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ORIGINAL ARTICLE

Learning to Read Vertical Text in Peripheral Vision

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ABSTRACT

Purpose. English-language text is almost always written horizontally. Text can be formatted to run vertically, but this is seldom used. Several studies have found that horizontal text can be read faster than vertical text in the central visual field. No studies have investigated the peripheral visual field. Studies have also concluded that training can improve reading speed in the peripheral visual field for horizontal text. We aimed to establish whether the horizontal vertical differences are maintained and if training can improve vertical reading in the peripheral visual field.

Methods. Eight normally sighted young adults participated in the first study. Rapid serial visual presentation (RSVP) reading speed was measured for horizontal and vertical text in the central visual field and at 10 degrees eccentricity in the upper or lower (horizontal text) and right or left (vertical text) visual fields. Twenty-one normally sighted young adults split equally between two training groups and one control group participated in the second study. Training consisted of RSVP reading using either vertical text in the left visual field or horizontal text in the inferior visual field. Subjects trained daily over 4 days. Pre- and post- horizontal and vertical RSVP reading speeds were carried out for all groups. For the training groups, these measurements were repeated 1 week and 1 month posttraining.

Results. Before training, RSVP reading speeds were faster for horizontal text in the central and peripheral visual fields when compared with vertical text. Training vertical reading improved vertical reading speeds by an average factor of 2.8. There was partial transfer of training to the opposite (right) hemifield. The training effects were retained for up to a month.

Conclusions. Rapid serial visual presentation training can improve RSVP vertical text reading in peripheral vision. These findings may have implications for patients with macular degeneration or hemianopic field loss.

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Key Words: reading, vertical text, horizontal text, rapid serial visual presentation (RSVP), visual span, peripheral visual field, macular degeneration

Readers of the English language usually read horizontal text, from left to right, although there are occasions where they may need to read horizontal text printed in vertical columns (columnar text) in tables or telephone directories. Text can also be formatted to run vertically, for example, the title of a book printed vertically along the spine. Vertical text can take three forms: horizontal text that has been rotated clockwise or anticlockwise by 90 degrees and marquee text. Marquee text refers to text where upright letters are presented one below the other and may be used when text needs to be written vertically because of limited horizontal space. For example, on buses, "watch your step" signs are often painted in marquee text on the poles next to the doors.

Several researchers have compared reading speed for horizontal, columnar,[1,2] and vertical text[3,4] in central vision and have found that reading speed is fastest for horizontal text. Byrne[3] used a page of text composed of 30 three-syllable words and found that marquee text had the slowest reading speeds. There were no differences in reading speeds between vertical text rotated clockwise and anticlockwise although horizontal reading speeds were always superior to vertical reading speeds. Byrne's subjects read lines of text requiring saccadic eye movements, making it difficult to ascertain whether horizontal-vertical differences were perceptual in origin or caused by differences in oculomotor control. Yu et al.[4] addressed this issue by studying the contribution of oculomotor factors using two different methods for displaying text: RSVP (rapid serial visual presentation), which minimizes the need for eye movements, and Flashcard (a four-line block of text), which required saccadic eye movements. Although reading speed for RSVP text was always faster than reading speed for flashcard text, reading speed for horizontal text was on average 139% faster than that for marquee text and 81% faster than that for rotated text. These results confirmed that the horizontal-vertical differences in reading speed are likely to have a perceptual origin. Furthermore, in this study, horizontal-vertical differences in reading speed were highly

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correlated with corresponding differences in the size of the visual span for horizontal and vertical strings of letters. The visual span can be defined as the number of characters that can be recognized reliably without moving the eyes.[5,6]

Most native English speakers have little experience reading vertical print. Oda et al.[7] found that Japanese readers who have experience reading both horizontal and vertical text read both types of text at about similar speeds. This result suggests that there is potential for English speakers to improve vertical reading speeds with practice. In support of this possibility, Tinker[2] had subjects practice reading text formatted into vertical columns of single, upright words. Before the practice, conventional horizontal text was read about 50% faster than columnar text. Columnar reading speed improved with practice but remained slightly slower (~20%) than horizontal reading speed.

Previous studies that have investigated vertical reading speeds have all done so for the central visual field only. However, the peripheral visual field plays an important role for people who have age-related macular degeneration (AMD). Age-related macular degeneration is one of the major causes of visual impairment in the Western world (e.g., see Congdon et al.[8]) and causes a loss in central visual function. Many subjects with AMD rely on their peripheral visual field to read. These subjects often choose a peripheral area of the retina that is located near the edge of the central vision loss for reading. This is known as the preferred retinal location (PRL) and can be located either above, below, or to the right or left of the central scotoma. There is a potential disadvantage to reading horizontal text using a left or right PRL because the central scotoma would block text on the line being read. Moreover, Peli[9] suggested that reading eye movements are more effective in the vertical direction for PRLs to the right and left of the visual field loss. Together, these observations imply that for certain subjects with AMD, it could be advantageous to read vertical text rather than horizontal text. Further evidence of the superiority of vertical text in certain situations comes from a study by Tanaka et al.[10] in which, depending on the extent of the field loss and position of the PRL, some Japanese readers read vertical text faster than horizontal text.[10] The first aim of the current study was to compare vertical and horizontal reading speed in the peripheral visual field of subjects with normal vision.

