Training improves reading speed in peripheral vision: Is it due to attention?

Hye-Won Lee Department of Psychology, Ewha Womans University, Seoul, Korea

MiYoung Kwon Department of Psychology, University of Minnesota, Minneapolis, MN, USA

Gordon E. Legge Department of Psychology, University of Minnesota, Minneapolis, MN, USA

Joshua J. Gefroh Department of Psychology, University of Minnesota, Minneapolis, MN, USA

Previous research has shown that perceptual training in peripheral vision, using a letter-recognition task, increases reading speed and letter recognition (S. T. L. Chung, G. E. Legge, & S. H. Cheung, 2004). We tested the hypothesis that enhanced deployment of spatial attention to peripheral vision explains this training effect. Subjects were pre- and post-tested with 3 tasks at 10° above and below fixation-RSVP reading speed, trigram letter recognition (used to construct visual-span profiles), and deployment of spatial attention (measured as the benefit of a pre-cue for target position in a lexical-decision task). Groups of five normally sighted young adults received 4 days of trigram letter-recognition training in upper or lower visual fields, or central vision. A control group received no training. Our measure of deployment of spatial attention revealed visual-field anisotropies; better deployment of attention in the lower field than the upper, and in the lower-right quadrant compared with the other three quadrants. All subject groups exhibited slight improvement in deployment of spatial attention to peripheral vision in the post-test, but this improvement was not correlated with training-related increases in reading speed and the size of visual-span profiles. Our results indicate that improved deployment of spatial attention to peripheral vision does not account for improved reading speed and letter recognition in peripheral vision.

Keywords: reading, attention, perceptual learning, peripheral vision, visual span

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Introduction

Reading speed in normal peripheral vision is slow. Chung, Mansfield, and Legge (1998) used an RSVP (Rapid Serial Visual Presentation) method to measure reading speed from 0 deg to 20 deg in the lower visual field of subjects with normal vision. To compensate for decreasing spatial resolution, character size was enlarged at each eccentricity to exceed the local critical print size. Nevertheless, maximum reading speed decreased by about a factor of 6 from central vision to 20 deg eccentricity, from 862 wpm in central vision to 143 wpm at 20 deg in the lower visual field. Slow reading in peripheral vision is of clinical interest because of the well-known reading problems of people with central-field loss (Faye, 1984; Fletcher, Schuchard, & Watson, 1999; Legge, Ross, Isenberg, & LaMay, 1992; Legge, Rubin, Pelli, & Schleske, 1985; Whittaker & Lovie-Kitchin, 1993).

Chung, Legge, and Cheung (2004) have shown that a form of training, based on perceptual learning, enhances reading speed in peripheral vision. In the current paper, we report on an experiment to replicate this finding and to test the hypothesis that learning to deploy attention to peripheral vision accounts for the improvements due to training. In the following paragraphs, we describe the relationship between reading speed and visual span, the visual-span training procedure, and the potential role of attention in producing the observed training effects.

The visual span for reading is the number of letters that can be recognized reliably without moving the eyes. The visual span decreases in peripheral vision, as does reading speed (Legge, Mansfield, & Chung, 2001). Legge et al. (2007) have amassed empirical evidence for a close association between reading speed and the size of the visual span. Pelli et al. (2007) have provided evidence that a major factor limiting the size of the visual span is crowding, the interference between adjacent letters, which becomes more pronounced in peripheral vision. Legge

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et al. (2007) have made the case that the visual span is primarily limited by front-end visual factors. Legge et al. (2001) presented a model showing how the decreasing size of the visual span would be expected to reduce peripheral reading speed. Lee, Legge, and Ortiz (2003) further showed that higher-level language processing is similar for inputs to central and peripheral vision, implying no extra linguistic difficulty in reading in peripheral vision.

It is likely that reduced visual span also contributes to slow reading by people with central-field loss. People with this condition usually adopt a retinal location outside the scotoma boundary for fixation, termed a preferred retinal locus or PRL. Letter recognition and reading involve pattern recognition in the region of the PRL. Cheong, Legge, Lawrence, Cheung, and Ruff (2008) showed that the visual spans of subjects with central scotomas from age-related macular degeneration (AMD) are smaller than the visual spans of age-matched normals. While shrinkage of the visual span probably contributes to slower reading in normal peripheral vision and in AMD, Cheong et al. (2008) also showed that a temporal processing deficit is a contributing factor.

Perceptual learning refers to improved performance on perceptual tasks following practice. This form of learning is presumed to be based on neural changes in the perceptual pathways rather than the learning of task-specific strategies to improve performance on a particular task. Chung et al. (2004) showed that training based on perceptual learning increased reading speed and visual span in peripheral vision.

Visual span profiles are plots of letter accuracy vs. letter position (see Figure 4). Chung et al. (2004) compared reading speed and visual span profiles at 10 deg in the upper and lower visual fields before and after 4-days of training on a trigram letter recognition task (described in the Method section of this paper). Trained subjects showed an increase in the size of the visual span, approximately equivalent to the addition of an extra perfectly recognizable letter, and improvement in peripheral reading speed averaging 40%. There was also evidence of transfer of the training effect from the lower to the upper visual field, and vice versa, and from the print size used in training to other print sizes. The transfer of training across visual-field locations indicates that the learning effect is not retinotopically specific, suggesting that the effect might have an origin at a higher non-retinotopic level of the visual pathway.

The question arises whether a higher-level process such as attention can account for the improvements in reading speed and visual span due to training of normal peripheral vision. It has been suggested that attention facilitates perceptual learning (Carrasco, Giordano, & Looser, 2007) or perceptual learning requires attention (Ahissar & Hochstein, 1993; Fahle & Harris, 1998; Shiu & Pashler, 1995) (see also conflicting views: Dosher, Han, & Lu, 2010; Seitz & Watanabe, 2005). Covert attention refers to the deployment of attention to locations or targets in the visual field away from fixation, without moving the eyes. It is possible that the perceptual learning effects in peripheral vision observed by Chung et al. (2004) were due to an improved use of covert attention. Peripheral training may function to enhance the ability of subjects to decouple attention from fixation and deploy it to targets in peripheral vision. There is evidence that pre-cueing the peripheral target location improves performance in various visual tasks (Davis, Kramer, & Graham, 1983; Posner, 1980; Shiu & Pashler, 1995; Yeshurun & Carrasco, 1998, 1999). Pre-cueing a peripheral location allows attention to be allocated in advance to the cued location, thereby enhancing the processing of any object that appears in that location.

The task of reading in peripheral vision would seem to require the ability to deploy attention to the peripheral location of text presentation. This is because current models of reading involve the focusing of attention locally on words, or perhaps neighboring words as in the E-Z Reader Model (Reichle, Pollatsek, Fisher, & Rayner, 1998), the SWIFT model (Engbert, Longtin, & Kliegl, 2002) and the Mr. Chips model (Legge, Klitz, & Tjan, 1997).

The issue of how effectively people can deploy attention to a nonfoveal retinal location is relevant to development of a preferred retinal locus in people with AMD. When a central scotoma first develops, they have a reflex to foveate a target, but gradually learn to overcome this reflex and deploy fixation to a nonfoveal PRL. Presumably, attention is bound to fixation and also moves to the PRL.

The primary question of this study is to determine whether the training effects in peripheral vision observed by Chung et al. (2004)—enlarged visual span and faster reading speed—were associated with an improved ability to deploy attention to peripheral vision. To address this issue, we replicated Chung et al.'s study, with the addition of a measure of the deployment of attention to peripheral vision (see Method).

