plotted word recognition accuracy as a function of exposure duration which was fitted with a Weibull function. Reading speed in words per minute was derived based on the duration corresponding to 80% reading accuracy. All subjects were able to reach 80% reading accuracy at the longest duration.

2.6. Training

Training consisted of four daily one-hour sessions of identifying the middle letters of trigrams presented at various positions 10° below fixation. The trigram presentation was similar to that used in the pre- and post-tests with the following exceptions. The training stimuli were presented only in the lower visual field. To utilize adaptive method to customize training, we chose to apply a dynamic cue (jitter motion) to the target letter (the middle letter of trigram) and varied the amplitude of jitter motion (ranging from 0× (static) to 0.108× letter size) on a block by block basis to keep task difficulty roughly at a performance level of 80%. Each training session consisted of 16 blocks with 55 trials in each block (5 trials per position; trials were randomized within each block).

We chose to use a dynamic cue instead of other stimulus parameters (e.g., letter spacing or contrast) to control task difficulty because a dynamic cue can leave the spatial properties of reading stimulus largely unchanged. In addition, previous studies have shown that crowding can be alleviated when dynamic cues are introduced to a crowded target letter (Haberthy & Yu, 2016; Husk & Yu, 2015; Yu, 2012). In the present study, the dynamic cue was jitter motion, defined as a rapid displacement along the vertical direction with a specified magnitude. There are two cycles of displacement during the total presentation duration of 188ms (16 frames). In each cycle, target letter has a positive displacement in the first 47ms

(4 frames), followed by a negative displacement in the second 47ms. Yu (2012) showed that crowded letter-recognition accuracy depends on amplitude of jitter motion. To confirm the relationship between the performance level and motion amplitude, a supplementary experiment was performed before carrying out the main experiment. As shown in the supplementary experiment (Figure 2), crowded letter-recognition performance, an indicator of task difficulty, changes with jitter amplitude. Based on the results, seven jitter amplitudes, ranging from 0% (static) to 10.8% of *x*-height (corresponding to 0 to 6 pixels on the display with an increment step of one pixel), were selected for training.

The amplitude of the motion was modified adaptively based on subject's performance using a one-up, one-down staircase procedure. Specifically, after completing each training block, the average letter recognition accuracy across all letter positions was calculated. If letter recognition accuracy exceeded the 80% criterion, jitter amplitude would be reduced for the subsequent block by one pixel (1.8% of *x*-height). Otherwise, if the percent correct was 80% or less, an increase of amplitude would occur. There were two occasions where amplitude of jitter motion could stay unchanged for two or more consecutive blocks: (a) when the performance accuracy is above 80% at the static condition (0% of *x*-height); (b) when the performance accuracy is equal or below 80% at the maximum amplitude (10.8% of *x*-height). For all subjects, training always began at the maximum amplitude on the first training day. For the other training days, the starting amplitude was always the same as the one tested in the final block of the previous day.

2.7. Supplementary Experiment

A separate group of subjects (seven normally-sighted young adults) participated in the supplementary experiment evaluating how crowded letter-recognition performance changes with amplitude of jitter motion. The findings helped us determine the appropriate range of motion amplitude used for training.

Subjects performed on a crowded letter recognition task in a single experimental session. The stimuli were trigrams presented at positions −3 and 3 at 10° below fixation. The jitter motion was applied to the middle letter only. Five amplitudes were tested: 0, 2, 4, 6, and 8 pixels (corresponding to 0%, 3.6%, 7.2%, 10.8%, and 14.4% of *x*-height). The task was the same as the training task—identify the middle letter of trigram while maintaining stable fixation. There were ten blocks, two for each amplitude. Each block had 40 trials with 20 trials per letter position. The order of testing sequence was randomized for each subject.

Figure 2 shows the data collapsed across the two testing positions. Accuracy of identifying the middle letters of the trigrams changes with the jitter amplitude, $F(4,12) = 26.4$; $p < 0.0005$. Specifically, averaged across subjects, letter identification accuracy improved from 53% to 76% as the amplitude increased from 0 (static) to 4 pixels (7.2% of x-height), and leveled off for larger amplitudes. On the individual level, some subjects showed continuous increase in performance until 6 pixels. These findings not only confirmed a large individual variation in letter recognition which supports the need for individualized training, but also validated the option of using jitter motion to control task difficulty. Based on the findings (both the group and individual levels), a range of motion amplitudes (0% to 10.8% of x-height corresponding to 0 to 6 pixels) were selected for the training.

3. Results

3.1. Training

Figure 3 shows changes of performance accuracy (left panel: block-by-block; right panel: day-by-day) for the group average. The block-by-block individual data are shown in Figure A1. Letter recognition performance (training difficulty) was successfully maintained around 80% accuracy through adaptively changing jitter amplitude. Since jitter amplitude used in the last block of each training day and the first block of the next training day are always identical, we can make direct comparison of the performance measured in these block pairs. Unlike other training studies (Yu, Legge et al., 2010; Yu et al., 2017) that showed little lapse after two days of training, we found significant reductions in training benefit between all training days (day2 – day1: −0.09±0.04 (SE); day3 – day2: −0.07±0.03; day4 – day3: −0.05±0.01; one-tailed t-test, $ps < 0.05$). This result suggests that learning did not become more stable as training progresses.