Given that there may be a potential advantage to reading vertical text for some subjects with AMD, the next question to ask is whether perceptual learning can help improve vertical reading speeds. Perceptual learning has been defined as "any relatively permanent and consistent change in the perception of a stimulus array, following practice or experience with this array."[11] Reading speed improves with perceptual learning in the peripheral visual field of normal subjects using a variety of different training tasks including a trigram letter recognition task,[12–14] a lexical decision task,[13] and an RSVP reading task.[13] The greatest improvement was obtained when the RSVP task was used for training. Subjects with AMD have also shown improvements in reading speed after training with the RSVP task[15,16] and with oculomotor training[16,17] although not all studies agree that training with RSVP reading results in an improvement.[17] These previous studies have investigated the effects of training using a variety of tasks with horizontal text and it is not clear whether these findings also apply to vertical text.

The second aim of the current study was to establish if practice on an RSVP task using vertical text in the left visual field improves RSVP reading speed. One group of subjects was trained on reading text in the left visual field. To establish if any improvements in reading speed are retinotopically specific or orientation specific, reading speeds were also measured for vertical text in the right visual field and for horizontal text in the lower visual field. We also wanted to investigate whether the previously observed benefits of training using horizontal text in peripheral vision would transfer to vertical reading. To address this issue, a second group of subjects was trained on peripheral reading of horizontal text, with vertical reading tested before and after training. A third group of control subjects was tested to determine the outcome if no training was provided.

EXPERIMENT 1: ESTABLISHING IF THERE ARE DIFFERENCES IN READING SPEED FOR VERTICAL AND HORIZONTAL TEXT IN THE PERIPHERAL VISUAL FIELD OF NORMAL YOUNG ADULTS

Methods for Experiment 1

Subjects

Eight normally sighted young adults (mean [±SD] age, 20.75 [±1.49] years) participated in the study. All subjects were recruited from the student population of the University of Minnesota and had best-corrected distance visual acuity of 0.0 logMAR or better. No subjects had prior laboratory experience of reading vertical text or participating in perceptual learning studies involving the peripheral field. All subjects were native English speakers. Subjects received monetary compensation for their participation. Ethical approval for the study was obtained from the institutional review board of the University of Minnesota and the study adhered to the tenets of the Declaration of Helsinki.

Apparatus

All stimuli were generated via MATLAB 5.2.1 (MathWorks, Massachusetts, USA) using Psychophysics Toolbox Extensions.[18,19] Stimuli were presented on a Sony Trinitron Color Graphic Display monitor (model: GDM-FW900; refresh rate, 76 Hz; resolution, 1600 by 1024) (Sony Corporation of America, New York USA) controlled by a Power Mac G4 (Apple, California, USA). Experiments were carried out binocularly in a dark room with subjects wearing their best distance correction.

Stimuli and Experimental Design

Reading speed measurements were carried out using the RSVP technique that has been described previously.[20] Words within a sentence were presented sequentially, at the same location on the display. Measurements were made using horizontal text and horizontal text rotated 90 degrees clockwise, which will be referred to throughout this article as vertical text. For horizontal text, the words were left justified, and for vertical text, the words were top justified. Fig. 1 illustrates examples of the horizontal and vertical text used in relation to the visual field. All words were displayed as black letters on a white background using lowercase Courier, a serif font with fixed width.