As a secondary focus of the study, we asked if there are differential attention effects across visual-field locations (quadrants or hemifields). Our interest is motivated by prior findings on visual-field anisotropy in the deployment of attention (He, Cavanagh, & Intriligator, 1997; Mackeben, 1999) and potential relevance to the adoption of a PRL outside a central scotoma. He et al. (1997) found that attentional resolution is greater in the lower visual field than in the upper visual field. Mackeben (1999) found differences in the ease with which normally sighted subjects (both young and old) could deploy attention to targets in different directions in the visual field. Subsequently, Altpeter, Mackeben, and Trauzettel-Klosinski (2000) proposed that the choice of a site for the PRL in the presence of central-field loss is determined by attentional hot spots in peripheral vision; people who lose their central vision may adopt a location in peripheral vision for fixation that is already intrinsically better at attending.

Method

Subjects

Twenty normally sighted students at the University of Minnesota were paid for their participation in the experiment. The mean age of the subjects was 23 with a range from 18 to 41 (only two were older than 30). They were all native English speakers with corrected-to-normal vision. The mean acuity was −0.18 logMar (Snellen 20/13) with a range from −0.32 (Snellen 20/10) to 0.26 (Snellen 20/36).

Stimuli and apparatus

Visual-span and reading-speed measurements were obtained using custom software running on a Silicon Graphics O2 workstation connected to a SONY Trinitron color graphic display (Model: GDM-17E21; refresh rate: 76 Hz; resolution: 1280 × 1024). For the attention task and eye tracking, visual stimuli were generated using a Cambridge Research System consisting of a 200 MHz PC (Dell Dimension XPS M200s) with a Visual Stimulus Generator graphics card (VSG 2/4-4 MB). Visual stimuli were displayed for the participants on a 21-inch monitor (Sony Trinitron MultiScan 20 se II) running at a frame rate of 160 Hz (640 × 480 pixel resolution). The PC was loaded with VSG software version 5.0 as well as custom software specially developed to run the experiment.

The size and font of letters were identical in attention, reading speed, and visual span measurements. The letters were rendered in lowercase Courier—a serif font with fixed width. We used a fixed-width font, rather than proportionally spaced font (more typical of modern text), because it has a constant center-to-center spacing between letters, which simplifies the measurement of visual-span profiles. We used standard spacing for Courier text in all conditions, equal to 1.5 times the x-height. The letter size was 2.2° (~72 pt) and was larger than the critical print size at 10° eccentricity of most subjects in Chung et al. (2004). Letter spacing and letter size were chosen to yield maximum reading speed. All stimulus characters were rendered as black characters on a white background (90 cd/m^2) at a high Michelson contrast greater than 90%. The stimuli were presented at a viewing distance of 60 cm for attention measurements and 30 cm for reading-speed and visual-span measurements.

Basic experimental design

As illustrated in Figure 1, the experimental design had three phases—pre-test, training period, and post-test. In the pre-test, measurements were obtained from all subjects on tests of attention, reading speed, and visual span at 10° in the upper and lower fields. We kept the same order of the pre/post tests across subjects: attention, reading speed,

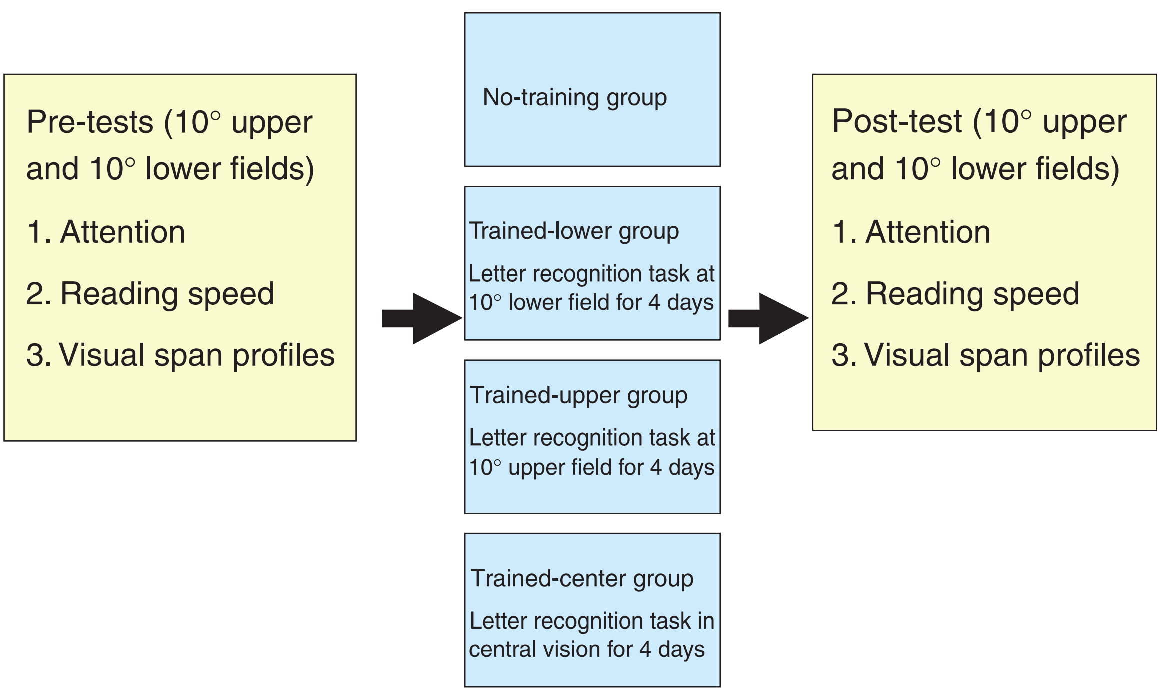

Figure 1. A schematic diagram of the experimental design.

and visual span. We, however, counterbalanced all the sub-tests within each task (e.g., the cued and uncued conditions in the attention task were randomized across subjects. Similarly, the lower and upper visual fields in visual span/reading speed tasks were counterbalanced as well). The pre and post test batteries, each took approximately 4 hours spread across two days, and each training session required about 2.5 hours.

Five subjects were randomly assigned to each of four groups—1) Trained-Upper group: trained with a letter recognition task for four consecutive days at 10° in the upper field. 2) Trained-Lower group: trained for four consecutive days on a letter recognition task at 10° in the lower field. 3) Trained-Center group: trained for four consecutive days on a letter recognition task on the horizontal meridian passing through fixation (The purpose of this group was to determine if training effects are transferred from central to peripheral vision.). 4) The No-Training group: received no training. In the post-test, measurements were once again obtained from all subjects on tests of attention, reading speed, and visual span at 10° in the upper and lower fields. The effects of training were assessed as an improvement in performance in the post-test compared with the pre-test for each task.

Attention measurements

Figure 2 illustrates the procedure for measuring deployment of attention to peripheral vision. In each trial, subjects fixated on a central circle subtending 0.5 deg. Trigrams (strings of three letters) were presented simultaneously in each of the four quadrants for 200 ms. Subjects made a lexical decision (word/nonword) for one of the trigrams. The probability was 50% that any given trigram in any quadrant was a word. In the cued condition, a digit (1 to 4) at fixation directed attention to one of the quadrants (termed the "target quadrant") before the onset of the trigram (1: upper-right, 2: upper-left, 3: lower-left, 4: lower-right). In the uncued condition, there was no indicator to guide the deployment of attention—the target quadrant was indicated only after the offset of the trigram. Trigrams were followed by masks (a series of X) for 1 s during which the target indicator in the cued condition was replaced with the neutral symbol and the neutral symbol in the uncued condition was replaced with the target indicator. To allow time to process the target indicator for the uncued trials, subjects were not allowed to respond while the mask was being presented. After the offset of the mask, the subject made a yes/no lexical decision for the trigram in the target quadrant by pressing a key.