Figures 4 and A2 show changes of jitter amplitude during training for the group average and the individual subjects. All subjects started training at the maximum amplitude (6 pixels). Amplitude was varied adaptively to maintain constant task difficulty. Despite large individual differences (shown in Figure A2), as a group, there is a clear trend of gradual decrease in jitter amplitude across training (from 4.29±0.49 pixels on day one to 1.91±0.35 pixels on day four), indicating reduction of crowding. During training, jitter amplitude reached one pixel for all subjects. Five out of the seven subjects practiced at the static condition for at least one block. For subjects T2 and T5, the static condition is an untrained condition.

3.2. Post-pre changes in visual-span size

Figure 5 shows the average visual-span profiles in the pre- and post-test for the control and training groups. An upward shift of the visual-span profile is observed in both the trained lower and untrained upper visual fields for the training group but not for the control group. Table 1 lists the post-pre changes in visual-span size. Figure A3 shows individual data.

Repeated measures ANOVA was used to analyze the post-pre difference in visual-span size. The within-subject factor was visual field (lower visual field and upper visual field). The between-subject factor was group (control group and training group). The effectiveness of the training was evaluated based on comparisons between the two groups. Transfer of learning was evaluated by comparing upper (untrained) and lower (trained) visual fields in the training group. Using repeated measures ANOVA, we also confirmed that the visual-span sizes of the training and control groups did not differ in the pre-test ($F(1,12) = 1.37$, $p = 0.27$).

Compared to the control group, the size of the visual span increased following training in both the trained lower (from 30.38±1.32 to 35.35±0.71 bits) and untrained upper visual fields (from 27.80±0.99 to 30.30±0.83 bits; $F(1,12) = 20.72$, $p = 0.001$). The enlargement of the visual span was greater in the trained field compared with the untrained field, indicating a substantial but not complete transfer of learning from the trained to the untrained field ($F(1,12) = 13.09$, $p = 0.004$). As shown in Figure A3, we also examined three trigram letters, middle, inner (the one closest to the midline) and outer letter (the one farthest from the midline), separately. We found that the enlargement of visual-span profile observed in the training group (comparing to the control group) was due to the improvement of middle letter recognition only ($F(1,12) = 41.53$, $p < 0.0005$). No significant post-pre changes were observed for the inner and outer letter recognition. In other words, learning did not transfer from the trained (middle) to untrained (inner and outer) letter positions within trigrams.

3.3. Post-pre changes in RSVP reading speed

Reading accuracy, proportion correct of word recognition, was plotted as a function of exposure duration (second) for both pre- and post-tests in Figure 6, from which reading speeds, in words per minute, were derived (see Figure 4A for individual data). The training and control groups had similar RSVP reading speeds in the pre-test ($F(1,12) = 2.41$, $p = 0.15$). Repeated measures ANOVA was used to analyze the post-pre ratio in reading speed. The within-subject factor was visual field (lower and upper fields). The between-subject factor was group (training and control groups). Transfer of learning to the RSVP task was evaluated by comparing the post-pre changes in reading speed between the training and control groups. We also compared upper (untrained) and lower (trained) visual fields to evaluate the possible transfer of learning across visual fields.

The training group showed significant post/pre improvements in RSVP reading speed compared to the control group ($F(1,12) = 10.40$, $p = 0.007$). No main and interaction effects of visual field were found, indicating a complete transfer of learning from the trained to the untrained visual field for RSVP reading. The training group had an average improvement in reading speed of 49% (from 152±15 to 224±24 wpm) in the trained lower visual field and 50% (from 104±11 to 154±16 wpm) in the untrained upper visual field (Table 1).

4. Discussion and conclusion

The primary aim of this study is to develop a perceptual learning paradigm that focuses on reducing crowding in reading while utilizing adaptive method for individual customization. We found that visual-span size was enlarged following four days of the adaptive training. The training benefit transferred to an untrained RSVP reading task. Learning was also successfully generalized to an untrained visual field. We found that amplitudes of learning are similar when comparing the current study to the previous learning studies (e.g., Chung et al., 2004; Yu, Legge et al., 2010). We understand that the direct comparison may not be entirely accurate because of the differences in experimental details across the studies. Despite being no more effective than the conventional trigram training, the current training paradigm offers a simple way to customize training for each individual, and is less demanding in terms of effort required from training subject (practicing on recognizing one letter instead of three letters in each trial) and task difficulty (average 80% accuracy in the present study vs. a lower accuracy in the conventional trigram training (e.g., 67% for middle-letter recognition in Yu, Legge et al., (2010)). These advantages may be particularly beneficial for clinical populations with greater individual variability and substantial difficulty in performing a reading task.

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In the present study, adopting jitter motion to manipulate task difficulty was guided by the following considerations. Yu (2012) showed that crowding can be reduced when jitter motion is introduced to a crowded target letter in the periphery, possibly because jitter motion can help better tag letter features to the corresponding target letter or improve deployment of spatial attention to the target location. In addition, the jitter motion has an advantage of leaving the spatial properties of letter stimulus largely unchanged. Previous study also showed that stimulus motion can have a positive effect on peripheral resolution acuity (Lewis, Holm, Baskaran & Gustafsson, 2013). Although we did not measure resolution acuity in the present study, it is possible that both crowding reduction and improvement in resolution acuity occurred following the training. When using peripheral vision to read, extra attentional capacity may be required. Since attention can be captured by stimulus motion to a peripheral location (Hillstrom & Yantis, 1994) and can improve with training (Anderson, 1980; McDowd, 1986; Richards, Bennett, & Sekuler, 2006), the training benefit may also possibly be explained by better attention deployment to peripheral vision. Subjects may become better at attending to target letters in the periphery after training, although evidence from a conventional trigram training (Lee, Gefroh et al., 2003) argued against this idea.