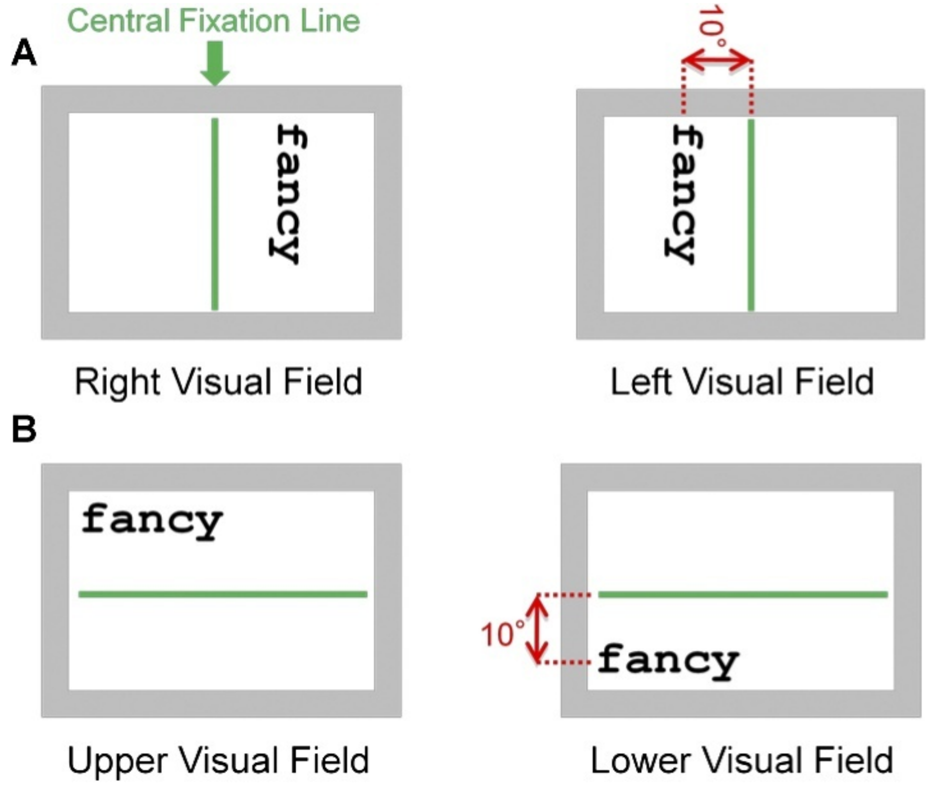

FIGURE 1.
Examples of (A) vertical and (B) horizontal text in relation to the central fixation line. A color version of this figure is available online at www.optvissci.com.

Sentences were randomly chosen by computer software from a pool of 2658 sentences assembled by Chung et al.[20] The length of a sentence ranged from 7 to 17 words (average, 11 words). Words ranged in length from 1 to 14 letters (average, 4 letters). None of the participants read any sentence more than once. A letter size of 2.5 degrees (defined as x-height in lowercase) at a working distance of 40 cm was chosen based on a pilot study using vertical text.[a] Measurements were carried out in the central visual field and at 10 degrees in the superior and inferior peripheral visual fields for horizontal text and the right and left visual fields for vertical text. Rapid serial visual presentation reading speeds (horizontal and vertical)[b] were measured in the peripheral visual field on all eight subjects and in the central visual field on four of the eight subjects.

For measurements involving the peripheral visual field, subjects fixated a line (10 degrees to the right, left, above, or below the text depending on the type of print and location being tested) while the words were presented in the periphery. Subjects were allowed to move their eyes along the line and were reminded from time to time to maintain fixation on the line. The subject's head was stabilized using a chin and forehead rest and subjects were instructed not to tilt their head or to alter the working distance in any way.

[a]The choice of letter size and working distance was based on pilot studies of four subjects using vertical (clockwise) text at 10 degrees eccentricity in the left visual field. Six letter sizes were used (0.55, 1, 1.8, 2.5, 3.2, and 5 degrees). For sizes 0.55, 1, 1.8, and 2.5 degrees, a working distance of 40 cm was chosen. For the remaining sizes, a working distance of 20 cm was chosen because of limitations imposed by the screen dimensions. A two-line fit was used to fit plots of reading speed versus print size to estimate critical print size (CPS). All four subjects had CPS smaller than 2.5 degrees for vertical text. Previous studies12 indicate that at least for horizontal text, this value is larger than the CPS for most subjects at 10 degrees eccentricity.

[b]It should be noted that throughout the Methods, Results, and Discussion sections, we use the term reading speed to refer to reading speed measured using the RSVP text.

Eye movements were monitored using a web camera for four subjects. The camera's image was displayed on a separate dedicated monitor visible to the researcher. If an eye movement away from the fixation line was detected by the researcher, the trial was discarded. This was similar to the method described by Cheong et al.,[21] who stated that the accuracy of detecting eye movements using this method is about 2 degrees. Trials were also discarded if subjects verbally reported moving their eyes. Typically no more than 5% of trials were discarded. It should be noted that no significant differences were observed between the results for subjects monitored for eye movements and those who were not.

At the commencement of each new trial, a row of crosses appeared, alerting subjects to the location of stimulus words. Subjects initiated a trial when ready by clicking a mouse. At the end of each trial, a row of crosses appeared as a post mask. Subjects read each sentence aloud and were permitted to complete their response after the last word had disappeared from the screen.

For each condition tested, six word exposure durations were used with six trials per duration (total of 36 trials). These durations were selected so that subjects could read fewer than 30% of words correctly at the shortest duration and more than 80% of words correctly at the longest duration. The condition tested was randomized and subjects were given breaks if required. Reading accuracy was measured as a proportion of words read correctly. The resulting data were fitted with a Weibull function, and reading speed was calculated from the exposure duration yielding 80% of words read correctly. Values obtained were converted to reading speed in words per minute (wpm).

Visual span measurements using a trigram letter recognition task[12] were also carried out as part of the experimental procedure during the pretesting and posttesting sessions, but these results will not be reported in this article.

Results for Experiment 1

Mean (±SD) reading speeds in the central visual fields were 559.20 (±193.02) wpm for horizontal text and 308.62 (±140.51) wpm for vertical text.