Stimuli were drawn from lists of 350 3-letter words and 350 nonwords. Appendix A describes the construction of the lists.

Given the likelihood of wide variability in response times for this task, we emphasized accuracy over speed. Subjects were asked to respond as accurately as possible, rather than responding as quickly as possible. Attention effects were measured as the difference in lexical decision accuracy between the cued and uncued conditions.

The middle letters of the trigrams in the four quadrants were displaced 10° horizontally and vertically from fixation, resulting in (x, y) coordinates as follows: (10, 10) in the upper-right quadrant, (−10, 10) in the upper-left quadrant, (−10, −10) in the lower-left quadrant, and (10, −10) in the lower-right quadrant. The spatial positions of these trigrams (i.e., the radial distance of

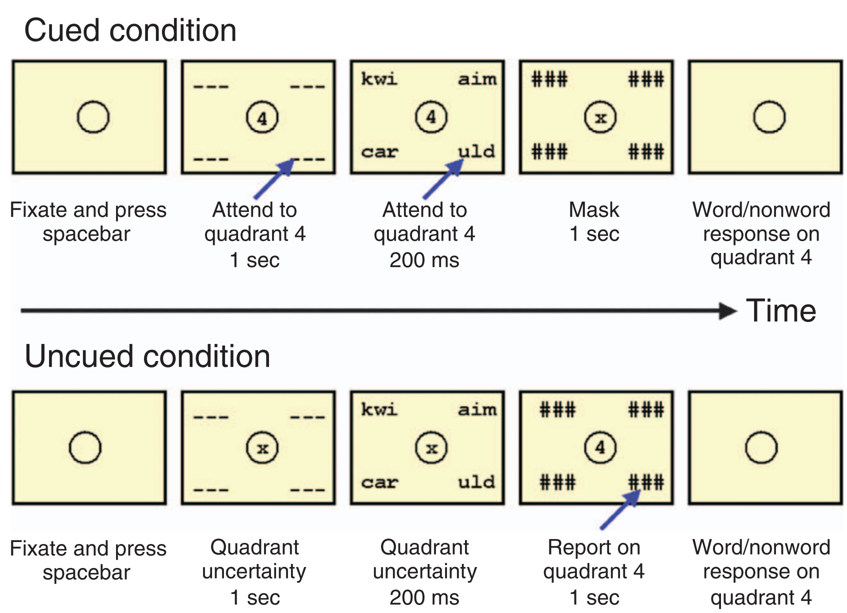

Figure 2. A schematic diagram of the attention task (one test trial) for the cued (top row) and uncued conditions (bottom row).

approximately 14 degree from fixation) were roughly matched to the letter spaces 3–5 left or right of the midline in the visual span measurements (see Footnote 1).

The task was composed of 8 blocks of 100 trials with 4 blocks in the cued condition alternating with 4 blocks in the uncued condition, and with the type (cued or uncued) of the starting block alternating across subjects. In each block, the target was distributed about equally across the four quadrants (i.e., each quadrant was the target quadrant for about 25 trials in a block). The assignment of a target quadrant was randomized so that it was not possible to predict the target quadrant of the next trial. Before the pre-test data collection, subjects received total 250 trials to get familiar with the procedure.

Reading speed measurements

We used the same procedures and sentences for measuring reading speed as Chung et al. (1998; Chung et al., 2004). Words from short sentences were presented 10° above and below the horizontal midline, using the rapid serial visual presentation paradigm (RSVP). Subjects were free to move their gaze along a horizontal fixation line, but were instructed not to look up (or down) at the words in the upper (or lower) visual field. Prior to a trial, a number sign "#" was displayed at the location subsequently occupied by the leading letters of the left-justified series of words.

On each RSVP trial, a single short sentence (average length = 11 words, average word length = 4 letters) was randomly selected from the pool of 2658 sentences. Subjects were instructed to read the sentences aloud as accurately as possible. Subjects were allowed to complete their verbalization after the sentence disappeared from the display. Words reported out of order were counted as correct, such as a correction made at the end of the sentence. None of the subjects was tested more than once with any given sentence.

The proportion of words read correctly was measured at six RSVP exposure times in the range 80 to 1064 ms per word corresponding to 6 to 80 frames per sec (1 frame = 13.3. ms). Three sentences were tested at each of the six RSVP exposure times.

We then fit each set of data using a cumulative-Gaussian function from which we derived our criterion reading speed. Each function was based on a total of 18 sentences (three sentences at each of six durations, with the durations in a random sequence). We derived our criterion reading speed from the RSVP exposure time yielding 80% of words read correctly, as in our previous studies.

The measurement of reading speed in the pre-test and post-test was composed of four blocks, with 2 blocks tested in the lower field and 2 blocks tested in the upper field. The order of lower and upper field blocks was interleaved so that the lower-field block was followed by the upper-field block, or vice versa.

Visual span measurements

Visual-span profiles were measured with the trigram method described in detail by Chung et al. (2004) and Legge et al. (2007). Figure 3 illustrates the procedure for a single trial of the trigram task. Trigrams (random strings of 3 letters) were presented for 200 ms on horizontal lines displaced 10° above or below the horizontal midline. Subjects reported the three letters in order.

In the pre-test and post-test, there were four 130-trial blocks with 2 blocks tested in the lower field and 2 blocks tested in the upper field. Across a block of trials, trigrams were presented with the position of the central letter ranging from −6 (left) to +6 (right) letter positions from the vertical midline (0 position). In a block of 130 trials, trigrams centered at each of the 13 positions were tested 10 times. Because each trigram permits scoring of three letters at three positions, the 130 trials per block yielded letter-recognition accuracy (% correct) based on 30 responses at each letter position. The profile of percent correct vs. letter position is termed a "visual-span profile" (see Figure 4 for examples.). Since the letter positions −6 and +6 provided responses only for the two letter positions of trigrams, these positions were excluded from plotting visual span profiles. Accordingly, visual-span profiles were plotted based on responses for the letters in positions from −5 to +5.[1]

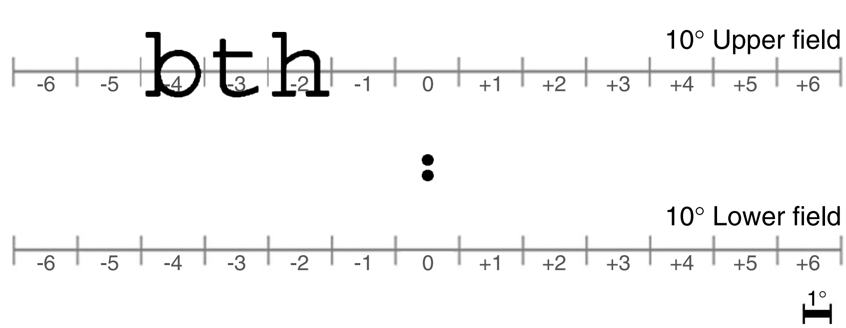

Figure 3. An illustration of the visual span task.