Transfer of learning is an important aspect to consider when developing training protocol for patients with central vision loss, given that these patients may have more than one PRL and their scotomas and PRL locations may change as disease progresses. Generalization of learning is determined by the cortical location where learning happens (Fahle & Poggio, 2002). Learning is more specific when it occurs at an early visual processing stage, and is more likely to generalize when it activates the neurons in higher-level visual area. Yu and colleagues (2015) showed that the neural bottleneck for slower reading with peripherally presented text likely extends over multiple stages along the visual pathway, from the early retinotopic cortex to the object category selective cortex. Therefore, learning to read with peripheral vision may induce neural changes at multiple cortical stages. Task difficulty has been a factor determining where learning occurs in the visual pathway (Ahissar & Hochstein, 1997). Easier tasks tend to be learned at higher cortical areas and modify neurons at the higher level of processing, and therefore likely induce generalization of learning, and vice versa. In the present study, the task difficulty was maintained at an intermediate level (average 80%). We expected and indeed observed transfer of learning to untrained conditions and tasks. Specifically, the training was performed only on the middle letters of trigrams in the lower visual field. We observed not only a reduction in crowding (reflected as the decrease of jitter amplitude across training blocks), but also significant post-pre improvements in visual-span size and RSVP reading speed in both lower (trained) and upper (untrained) visual fields. For visual-span measurement, learning only occurred at the trained (middle) but not untrained (inner and outer) letter positions within trigrams. It may be due to the higher baseline performance at the untrained letter positions, that is, the inner and outer letters were more legible than the middle letters prior to the training, leaving less room for improvement. Consistent with previous studies (e.g., Yu, Legge et al., 2010; Yu et al., 2017), we found a partial transfer of learning from the trained to the untrained field for the size of visual span. The incomplete generalization of learning implies that the neural locations for the current learning likely include multiple cortical levels—both retinotopic and nonretinotopic areas. Alternatively, the pathway connecting various processing stages may play a role as well.

It has been suggested that improvements in visual-span size and reading speed are mainly accounted for by the reduction in crowding (He et al., 2013). Can learning to identify crowded letters improve reading speed in the periphery? In the present study, we found that crowding can be significantly reduced by training on crowded letters, which led to faster reading speed in the periphery. The same question has also been investigated in another training study (Chung, 2007). Unlike our study, the author did not find evidence supporting the link between the change in crowding and the change in reading speed. A basis for the discrepancy between the two studies may lie in the difference in the trained letter position. Fluent reading, even for text presented in the RSVP format, requires processing multiple letters in parallel within each fixation. The current study trained letter identification performance at multiple letter positions left and right of the midline while the study by Chung (2007) only trained at a single letter position (10° directly below the fixation). It is possible that learning (reduction in crowding) in Chung's study was specific to the trained letter position, and that training multiple letter locations is the key for improving peripheral reading.

Performance improvement versus training time typically follows an exponential function form where learning is fastest at the beginning and then slows down over time (Dosher & Lu, 2007). Consistent with previous learning studies (Chung et al., 2004; Yu, Legge et al., 2010), our training data showed that three days of consecutive training seems adequate to reach an asymptotic level of learning. There was no significant change in average motion amplitude after day three (see Figure 4). However, we cannot be certain that learning has reached its maximal potential. Further substantial improvement is possible when extending the learning period beyond the initial plateau especially for people with severe visual impairment (Li, Klein, & Levi, 2008). When examining the effectiveness of the current training paradigm in low-vision patients, prolonged training may be necessary before concluding on the ultimate benefit of the training. Patients with central vision loss have a high degree of inter-individual variability and can be different in many aspects such as the amount of vision loss, the specifics of scotoma(s), and the capacity and speed of learning. Our study shows that incorporating adaptive procedure in training may be a viable option for reading rehabilitation of these patients.