A paired sample *t* test comparing horizontal and vertical reading speeds in central vision found that mean horizontal reading speed was significantly faster than vertical reading speed ($p = 0.001$). Across the eight subjects, the ratios of horizontal to vertical reading speeds ranged from 1.17 to 3.39 with a mean (±SD) of 1.96 (±0.75).

Mean (±SD) reading speeds in the peripheral visual fields in units of wpm were as follows: 200.84 (±77.71) for horizontal text in the superior field, 199.76 (±80.41) for horizontal text in the inferior field, 125.94 (±27.24) for vertical text in the right visual field, and 126.16 (±26.11) for vertical text in the left visual field. Paired samples *t* tests showed no significant differences between mean reading speeds in the superior and inferior visual fields ($p = 0.95$) and the right and left visual fields ($p = 0.94$). Accordingly, for each subject, a vertical reading speed was based on the average values from the left and right visual fields, and a horizontal reading speed was based on the average values from the superior and inferior visual fields. Similarly, for peripheral vision, the resulting mean peripheral horizontal reading speeds were significantly faster than the peripheral vertical reading speeds (paired samples *t* test) ($p < 0.05$). Across the eight subjects, the ratios of horizontal to vertical reading speeds ranged from 1.10 to 2.37 with a mean (±SD) of 1.69 (±0.43).

Using a paired samples *t* test, we compared the mean horizontal/vertical reading speed ratios in the central and peripheral visual fields. We found no statistically significant differences between the two measures ($p = 0.37$), suggesting that horizontal/vertical ratios are similar in the central and peripheral visual fields.

EXPERIMENT 2: TRAINING TO IMPROVE READING SPEED FOR VERTICAL TEXT IN THE PERIPHERAL VISUAL FIELD

Methods for Experiment 2

Subjects

Twenty-one normally sighted young adults (mean [±SD] age, 21.3 [±2.98] years) participated in the study. Thirteen subjects were recruited from the student population at the University of Minnesota (five in each of the two training groups and three in the control group), and eight subjects were recruited from the student population at City University London (four in the control group, and two in each of the training groups). Subjects were randomly allocated to either a training group or a control group. There were two training groups and one control group. Each group had seven participants.

All subjects had best-corrected distance visual acuity of 0.0 logMAR or better. No subjects had prior laboratory experience of reading vertical text or participating in perceptual learning studies involving the peripheral field. Subjects were ineligible to participate in the training experiment if they had participated in experiment 1. All subjects were native English speakers. Subjects received monetary compensation for their participation. Ethical approval for the study was obtained from the institutional review board of the University of Minnesota and the Research and Ethics Committee at City University London. The study adhered to the tenets of the Declaration of Helsinki.

Apparatus

The apparatus used was slightly different for subjects tested at City University London, as follows. Stimuli were generated via MATLAB (2009b) (MathWorks) using Psychophysics Toolbox Extensions.[18,19] Stimuli were presented on a Sony display monitor (model: Multiscan E400; refresh rate, 75 Hz; resolution, 1600 by 1200) (Sony Corporation of America) controlled by MacBook Pro (Apple). Similar to experiment 1, a letter size of 2.5 degrees was used throughout the experiments at both sites. Because of limitations of the screen size at City University London, all reading speed measurements with vertical text were carried out at a viewing distance of 30 cm and reading speed measurements with horizontal text were carried out at 40 cm. At the University of Minnesota, both vertical and horizontal measurements were carried out at 40 cm.

Experimental Design

There were three groups, each with seven subjects—a control group and two training groups. Subjects in the control group attended two pretest sessions and one posttest session. Subjects in the training groups attended two pretest, one posttest, and two retention sessions, in addition to four training sessions that were conducted over four consecutive days. A series of experiments usually commenced on a Thursday (week 0), when the first pretest session was held. The second pretest session was normally held the following day on Friday (week 0). Training, where applicable, took place from Monday to Thursday of the following week (week 1), with the posttest session being held on the Friday of that week (week 1). The first retention session was held a week later on a Friday (week 2) and the second retention session was held a month after the test session, usually on a Friday (week 5).

The first pretest session was devoted to preliminaries including informed consent and introduction to the RSVP test. During the second pretest visit, baseline measurements were made for reading speeds using horizontal and vertical text at 10 degrees in the peripheral visual field. Vertical text measurements were made in the right and left visual field and horizontal text measurements were made in the inferior visual field. For each RSVP condition tested (e.g., horizontal text inferior visual field), six word exposure durations were used with six trials per duration (total of 36 trials). This constituted a block of trials. During the posttest and retention sessions, the same measurements carried out in the second pretest visit were repeated. Field location (inferior, right, or left) and the text tested (horizontal or vertical) were randomized at each pretest and posttest visit. Visual spans were also measured in the pretests and posttests, but the results are not reported in this article.