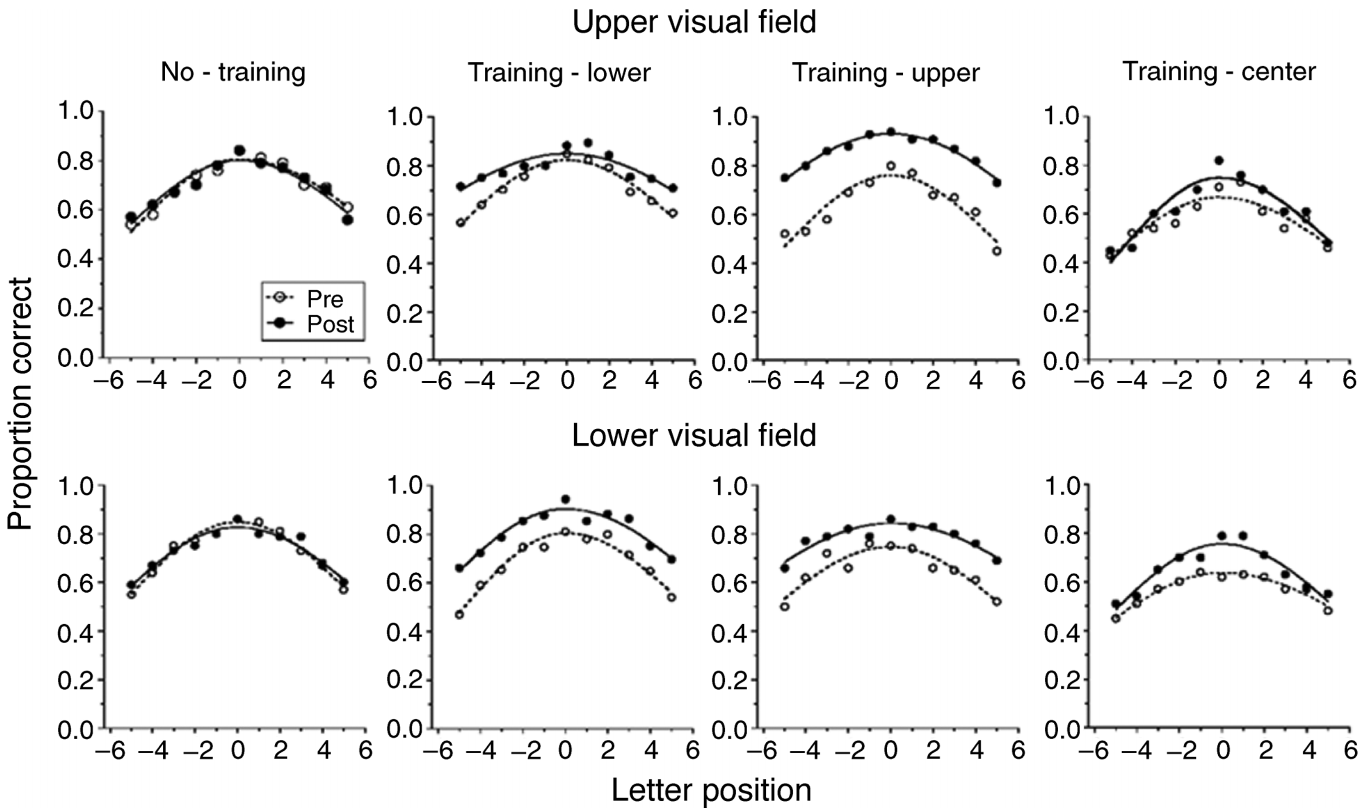

Figure 4. Visual span profiles in two visual fields: upper field (top row) and lower field (bottom row), for the four groups.

Training procedure

The four-day training period was devoted to the repeated measurement of visual-span profiles at the trained retinal location. Each day the task was composed of five blocks of trigram trials. In a block of 260 trials, trigrams centered at each of the 13 positions were tested 20 times.

For the peripherally trained groups (Trained-Lower and Trained-Upper groups), the trigram trials involved the same procedure used in the pre- and post-tests.

By testing trigrams at each of 13 positions 20 times in the training blocks, we matched the procedure used by Chung et al. (2004).The Trained-Center group was trained with trigrams presented on the horizontal midline. We, however, shortened the trigram exposure time to 30 ms with the goal of approximately matching overall performance levels for central and peripheral vision. This was done because prior research has shown that perceptual learning is influenced by task difficulty (Ahissar & Hochstein, 1997).

Eye movement monitoring

We monitored the fixation behavior of subjects during the attention measurements using a video-based eye-tracker (ISCAN RK-726PCI) which was interfaced with the computer. Its signal was sampled every 16.7 ms by the computer (60 Hz). Viewing was binocular, with eye movements recorded from the right eye. (For the first few subjects, we monitored only the first cued and uncued blocks of trials. We then decided to monitor eye movements for the entire block of trials. Overall, 76.6% of attention trials were monitored).

The goal of eye tracking was to ensure that subjects did not divert their eyes during the attention trials from fixation to the trigram stimuli in the four quadrants. The central letters of the trigrams were located 10° above and below fixation and 10° to the left and right of fixation. All the horizontal eye positions fell into the range from −1.65 to 2.21 deg with a mean eye position of .38 deg (*SD* = .27 deg) (the negative value indicates an eye position to the left of fixation and the positive value indicates an eye position to the right of fixation). All the vertical eye positions fell into the range from −4.58 to 5.92 with a mean eye position of 0.04 deg (*SD* = 1.45 deg) (the negative value means below fixation and the positive value means above fixation). 99% of vertical eye positions fell into the range from −4.32 to 4.42 deg. In spite of the deviations of eye positions away from fixation for some trials, the eye monitoring results show that subjects rarely, if ever, looked directly at the stimuli in the attention measurements. The eye-tracking data were compared before and after the training to see if any changes in performance in the attention task were associated with eye movements. We did not find any substantial changes in the magnitude and variance of eye movements between the pre- and post-tests.

To expedite testing, and the comfort of the subjects, we did not monitor fixation for reading speed and visual span measurements. Instead, we asked subjects to inform the experimenter whenever they failed fixation so that the trial could be cancelled. We acknowledge that subjective reporting of fixation stability is less accurate than eye tracking. However, Chung et al. (2004), who monitored eye movements in reading speed and visual span measurements for some subjects, reported that the pattern of results were quite consistent between the subjects whose eyes were monitored and those who were not monitored.

Results and discussion

Visual span: Effects of training

Figure 4 shows the visual span profiles of the 4 groups before and after training in the upper and lower fields. The profiles show average data for 5 subjects in each group. Individual visual span profiles are presented in Appendix B. The No-Training group showed no improvement, whereas peripherally trained groups (Trained-Lower and Trained-Upper groups) showed noticeable growth in the size of the profiles following training. The Trained-Center group showed smaller improvement after training, confined mostly to the letters at or near fixation.

To quantify the size of the visual-span profiles, we first transformed percent correct at each letter position in Figure 4 to *bits of information transmitted*. The information values range from 0 bits for chance accuracy of 3.8% correct (the probability of correctly guessing one of 26 letters) to 4.7 bits for 100% accuracy. For details of this transformation, see Legge et al. (2001, Footnote 9). We then quantified the size of the visual span by summing across the information transmitted in each slot (similar to computing the area under the visual-span profile). In the pre-test, the mean size of the visual span in the upper visual field, averaged across all 20 subjects, was 33.43 bits, and in the lower visual field 33.46 bits.