Acknowledgments

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Appendix

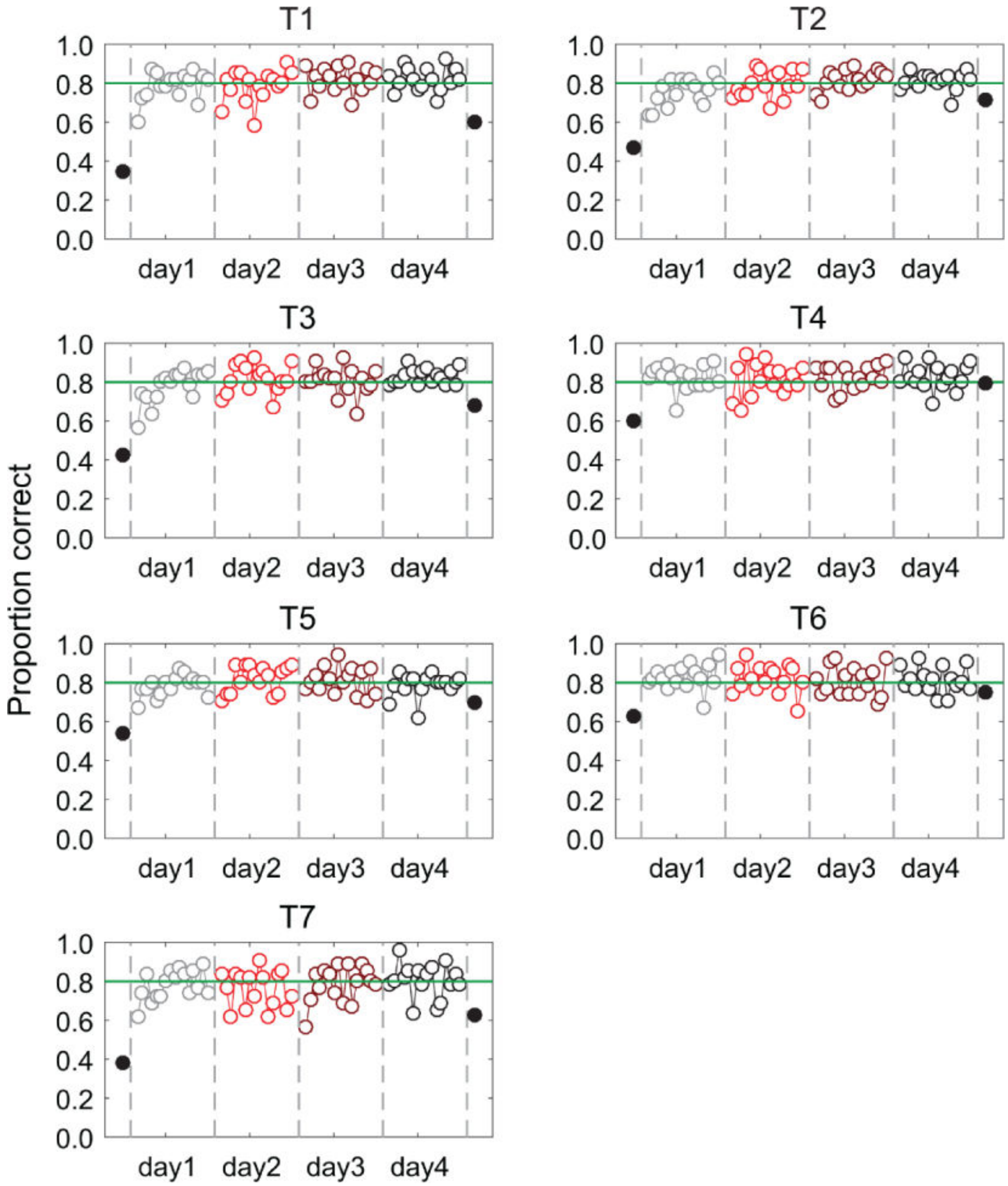

Figure A1.

Block-by-block performance accuracy during training for the seven trained subjects. Each panel shows data obtained from one individual subject. Each open circle represents performance accuracy and is derived from one training block (55 trials). The solid dots represent the performance accuracy of the middle letter recognition in the pre- and post-tests. The data for different days (16 blocks per day) were plotted in different colors. Vertical dashed lines indicate the boundaries between days. The green horizontal lines represent the 80% accuracy criterion.