Subjects were either trained on reading vertical or horizontal text at 10 degrees in the left or lower visual field (training groups) or received no training (control group). Each training session consisted of six blocks of 36 trials (one sentence per trial), resulting in

TABLE 1.

Mean and SD for RSVP reading speeds and ratios pretraining and posttraining for vertical training, horizontal training, and control groups

	Pretest RSVP			Posttest RSVP			Post-RSVP/pre-RSVP ratios		
Group	Horizontal	Vertical (left)	Vertical (right)	Horizontal	Vertical (left)	Vertical (right)	Horizontal	Vertical (left)	Vertical (right)
Vertical training group	203.50 (94.52)	**85.67 (30.68)**	101.24 (45.31)	270.14 (91.17)	**217.78 (49.09)**	173.08 (44.28)	1.46 (0.40)	**2.80 (1.1)**	2.01 (1.02)
Horizontal training group	**158.05 (76.84)**	90.65 (29.56)	106.24 (47.10)	**281.88 (104.38)**	158.88 (33.26)	168.75 (64.91)	**2.08 (1.08)**	1.96 (0.90)	1.68 (0.39)
Control group	157.34 (31.27)	101.74 (25.25)	112.11 (24.29)	183.30 (30.61)	126.31 (32.26)	126.82 (20.35)	1.19 (0.27)	1.25 (0.19)	1.14 (0.14)

It should be noted that the post-RSVP/pre-RSVP ratios have been computed by taking an average of each individual post-RSVP/pre-RSVP ratio and not from the group average of the RSVP reading speeds. Bold numbers represent the trained conditions.

a total of 864 trials across 4 days. At the start of each training session, subjects completed a "subject alertness questionnaire" to determine their suitability for the training session. The subject alertness questionnaire consisted of all the questions from the Stanford Sleepiness Survey[22] and two questions from the Pittsburgh Sleep Quality Index.[23] All subjects had a score of either 1 or 2 for all training sessions (indicating they were fully awake and able to concentrate) and reported very good sleep quality the previous night. Each training session lasted 1 hour and subjects were given a break if they desired.

We chose reading as the training task because a previous study showed that this form of training produced larger improvements than two other related forms of training.[13]

Results for Experiment 2

Table 1 summarizes group means and SDs for reading speeds in the pretest and posttests for the various conditions. Bolded cells refer to results when groups were tested with the same conditions used for training. The table also summarizes changes in reading speed from pretest to posttest. Changes in reading speed are presented as ratios, with values greater than 1.0 meaning that reading speed improved.[c]

Mean (±SD) reading speeds pretraining and posttraining for the vertical training group in wpm were 85.67 (±30.68) and 217.78 (±49.09) for vertical text in the left visual field, 101.24 (±45.31) and 173.08 (±44.28) for vertical text in the right visual field, and 203.50 (±94.52) and 270.14 (±91.17) for horizontal text.

Mean (±SD) reading speeds pretraining and posttraining for the horizontal training group in wpm were 90.65 (±29.56) and 158.88 (±33.26) for vertical text in the left visual field, 106.24 (±47.10) and 168.75 (±64.91) for vertical text in the right visual field, and 158.05 (±76.84) and 281.88 (±104.38) for horizontal text.

Mean (±SD) reading speeds pretraining and posttraining for the control group in wpm were 101.74 (±25.25) and 126.31 (±32.26) for vertical text in the left visual field, 112.11 (±24.29) and 126.82 (±20.35) for vertical text in the right visual field, and 157.34 (±31.27) and 183.30 (±30.61) for horizontal text.

Pre/Post Comparisons for RSVP Reading Speed

Separate statistical analyses were performed to compare the vertical training group with the control group and the horizontal training group with the control group. In each case, a two-by-two repeated-measures analysis of variance (ANOVA) on log reading speed[d] (pretest/posttest, vertical training group/control group, or horizontal training group/control group) was performed. A significant interaction indicated a training-related difference in performance.

Transfer of training from a trained condition to an untrained condition was also assessed by 2x2 repeated-measures ANOVAs (pretest/posttest, trained/untrained field location). In these cases, significant main effects of the pre/post variable coupled with a significant interaction provided evidence for partial transfer of training. A significant main effect of the pre/post variable without a significant interaction provided evidence for complete transfer of training. We recognize that analysis of transfer effects are based on statistical criteria and that data from additional subjects could reveal a significant interaction in cases where we find "complete transfer."

Both training groups and the control group had improved log posttest reading speeds (all $p < 0.05$) in all three conditions: left vertical, right vertical, and horizontal text.

For the group trained with vertical text in the left visual field, there was a greater improvement in log reading speeds than for the control group (significant interaction, $p < 0.0005$), providing evidence for the effect of training. The large training effect in the trained left visual field transferred to the untrained right visual field, but this transfer was incomplete (significant interaction, $p = 0.02$), providing evidence for partial transfer of training from the left to the right visual field. This group also showed posttest improvement in horizontal reading speed in the lower visual field, but this improvement did not differ significantly from the improvement exhibited by the control group in the horizontal condition. Therefore, we cannot conclude that there is transfer of training from vertical to horizontal reading in our study.