We performed an analysis of variance (ANOVA) on the visual span size (in bits)—2 (test session: pre vs. post) × 4 (training group: central, lower, upper, control) × 2 (visual field: lower, upper) repeated measures ANOVA with test session and visual field as within-subject factors and training group as a between-subject factor. There was a main effect of test session ($F_{(1,19)} = 50.391$, $p < 0.001$). We also found significant interaction effects between test session and training group ($F_{(3,16)} = 9.424$, $p = 0.001$) and among all three factors ($F_{(3,16)} = 10.037$, $p = 0.001$).

Mean values and standard errors are shown in the bar graphs in Figure 5. P-values of the paired t-test (two-tailed) refer to significance of the difference in pre-test and post-test values (* for $p < 0.05$). The No-Training group exhibited no significant training effect. The Trained-Lower group showed a significant training effect in the lower field and marginally significant effect in the upper field. The Training-upper group showed significant training effects in both fields. The Trained-Center group showed a marginally significant training effect in the lower field and a significant effect in the upper field.

Figure 5 reveals that the three trained groups showed significant growth in the size of the visual span from pre-test to post-test, while the No-Training group did not. Clearly, training had an effect. For the two groups trained in peripheral vision, the training effects were strongest in the trained hemifield (mean 8.78 bits increase in the size of the visual span), compared with the untrained hemifield (mean 5.15 bits), $p < .05$. as shown in Figure 6. These values are larger than the corresponding values reported by Chung et al. (2004) of 6 bits (trained field) and 4 bits

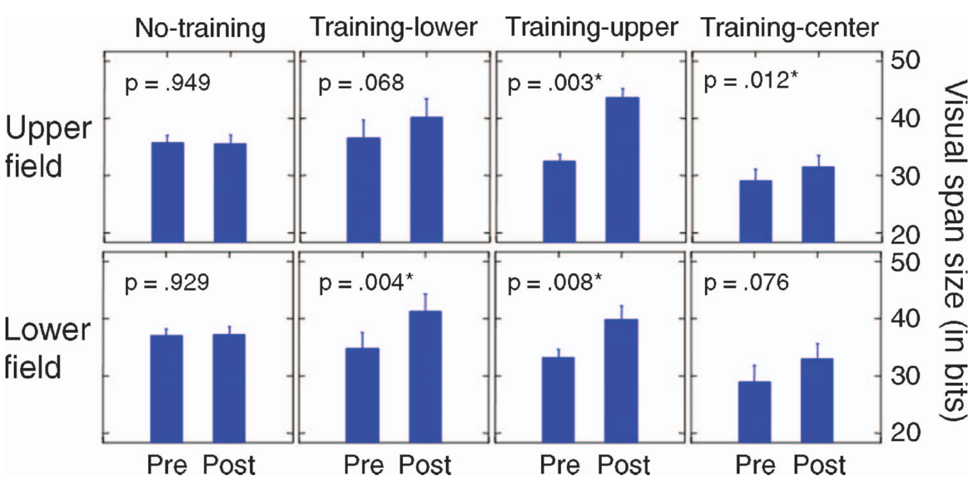

Figure 5. The size of visual span (in bits) of the four groups in the pre- and post-test. The error bars indicate ±1 *SEM*.

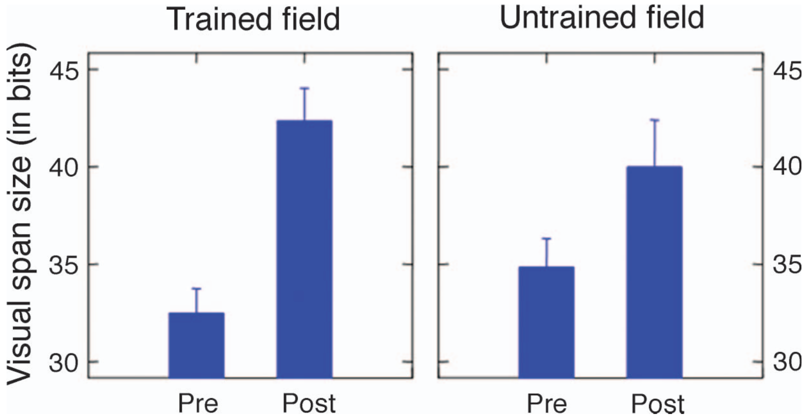

Figure 6. The size of visual span (in bits) for trained and untrained fields in the pre- and post-test. The error bars indicate ±1 *SEM*.

(untrained field). Recall that an increase of 4.7 bits is equivalent to adding one perfectly recognized letter to the visual span.

The Trained-Central group also showed evidence of training, but unlike the peripherally trained groups, the effects appeared to be confined to the central portion of the visual-span profiles (see Figure 4). The Trained-Central group showed smaller growth of their peripheral visual spans (approximately 3 bits) compared to the groups who were trained in peripheral vision.

Reading speed: Effects of training

We conducted an ANOVA on reading speed (wpm)—2 (test session: pre vs. post) × 4 (training group: central, lower, upper, control) × 2 (visual field: lower, upper) repeated measures ANOVA with test session and visual field as within-subject factors and training group as a between-subject factor. There were significant main effects of testing session ($F_{(1,19)}$ = 29.464, p < 0.001) and visual field ($F_{(1,19)}$ = 7.690, p = 0.014). There was also a significant interaction effect between test session and training group ($F_{(3,16)}$ = 4.279, p = 0.021).

Figure 7 shows the reading speeds of the four groups in the upper and lower fields in the pre-test and post-test. P-values of the paired t-test (two-tailed) refer to comparing pre and post-test reading speeds (* for p < 0.05). The No-Training group showed no improvement in reading speed in the post-test. The Trained-Lower group showed a significant improvement in the post-test in both fields. Likewise, the Trained-Upper group showed improvement in both fields. Subjects in the Trained-Center group showed no significant improvement in the post-test. Individual reading speed data are presented in Appendix C.

As shown in Figure 7, there were group differences in the pre-reading speed values: the No-Training group had higher mean reading speed than the training groups. It is reasonable to ask whether this higher baseline at pre-test for the No-Training group might have contributed to our failure to find any improvement in this group. We examined the possible effect of baseline performance differences by computing the correlation between pre-test reading speed and the amount of perceptual learning (i.e.,

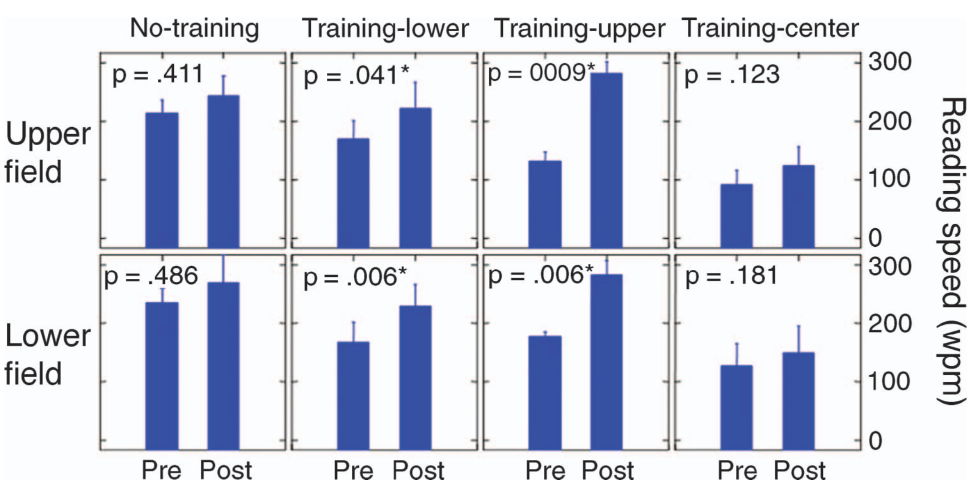

Figure 7. Reading speed (wpm) of the four groups in the pre- and post-test. The error bars indicate ±1 *SEM*.