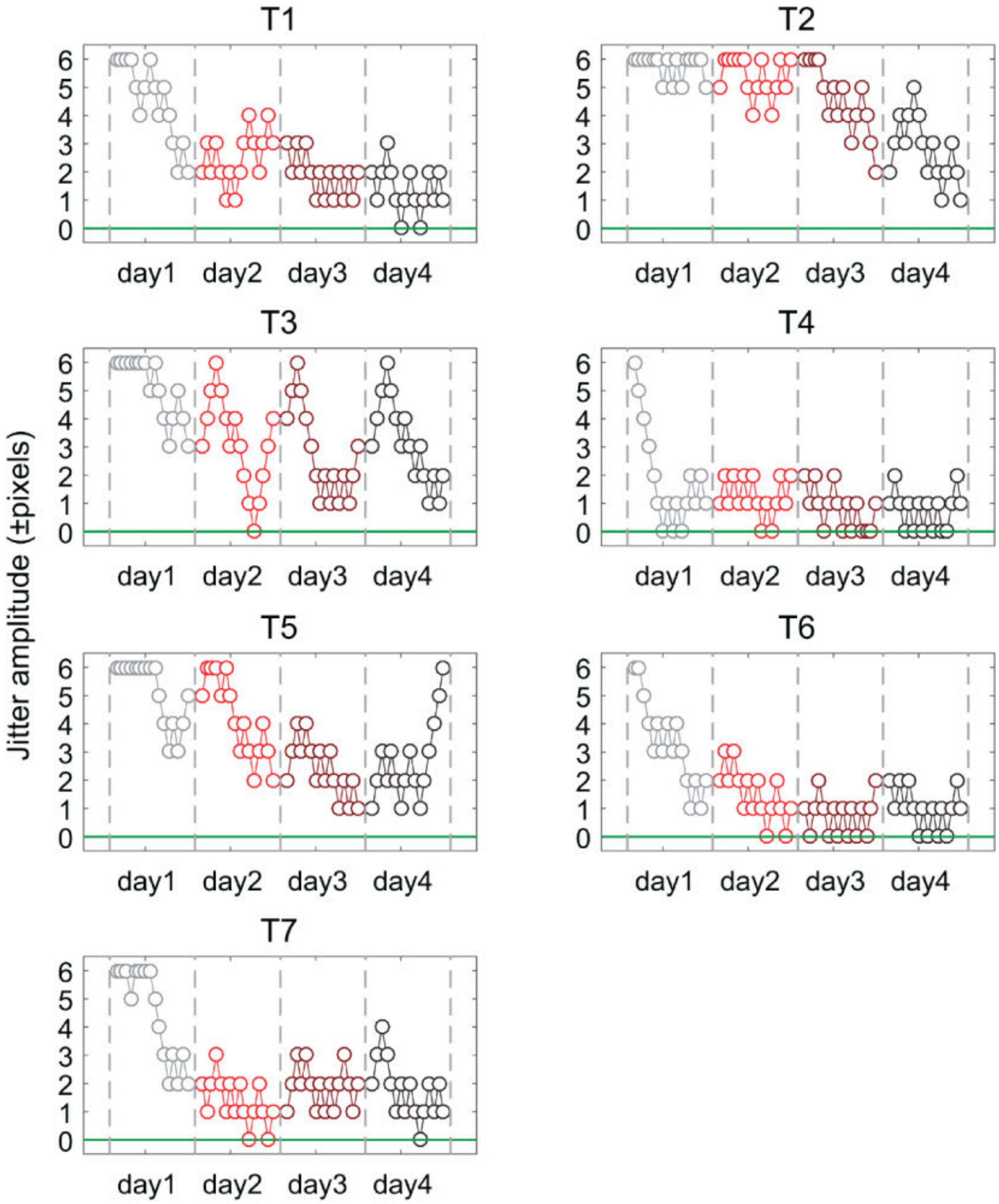

Figure A2.

Block-by-block selection of motion amplitude (pixels) during training for the seven trained subjects. Each panel shows data obtained from one individual subject. Each open circle represents amplitude of motion used for one training block. The green horizontal lines represent the amplitude tested in the pre- and post-tests (i.e., 0 pixel). The data for different days (16 blocks per day) were plotted in different colors. Vertical dashed lines indicate the boundaries between days.