For the group trained with horizontal text in the lower visual field, there was a greater improvement in reading speed than for the control group (significant interaction, $p = 0.04$), providing evidence for the effect of training. The training effect showed significant and complete transfer to vertical reading in both the left (significant effect of time: pretest/posttest, $p = 0.007$, and nonsignificant interaction, $p = 0.93$) and right (significant effect of time: pretest/posttest, $p = 0.005$, and nonsignificant interaction, $p = 0.39$) visual fields. These effects imply that there was complete transfer of training from the horizontal reading to vertical reading.

[c]Ratios of reading speeds convey the same information as differences in log reading speeds.

[d]Log reading speeds were used to be consistent with other studies. It should however be noted that the same pattern of significant results was found when the analysis was conducted directly on reading speed.

To summarize, both training groups showed posttest improvements in reading speed exceeding controls. Training on horizontal text appeared to transfer completely to improved reading on vertical text. Training on vertical text in the left visual field partially transferred to vertical reading in the right visual field, but transfer to horizontal reading was equivocal.

Progression Retention and Transfer of Learning Effects

Figs. 2 and 3 indicate that for both training groups, there were improvements in the trained reading speed after every training session with maximal improvement occurring after the first session (264 trials) and less improvement occurring thereafter. Improvements normally occurred within the first three sessions with no to minimal improvement at the fourth and final session. For both training groups, improvements in reading speed for left and right vertical and horizontal text were maintained for up to 1 month posttraining. This was substantiated by repeated-measures ANOVAs ($p > 0.1$) using post/pre ratios of posttest, 1-week, and 1-month posttest.

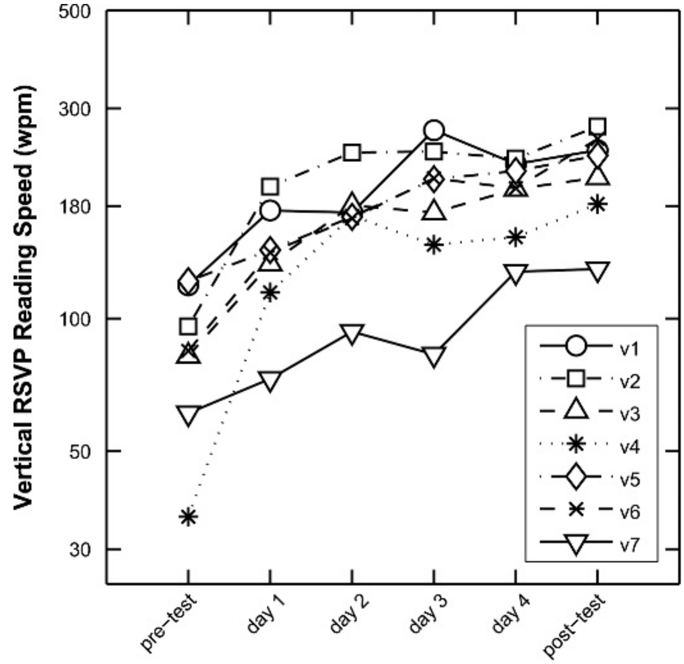

FIGURE 3.
Left vertical reading speeds for the vertical training group in the pretest, posttest, and training sessions.

Differences between Horizontal and Vertical Reading Speeds

One research question was whether training would yield vertical reading speeds that would match or exceed horizontal reading speeds. After training using vertical text, vertical speed improved on average (±SD) from 85.67 (±30.68) wpm to 217.78 (±49.09) wpm. There were no statistically significant differences between the mean vertical reading speeds in the posttest and either the pretraining horizontal reading speeds (mean [±SD], 203.50 [±94.52] wpm) ($p = 0.657$) or the posttraining horizontal reading speeds (mean [±SD], 270.14 [±91.17] wpm) ($p = 0.091$). These results indicate that training using vertical text may yield vertical reading speeds that almost match horizontal speeds. From inspection of results of individual subjects in the vertical training group, only one subject's trained vertical reading speed exceeded the posttraining horizontal reading speed, with the ratio being 1.36. For the remaining six subjects, horizontal speed was greater than vertical speed by factors of 1.20, 1.21, 1.26, 1.31, 1.39, and 1.59.