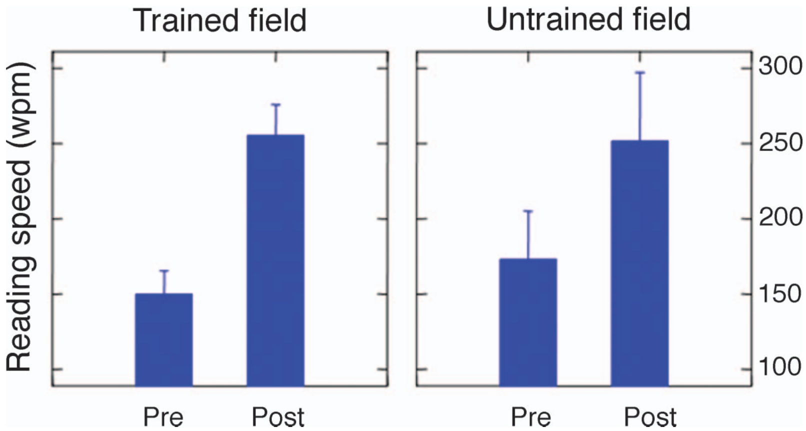

Figure 8. Reading speed (wpm) for the trained and untrained fields in the pre- and post-test. The error bars indicate ±1 *SEM*.

the gain in reading speed from pre-test to post-test). No significant correlation was found. Similarly, corresponding correlations for performance on the size of the visual span and attention measure were not significant.

Combining across the two peripherally trained groups, the post-test reading speed was 66% faster in the trained field and 46% faster in the untrained field than in the pre-test (see Figure 8). By comparison, the No-Training group showed a statistically insignificant increase of 16% in reading speed in the post test.

These training effects were stronger than those found by Chung et al. (2004)—increases in reading speed after training of 8%, 30%, and 40%, respectively, in the No-Training, Transferred, and Trained fields. We cannot be sure why our training effects were stronger than those reported by Chung et al. For the training groups, the only major difference in the paradigm was the current study's inclusion of the attention measurements in the pre- and post-test. In a recent study on perceptual learning of orientation discrimination, Zhang, Xiao, Klein, Levi, and Yu (2010) demonstrated that a brief pretest (no more than 200 trials) in the periphery enables substantial transfer of foveal learning, suggesting that some preliminary exposure to stimuli may play a priming role in facilitating subsequent perceptual learning. In our study, it is possible that the attention task, conducted as part of the pre-test, somehow acted as a catalyst to amplify the effects of training. The improvement in the attention task across pre-test trials (see below) may add some weight to this speculation.

Attention: Effects of training

Our method for testing the deployment of attention to peripheral vision required subjects to make a lexical decision for one of the four trigrams presented simultaneously in the four visual-field quadrants. In the cued condition, subjects were informed about the target quadrant before the trigrams were presented, allowing for the deployment of attention to the target quadrant. In the uncued condition subjects were informed about the target quadrant only after stimulus offset, so there was no reliable cue for deployment of attention to the target stimulus (see Figure 2).

Table 1 presents lexical decision accuracy for pre vs. post test and cued vs. uncued conditions in the four training groups. We analyzed accuracy as measured in d'—the index of discriminability between words and nonwords. d' was computed as the difference in Z scores associated with the hit rate when words were presented and false alarm rate when non-words were presented.

Our major question was whether there were larger attention effects associated with our peripheral training procedure. Did subjects who were trained in peripheral vision learn to deploy attention more effectively to targets

	Cued		Uncued	
	pre-test	post-test	pre-test	post-test
No Training	1.24 (±0.20)	1.78 (±0.08)	0.33 (±0.07)	0.33 (±0.09)
Trained-Center	0.97 (±0.27)	1.43 (±0.29)	0.16 (±0.04)	0.27 (±0.14)
Trained-Upper	1.51 (±0.16)	1.78 (±0.12)	0.18 (±0.04)	0.42 (±0.05)
Trained-Lower	1.35 (±0.10)	1.63 (±0.08)	0.23 (±0.08)	0.39 (±0.09)
Mean	1.27 (±0.10)	1.65 (±0.08)	0.23 (±0.03)	0.35 (±0.05)

Table 1. Lexical decision accuracy (d').

in peripheral vision? To address this question, we defined the peripheral attention index as follows:

$$PAI(Peripheral\ Attention\ Index) = d'(cued) - d'(uncued). \quad (1)$$

If enhanced deployment of attention underlies improved reading speed and visual span after training, there should be a greater increase in PAI in the post test for the peripherally trained groups than for the control groups (No-Training or Trained-Center groups).

In Figure 9, the pre–post PAI changes for the 4 groups are compared. We conducted an ANOVA on PAI—2 (test session: pre vs. post) × 4 (training group: central, lower, upper, control) repeated measures ANOVA with test session as a within-subject factor and training group as a between-subject factor. There was a significant main effect of test-type ($F_{(1,\ 19)} = 8.68$, $p = 0.009$), indicating that PAI increased overall from pre-test (PAI = 1.04) to post-test (PAI = 1.30). However, there was no main effect of group ($F_{(3,16)} = 1.23$, $p = 0.33$), and no interaction effect between test-type and group ($F_{(3,16)} = 1.64$, $p = 0.22$).

The peripherally trained groups did not show any larger pre–post changes in PAI than the control groups; rather, the pre–post increase in PAI was actually smaller (although the difference was not statistically significant) for the peripherally trained groups (pre–post difference in PAI: No-Training = 0.53, Trained-Lower = 0.12, Trained-Upper = 0.04, Trained-Center = 0.34, ps > 0.05). This pattern of results indicates that the pre–post changes in PAI are not associated with training.

Although pre–post changes in PAI do not appear to be associated with training, all groups did show an increase in PAI, indicating improved deployment of attention. What accounts for this overall improvement across groups? One possibility is that all groups improved in attentional deployment during pre-testing. The pre-test values of PAI were based on 800 trials—400 cued and 400 uncued. (There were also 250 trials prior to the pretest to familiarize subjects with the task, including the meaning of the numerical cues at fixation.) In order to evaluate the possibility that subjects improved substantially in deployment of peripheral attention during the pretest, we compared the PAI value from the first 100 trials of the pretest and the last 100 trials. The PAI values did improve ($F_{(1,19)} = 11.957$, $p = 0.003$), with a mean increase of 0.51. There was an additional small improvement of 0.04 in the post test. We interpret these results to indicate that all subjects improved in deployment of attention to peripheral vision during the pre- and post testing. But the lack of association of this improvement with the four days of trigram training implies that this improvement does not account for the impact of training on reading speed and visual span.