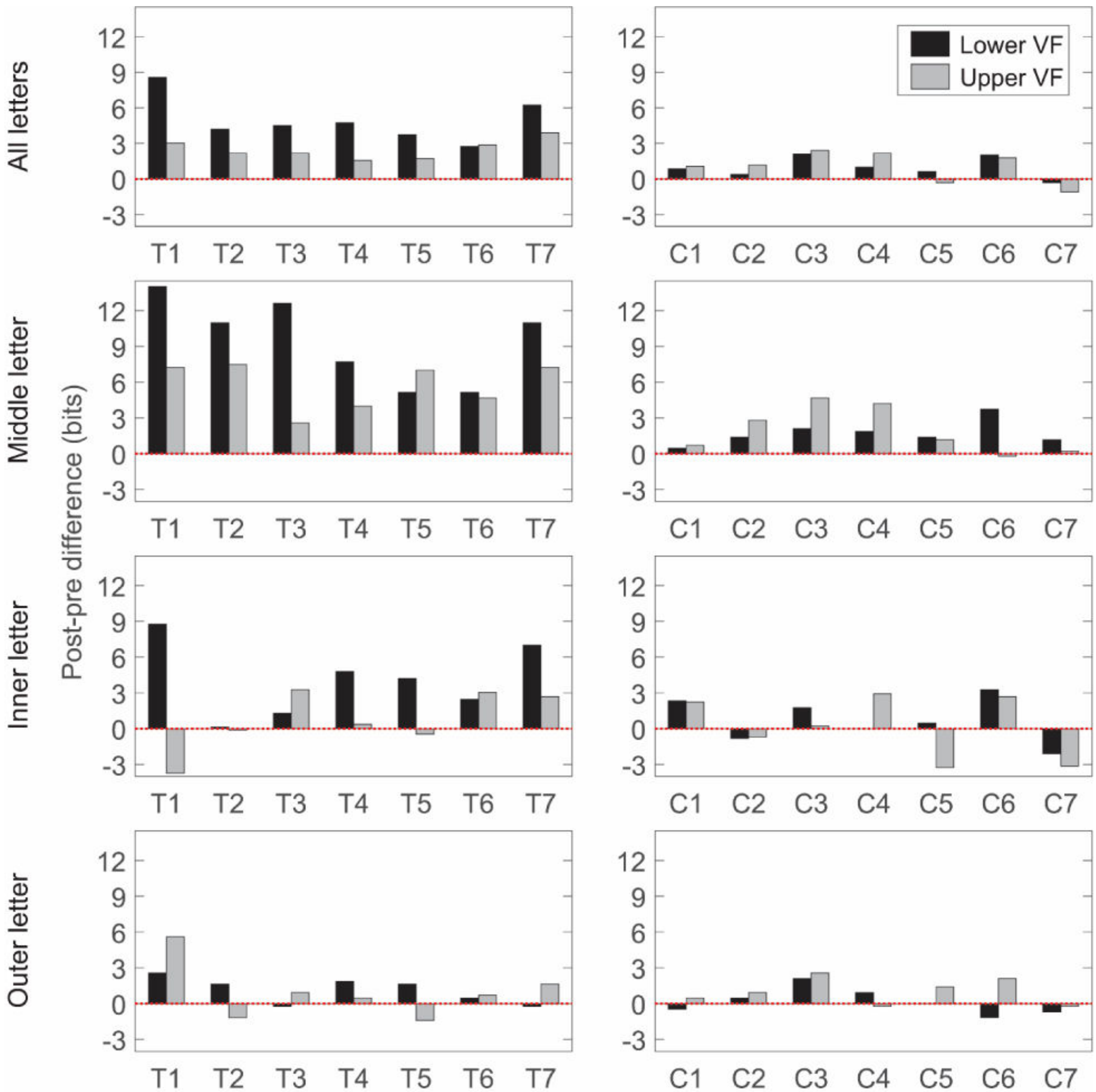

Figure A3.
Improvements (differences between pre- and post-tests) of the size of the visual span in the lower (trained) and upper (untrained) visual fields for individual subjects in both training and control groups. There are three within-trigram letter positions – middle (the center one), inner (the one closest to the midline), and outer (the one farthest from the midline). Besides accumulating data from all three positions (middle, inner and outer letters), we can also examine the recognition accuracy of middle (second row), inner (third row) and outer letters (the bottom row) separately and calculate visual-span sizes correspondingly. The size of visual span was assessed by summing the information across 9 letter positions (-4 to 4). The horizontal line corresponds to no change. Bar above the line indicates an enlargement of the visual span. Bar falling below the line indicates a constriction of the visual span.

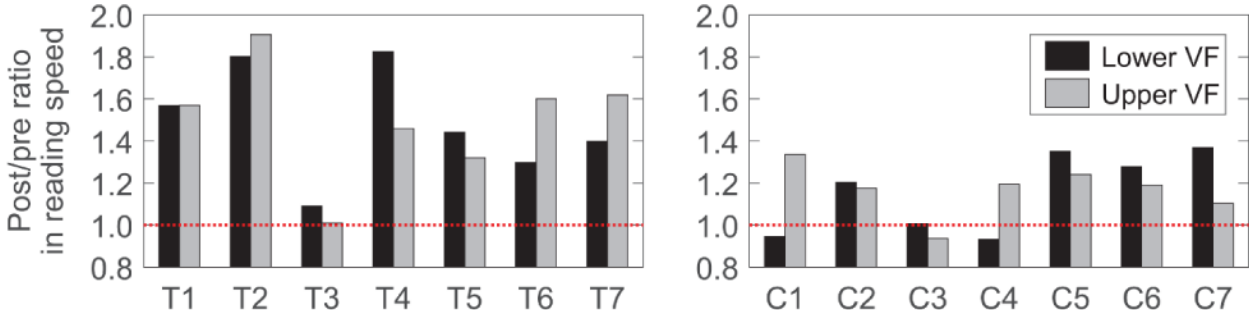

Figure A4.
Improvements (post/pre ratios) of RSVP reading speed in the lower (trained) and upper (untrained) visual fields for individual subjects in both training and control groups. The horizontal line corresponds to the post/pre ratio of one and represents no change. Bar above the line indicates an increase in reading speed. Bar falling below the line indicates a decrease in reading speed.

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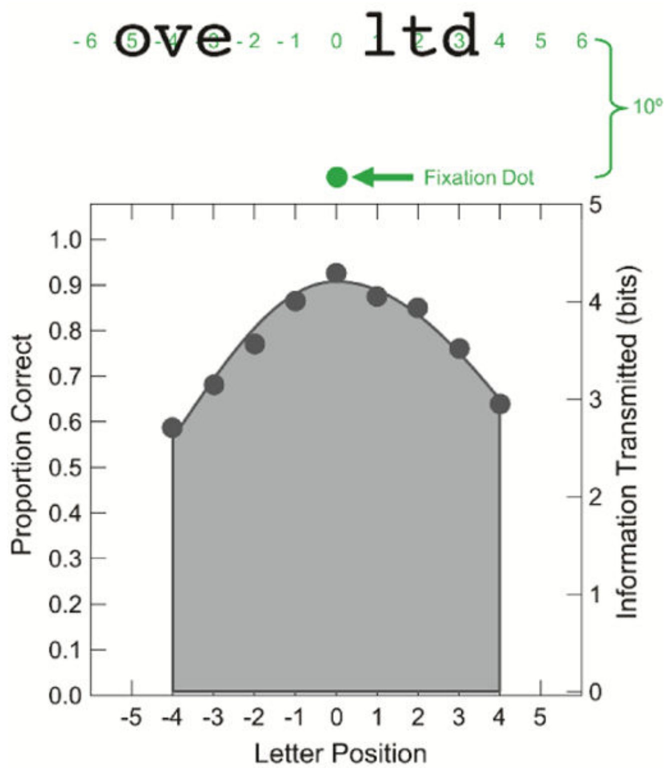

Figure 1.
Examples of trigrams (presented 10° above fixation) and a sample visual-span profile. Trigram “ove” is presented at position -4 (to the left of the midline). Trigram “ltd” is at position 2 (to the right of the midline). The right vertical scale shows a conversion from proportion correct of letter recogntion to bits of information transmitted. The shaded area under the curve indicates the size of the visual span.