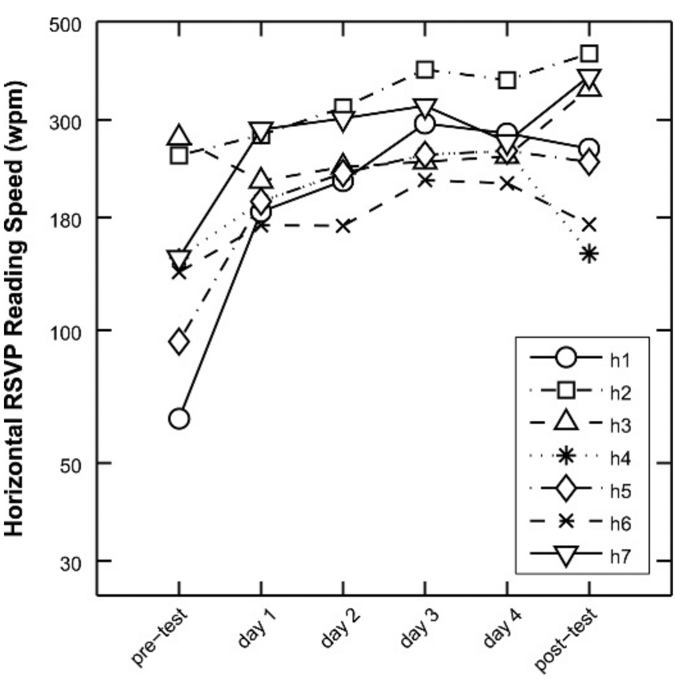

FIGURE 2.
Horizontal reading speeds for the horizontal training group in the pretest, posttest, and training sessions.

DISCUSSION

Our goal in experiment 1 was to ascertain whether the differences in reading speed for horizontal and vertical text previously found in central vision[4] extend to the peripheral visual field. In untrained observers, reading speed with horizontal text was always faster than with vertical text regardless of whether the text was presented in the central or peripheral visual field. The horizontal/vertical reading speed ratios were similar in the central and peripheral visual fields, suggesting similar underlying constraints across locations.

Our goal in experiment 2 was to determine if vertical reading speed in peripheral vision improves with training. There were three groups of subjects—one trained with vertical text in peripheral vision, one trained with horizontal text in peripheral vision, and a control group who did not receive training.

Before discussing the training effects, we will briefly comment on left versus right hemifield effects on reading. There has been a debate regarding whether the hemispheric projections split at the fovea or whether there is a foveal region of bilateral projections, and the potential implications for reading. For a review, see Ellis and Brysbaert.[24] Regardless of the debate, it is certain that the vertical text in our study, located 10 degrees from the fovea, projected to the contralateral hemispheres. Further, there is some evidence for a right visual field (left hemisphere) advantage for word recognition (reviewed by Ellis and Brysbaert[24]). In experiment 1, there was little difference in the average reading speeds for vertical text in the left and right visual fields. However, in experiment 2, combining data across all three groups, there was a significantly greater mean reading speed for vertical text in the right visual field (mean [±SD], 106.53 [±38.46] wpm) than in the left visual field (mean [±SD], 92.69 [±27.98] wpm) (p = 0.048). This small advantage for the right visual field is consistent with previous findings of a right visual field advantage for word recognition.

Experiment 2 showed that training improves reading speed for both vertical and horizontal text in peripheral vision. On average, vertical reading speeds improve by a factor of 2.8 with individual improvements ranging from a factor of 1.9 to 5.1. This study demonstrated again that training yields increased reading speed in peripheral vision for horizontal text—an increase by a factor of 2.08, compared with the increase of 1.72 reported by Yu et al.[13] who also trained normal subjects with an RSVP training task using a similar protocol. The greater improvement in our study is primarily attributed to one subject whose reading speed improved by a factor of 4.1. Excluding this subject from the analysis results in reading speed improving by a factor of 1.74, similar to the average improvement found by Yu et al.[13]

Several types of learning could contribute to the training-related improvement in vertical and horizontal reading speeds in peripheral vision. We briefly consider task-specific, attentional, and perceptual possibilities.

Task Specificity

Subjects may be learning to perform the RSVP task, which differs from conventional eye movement–mediated reading. If the learning is solely attributed to learning how to perform the RSVP task, we would expect complete transfer among all peripheral RSVP conditions in our study and no transfer to non-RSVP reading tasks in peripheral vision. However, complete transfer of training across RSVP tasks did not occur in experiment 2. Moreover, Yu et al.[13] showed partial transfer of learning from training with RSVP reading to other tasks in peripheral vision (trigram letter recognition and lexical decision). These observations imply that task-specific learning is not the sole explanation for our training effects.

Attention

Subjects may be learning to deploy attention to peripheral vision while maintaining central fixation. Lee et al.[25] investigated whether attention could account for improvements observed in reading speed and visual span through training in the peripheral visual field. Their training protocol was similar to ours but differed in two ways: the study tested only horizontal reading and the training task involved recognition of trigrams (strings of three unrelated letters) in peripheral vision. Although training did result in an improvement in their measure of peripheral attention (based on a lexical decision task), the improvement was not correlated with the training-related improvements in peripheral reading speed. They concluded that deployment of attention to peripheral vision was not the major factor accounting for training-related benefits in peripheral reading. Although we did not measure attention in the present study, the results from Lee et al.[25] suggest that attention may not account for the improvements in vertical reading speeds observed in our study.