Our PAI measure of attention is a relative value, the difference in d' values between cued and uncued conditions. The interpretation of PAI is complicated by variations in uncued performance. Although the four groups had low and fairly similar pre-test values of d' in the uncued condition (Table 1), the trained groups showed small, but significant, improvements in uncued performance in the post test (the largest change was an increase in d' from 0.18 to 0.42 for the Trained Upper group). In order to determine if this instability in uncued values might have affected our interpretation of PAI changes, we conducted three supplementary analyses:

i. The PAI values for the post-test, as well as pre-test, were computed using the pre-test uncued values (i.e., $PAI_{post} = d'_{cued\ post} - d'_{uncued\ pre}$). Using this revised definition of PAI, we tested the effect of training on the PAI values. We conducted an ANOVA on PAI—2 (test session: pre vs. post) × 4 (training group: central, lower, upper, control) repeated measures ANOVA with test session as a within-subject factor and training group as a between-subject factor. Once again, we found no significant main effect of training group on the PAI ($F_{(3,16)} = 1.23$, $p = 0.331$) nor interaction between training group and test ($F_{(3,16)} = 0.884$, $p = 0.47$).
ii. Instead of computing the PAI values, we considered only changes in the cued d' values from pre-test to post-test. Once again, we did not find any significant main effect of training group on the cued d' ($F_{(3,16)} = 0.878$, $p = 0.473$) nor interaction between training group and test ($F_{(3,16)} = 1.256$, $p = 0.323$).

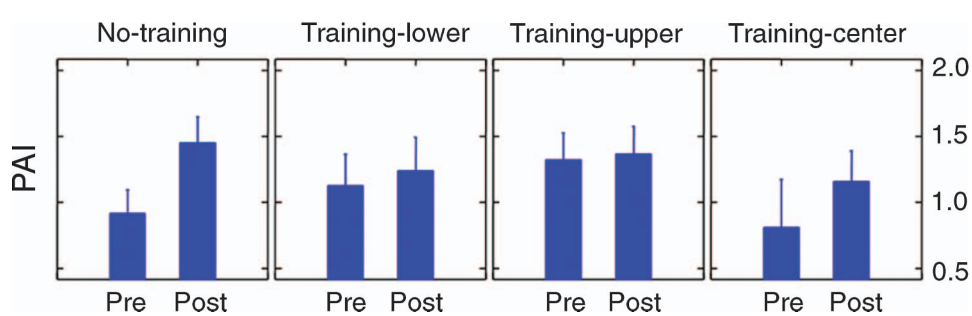

Figure 9. PAI values (Peripheral Attention Index) for the four groups in the pre- and post-test. The error bars indicate ±1 *SEM*.

iii. Finally, we considered only the post-test cued d' values. No significant main effect of training group ($F_{(3,16)} = 1.552$, $p = 0.24$) nor interaction between training group and test ($F_{(3,16)} = 1.238$, $p = 0.329$) was found.

These supplementary analyses strengthen our confidence that training-related changes in the deployment of attention to peripheral vision do not account for the effects of training on reading speed and visual span.

The small but significant pre–post improvement in uncued performance for the trained groups implies enhanced ability to distribute attention among multiple targets in different visual-field locations. (Recall that in the uncued tasks, subjects were presented with trigrams in all four quadrants, and only after stimulus presentation were they told the quadrant for the lexical decision.) Our training paradigm did not require subjects to distribute their attention to multiple targets. The training involved the presentation of a single trigram at an unknown location along a horizontal line left or right of the vertical midline. We have shown previously (Legge et al., 2001) that this task does not benefit from a stimulus pre-cue, nor does it involve distributing attention to multiple targets. We remain unsure about how to account for the small, training-related improvement in uncued performance.

Our motivation in the present study was to ask if the deployment of attention to a target in peripheral vision might account for effects of training on reading speed and visual span. Although our answer is no, the effect of training on the uncued task raises the possibility that attention might be affected in some other way by the training procedure.

The main finding emerging from our study is that there is no convincing evidence for an association between training-related improvements in peripheral reading speed and visual span and improved deployment of spatial attention to peripheral vision.

Visual-field effects and individual differences

Are people better at deploying attention to some regions of the visual field than other regions? We compared the PAI values of pre- and post-tests for targets presented in the left vs. right fields, lower vs. upper fields, and in the four quadrants. The results are presented in Table 2. PAI values were not significantly different between left vs. right fields (left PAI = 1.14; right PAI = 1.19, $p = 0.255$), but the difference between upper and lower fields was significant (upper PAI = 1.065; lower PAI = 1.27, $p = 0.011$).

An ANOVA on PAI—4 (visual field quadrant: 1, 2, 3, 4) repeated measures ANOVA showed a main effect of visual field ($F_{(3,57)} = 4.726$, $p = 0.005$). There was a significant difference across quadrants—Upper Right 1.05; Upper Left 1.09; Lower Left 1.18; Lower Right 1.37. The PAI in the lower-right quadrant was significantly larger than the other quadrants.

These results demonstrate that there are visual field effects on deployment of spatial attention. Attention effects were larger in the lower field than upper field, and larger in the lower-right quadrant than the other three quadrants.

We found individual differences in the pattern of PAI values across the visual field, with the optimal field location for deploying attention varying across subjects. Optimal field locations for deploying attention may be referred to as attentional "hot spots." It is possible that a mismatch between the training field and these hot spots could have masked the relationship between changes in PAI and the training effects we observed. We addressed this possibility by dividing our trained subjects into two groups: those subjects whose field for training matched the field (upper or lower) containing their attentional hot spots, and those subjects with mismatched training field and hot spots. We found no significant difference in the size of training effects between these two groups, and hence no evidence for an association between the effectiveness of peripheral training and the presence of an attentional hot spot.

Summary and conclusions

Our main findings can be summarized as follows. First, our results confirm the finding by Chung et al. (2004) that

Visual Field		Pre-test	Post-test	Mean	P-value
Left vs. Right	Left	0.97 (±0.10)	1.31 (±0.08)	1.14 (±0.07)	0.255
	Right	1.1 (±0.11)	1.28 (±0.09)	1.19 (±0.07)	
Upper vs. Lower	Upper	0.94 (±0.10)	1.19 (±0.06)	1.065 (±0.06)	0.011
	Lower	1.14 (±0.12)	1.4 (±0.09)	1.27 (±0.08)	
Quadrants	Upper-Right	1.01 (±0.12)	1.09 (±0.10)	1.05 (±0.08)	0.005
	Upper-Left	0.87 (±0.11)	1.3 (±0.10)	1.085 (±0.08)	
	Lower-Left	1.07 (±0.15)	1.27 (±0.11)	1.17 (±0.09)	
	Lower-Right	1.2 (±0.13)	1.53 (±0.11)	1.365 (±0.09)	

Table 2. PAI across different visual fields (±1 *SEM*).