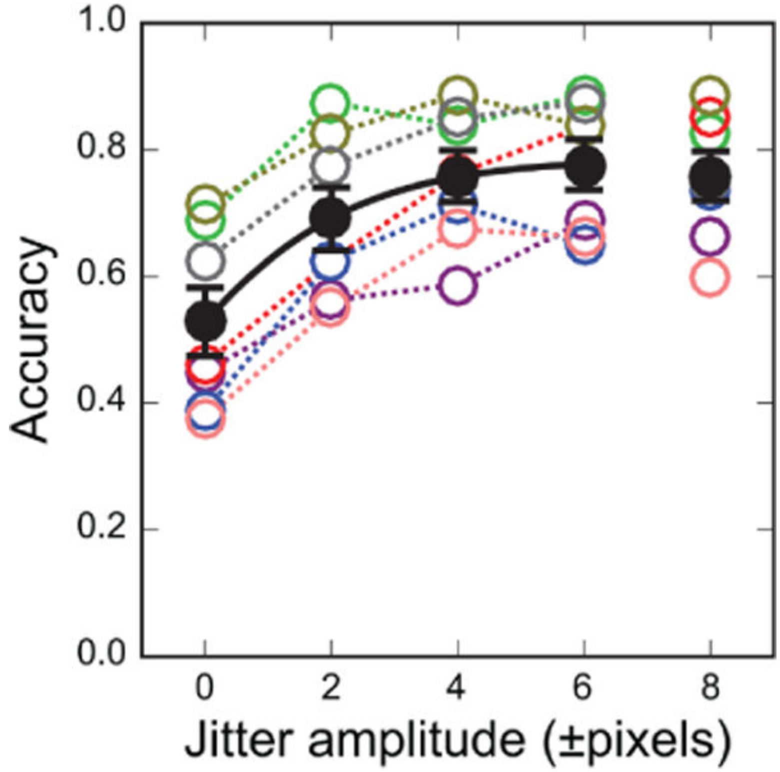

Figure 2.

Accuracy of letter identification is plotted as a function of jitter amplitude for the seven individual subjects (open circles and dotted lines; different colors represent different subjects) and the group average (filled black circles; error bars indicate standard errors). The black line represents the best-fitted exponential function for the group data between 0 and 6 pixels (the range of jitter amplitude used for training).

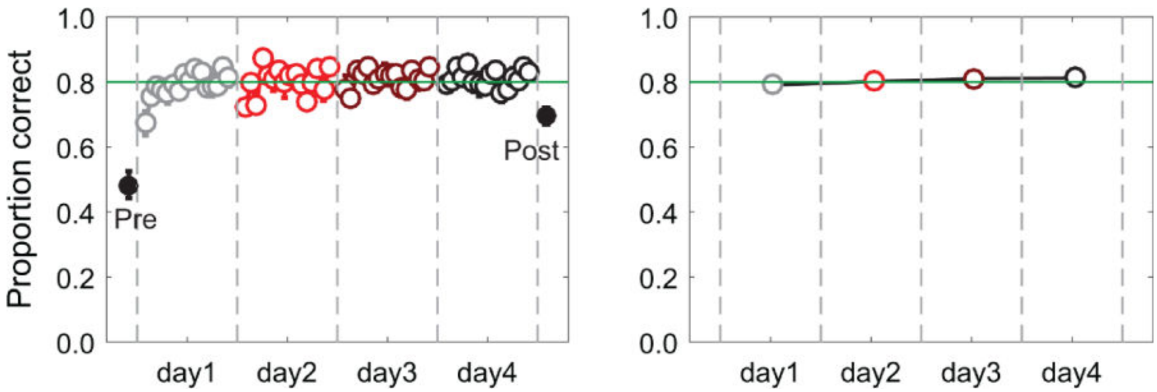

Figure 3.

Changes of performance accuracy during training. Left panel: block-by-block changes of performance accuracy (averaging across subjects). The open circles represent performance accuracy during training, one for each block (16 blocks per day). The solid dots represent the performance of the middle letter recognition in the pre- and post-tests. The data for different days were plotted in different colors. Right panel: day-by-day changes (averaging across subjects and blocks). Vertical dashed lines indicate the boundaries between days. The horizontal line represents the 80% accuracy criterion. Error bars indicate standard errors.

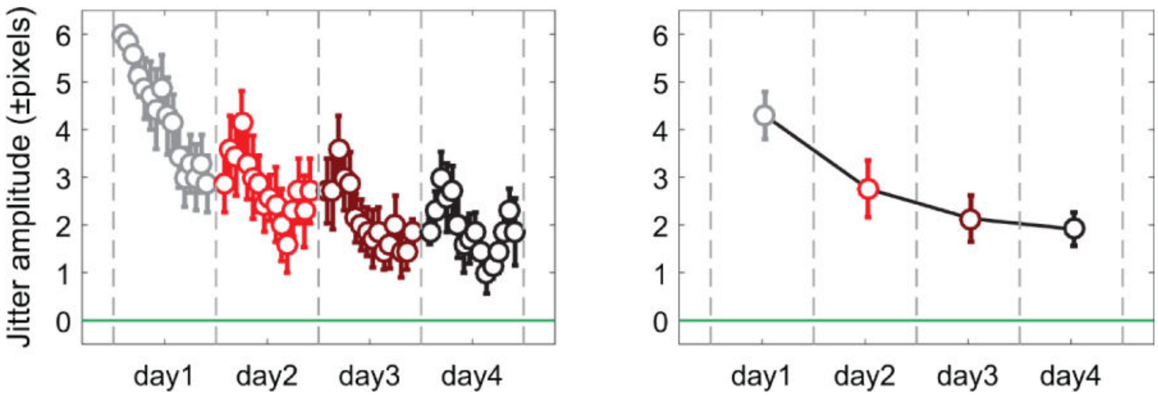

Figure 4.