Perceptual Learning

We consider two types of perceptual changes that may contribute to improved vertical reading speed. First, training may result in a reduction in the effect of crowding between adjacent letters. In support, He et al.[26] trained the peripheral vision of subjects using a trigram recognition task. Training resulted in an increase in the size of the visual span and an associated increase in reading speed. He et al. used a decomposition analysis to infer that a reduction of crowding accounted for most of the enlargement of the visual span, likely contributing to the improvement in reading speed. Similarly, Yu et al.[27] reported that differences in horizontal and vertical reading speed in central vision were correlated with differences in the size of the visual span, with the visual span being limited by crowding. Pelli et al.[28] have also demonstrated a close relationship between crowding, the size of the visual span, and reading speed.

A second perceptual factor may be learning to transform vertical words with letters rotated by 90 degrees into a representation suitable for lexical access. As shown in previous studies, whereas recognition time for single letters is largely independent of letter orientation, rotated words take longer to be recognized than upright words.[29–31] It appears plausible that recognition times for rotated words could decrease with practice, as a separate effect from crowding.

Although we cannot exclude task-specific learning and effects of attention, it appears likely that perceptual factors played a major role in accounting for the training-related improvement in reading speed we observed.

Transfer of Learning Effects

An ancillary aim of our study was to determine whether training with vertical text transfers across location (to the untrained hemifield) and orientation (to horizontal text). Other studies of training with reading-related tasks in peripheral vision have found varying levels of transfer across location and task. For example, Chung et al.[12] found that training with a letter recognition task in the peripheral visual field resulted in increased reading speeds and a transfer of training to an untrained retinal location. Yu et al.,[14] who used similar RSVP training of horizontal text in the lower visual field, found substantial transfer to reading speed in the upper visual field, to a print size not used in training, and to enlargement of the visual span. Our results indicate that training effects can transfer. We found that training horizontal reading in the lower visual field transferred to vertical reading in the left and right visual fields. For vertical training in the left visual field, there was partial transfer of learning to the right hemifield but transfer to horizontal text was not statistically significant. This difference may represent a lack of reciprocity in transfer of learning between horizontal and vertical training or might be attributed to our small sample size. The lack of reciprocity in transfer of training effects may also depend on the difficulty of the task involved. Tasks that are harder result in more specific training effects.[32] Given that readers are more familiar with horizontal text, it is likely that this is an easier training task and might result in greater generalization than training with vertical text in peripheral vision.

What might be the cortical site of the training effect? A previous study,[13] using a similar paradigm, found partial transfer from the lower visual field to the upper visual field. The authors suggested that these results might reflect effects of training at both an early retinotopic site in the visual pathway and a higher-level nonretinotopic site.

Retention of Learning Effects

Because training is time intensive, the practical value of training would be questionable if the training effects are short lived. Chung et al.[12] found that improvements in reading speed and visual span in the inferior and superior visual field obtained through training could be maintained for at least 3 months after the training. The current study found similar results, with good retention of horizontal and vertical reading speeds across both training groups up to 1 month posttraining. If patients with visual impairment were to find vertical training useful, it is likely that repeated use would sustain the training gains over a prolonged period.

Possible Clinical Implications

Our study has demonstrated that it is possible to train vertical reading to achieve speeds that are similar to untrained horizontal speeds. This finding may have clinical implications for people with macular degeneration who have a PRL lateral to a central scotoma. In these cases, there may be difficulty reading horizontal text because the scotoma occludes text either to the left or to the right of fixation. For such subjects, reading vertical text can potentially result in uninterrupted reading. The same would hold true for people with hemianopias. In both instances, it may be possible to improve reading performance by simply rotating a page of text 90 degrees to produce vertically oriented text, although this will involve vertical eye movements that may also require training.

Although we did not specifically measure whether training on an RSVP reading task leads to improvements in page reading, previous findings by Nguyen et al.[16] are promising. They showed that improvements in reading speed made through RSVP training in subjects with macular disease lead to improvements in normal reading of a page of text.

Yu et al.[15] found that training peripheral vision with trigram stimuli resulted in larger improvements in the visual span and reading speed of young subjects when compared with their older counterparts. Training effects did not transfer to an untrained location for an untrained task in these elderly subjects. It is likely that there will be less transfer of learning effects if we train vertical reading speeds in elderly subjects.

In our study, we used a time-intensive training schedule where subjects trained daily for 4 days. Many subjects who suffer from age-related macular degeneration and hemianopias are elderly and it may be difficult for them to adhere to such a schedule. Chung and Truong[33] found that reading speed and visual span improve regardless of whether training takes place daily, weekly, or biweekly. Given these findings, it is likely that a flexible training schedule could be used.

To conclude, our study has established that reading of RSVP vertical text in the peripheral visual field can be improved with training and that the levels of reading speed obtained with vertical text are similar to those obtained with horizontal text.

Data Sharing

All data from this study, including the visual span data, are available from the first author upon request.

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