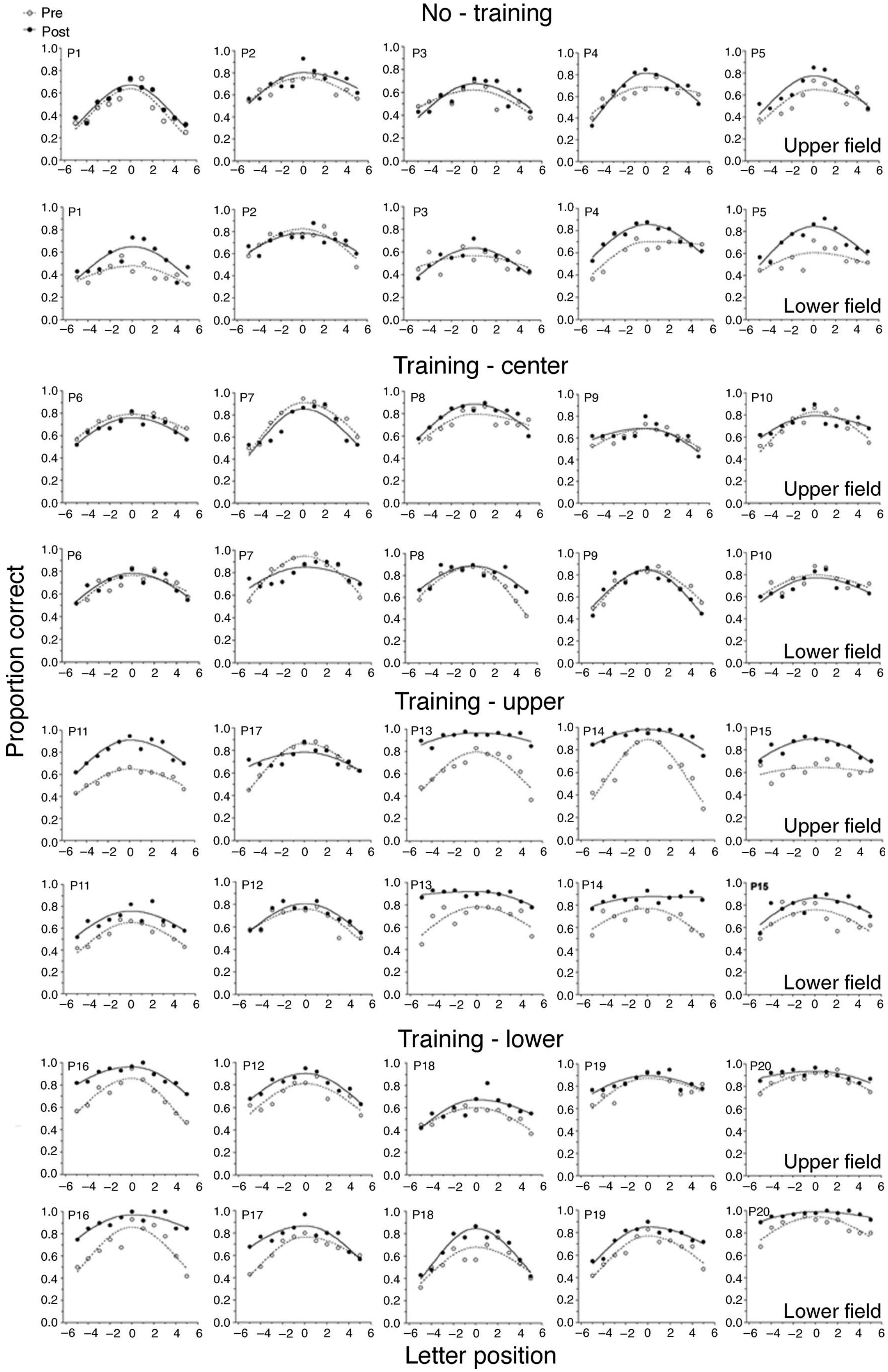

Figure B1. Individual visual-span profiles.

both reading speed and visual span improve following training with the trigram letter-recognition task in peripheral vision.

Second, our attention data showed a reliable difference in lexical decision accuracy (d') between cued and uncued conditions, demonstrating that our attention paradigm provided a measure of the deployment of attention to peripheral vision. This differential measure was termed the Peripheral Attention Index (PAI).

Third, the pattern of pre–post changes in the PAI did not depend on the type of training received by a group (controls, peripheral training, or central training), and did not correlate with pre–post changes in reading speed or visual span. The lack of association between pre–post changes in the PAI and the type of training is the key result of this study. This result contradicts the hypothesis that improved deployment of spatial attention to peripheral vision accounts for the improvement in peripheral reading speed and visual span following training.

Fourth, two subtle findings leave open the possibility that attention may be facilitating training by means not directly assessed by our paradigm. The small but significant increase in uncued performance may indicate that peripheral training enhances the ability to distribute attention to multiple locations. The rapid improvement in the attention task, demonstrated by all groups in the pretest, may amplify the subsequent effects of peripheral training.

Fifth, there were visual field effects and individual differences in deployment of attention to peripheral vision. The PAI was larger in the lower field than upper field, and was larger in the lower-right quadrant than the other quadrants. But individual differences in deployment of attention to the upper or lower field did not seem to be associated with the effectiveness of training in the upper or lower visual field.

We conclude that improved deployment of attention to peripheral vision does not account for improved reading speed and visual span following perceptual training in peripheral vision.

Appendix A

Construction of word and nonword lists used in the lexical-decision task

Lists of 350 word and nonword trigrams were used in the assessment of spatial attention. The two lists were created as follows. First, approximately 450 meaningful trigrams were identified from a prior study (Ortiz, 2002). Acronyms (e.g., ibm) and strings not found in the dictionary were removed from the list. Second, ten undergraduates judged each of the remaining items as a word or nonword. Only items identified as words 80% of the time or more were retained. Some further pruning was done to remove offensive words or strings deemed to have questionable status as words such as "boo" and "ole."

The list of 350 nonwords was constructed by shuffling letter order in the words with two primary constraints: 1)

		Lower Field			Upper Field		
Participant	Group	pre	post	Increase (%)	pre	post	Increase (%)
P1	No Training	321	246	−23	289	223	−23
P2	No Training	204	207	1	179	198	11
P3	No Training	269	448	67	221	360	63
P4	No Training	201	186	−7	203	242	19
P5	No Training	183	258	41	180	199	11
P6	Trained-Center	80	93	16	107	126	18
P7	Trained-Center	239	246	3	163	194	19
P8	Trained-Center	45	50	11	40	59	48
P9	Trained-Center	97	107	10	57	52	−9
P10	Trained-Center	172	251	46	96	185	93
P11	Trained-Upper	185	260	41	127	237	87
P12	Trained-Upper	189	249	32	134	275	105
P13	Trained-Upper	189	365	93	183	337	84
P14	Trained-Upper	173	290	68	99	308	211
P15	Trained-Upper	152	249	64	119	250	110
P16	Trained-Lower	188	224	19	227	276	22
P17	Trained-Lower	170	263	55	172	216	26
P18	Trained-Lower	148	180	22	135	140	4
P19	Trained-Lower	68	146	115	80	128	60
P20	Trained-Lower	262	334	27	231	345	49

Table C1. Individual reading-speed data.

the string should be a nonword (e.g., "het" was derived by rearranging the letters of "the"), and 2) the distribution of vowels across letter position should be approximately equal for the words and nonwords. In the resulting lists, the frequency of vowels in first, second and third letter positions were: words (56, 283, 48), and nonwords (78, 227, 82).

Prior to testing, the subjects reviewed the word and nonword lists.

Appendix B

Individual visual-span profiles

Figure B1.

Appendix C

Individual reading-speed data

Table C1.

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Commercial relationships: none.
Corresponding authors: Hye-Won Lee; Gordon E. Legge.
Emails: hwlee@ewha.ac.kr; legge@umn.edu.
Addresses: Department of Psychology, Ewha Womans University, 11-1 Daehyun-dong, Seodaemun-gu, Seoul 120-750, Korea; Department of Psychology, University of Minnesota, 75 East River Road, Minneapolis, MN 55455, USA.

Footnote

[1]For the trigrams, we had 6 letter slots left and right of the central letter on the midline. The letters had x-height of 2.2 deg and standard letter spacing (1.25 times x-height) yielding center to center spacing of 2.75 deg). Therefore, the trigrams centered in the sixth slot were about 16.5 deg left or right of the midline. In the attention task, 3-letter strings of the same size and spacing were centered 10 deg left or right of the midline, well within the range trained in the trigram task.

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