Changes of jitter amplitude during training. Left panel: block-by-block changes of jitter amplitude (averaging across subjects). The open circles represent performance accuracy during training, one for each block (16 blocks per day). The data for different days were plotted in different colors. Right panel: day-by-day changes (averaging across subjects and blocks). Vertical dashed lines indicate the boundaries between days. The horizontal line represents the zero jitter amplitude. Error bars indicate standard errors.

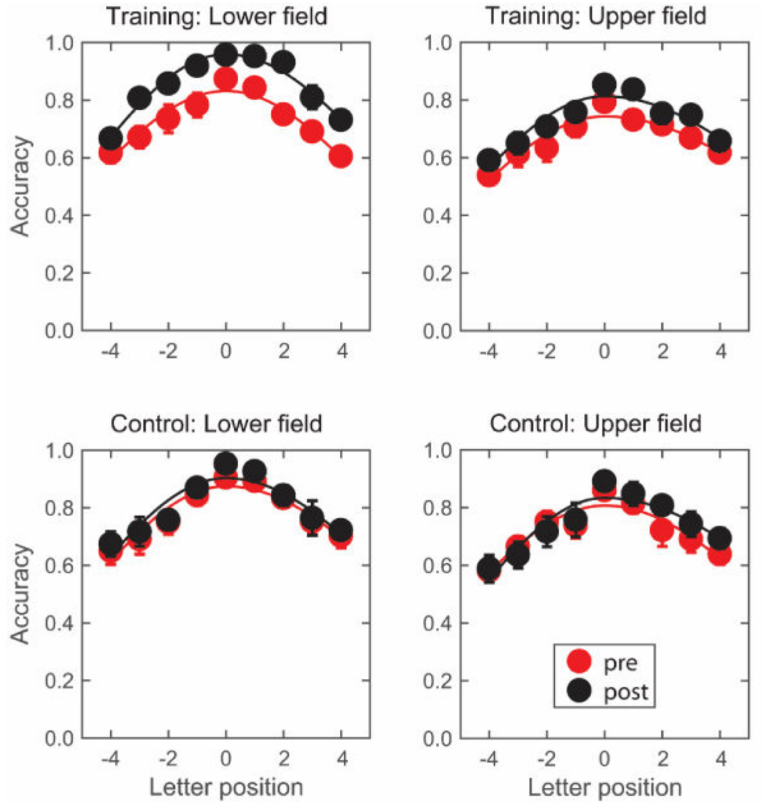

Figure 5.
Pre- and post-measurements of visual-span profiles at 10° in the lower and upper visual fields for both the training group (top panels) and no-training control group (bottom panels). Error bars represent ± standard errors.

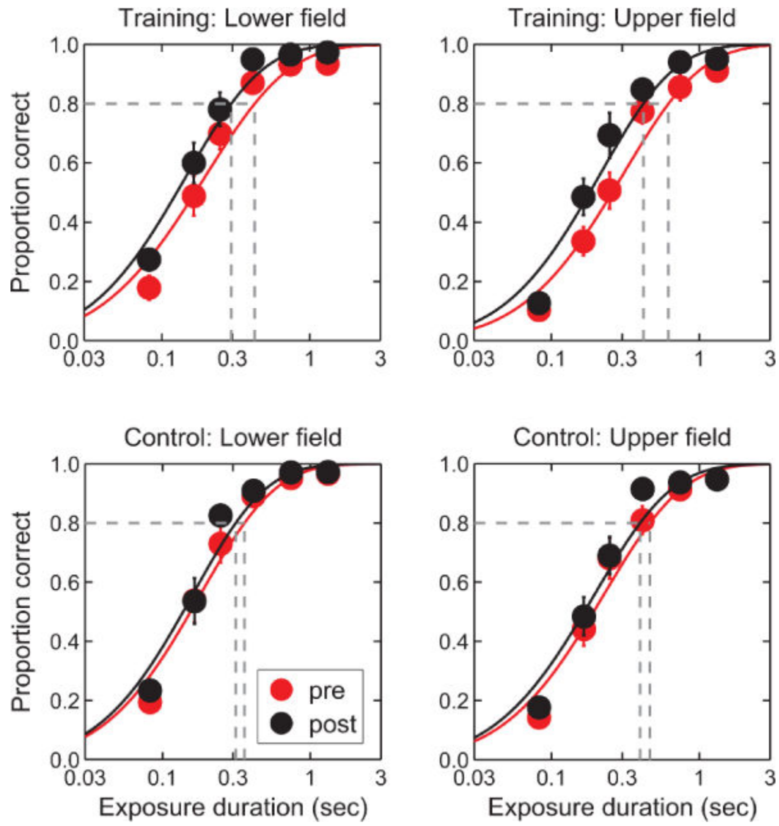

Figure 6.

Pre- and post-measurements of RSVP reading performance at 10° in the lower and upper visual fields for both the training group (top panels) and no-training control group (bottom panels). The vertical dashed lines indicate the exposure durations corresponding to 80% accuracy of word recognition (represented by the horizontal dashed lines). Error bars represent ± standard errors.

Table 1

Post-pre changes in performance (mean ± standard error) for the control and training groups.

		Lower Visual Field	Upper Visual Field
Visual-span Size (post-pre difference in bits)	Control	0.96 ± 0.33	1.04 ± 0.49
	Training	4.97 ± 0.72	2.49 ± 0.31
RSVP Reading Speed (post/pre ratio)	Control	1.16 ± 0.07	1.17 ± 0.05
	Training	1.49 ± 0.10	1.50 ± 0.11