Improving reading performance in peripheral vision: An adaptive training method

THESIS

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Abstract

Purpose

Reading is slow and difficult for patients with central vision loss, who must rely on their peripheral vision. Previous studies showed that peripheral reading performance can be improved with training on character-based tasks. While these studies mainly focused on the effectiveness of training, it is also important to develop a customizable training protocol because of the unique ocular condition of each patient. In this study, we developed a training paradigm that individualizes training by adaptively adjusting a testing parameter to maintain the task difficulty at a constant level.

Methods

Fourteen normally-sighted adults participated in the main experiment and were randomly assigned to a training group and a control (no-training) group. All subjects in the main experiment completed a pre- and post-test one week apart. During pre- and post-testing, RSVP reading speeds and visual-span sizes (the number of letters recognized reliably without moving the eyes) were measured at 10° above and below fixation. Training consisted of four daily sessions (16 blocks per session, 55 trials per block) of identifying the middle letters of trigrams presented at various positions 10° below fixation. Adaptive adjustment was achieved by applying jitter with various amplitudes to
the crowded middle letter. A separate group of subjects (7 normally-sighted young adults) participated in a supplemental experiment. In the supplemental experiment, image jitter was found to reduce the difficulty of recognizing crowded letters in the periphery. During training, jitter amplitude, ranging from 0× (static) to 0.108× letter size, varied on a block by block basis to keep task difficulty roughly at a performance level of 80%.

Results

The training group showed significant improvements in both reading speed and visual-span size compared to the control group. In the trained field, visual span was enlarged by 5.0 bits (about 1 letter) and reading speed was improved by 49%. The learning transferred to the untrained upper field for both measurements (50% improvement for reading speed and an increase of 2.5 bits for visual-span size). The transfer for visual-span size was not complete.

Conclusion

The adaptive training method developed in this study provides simple customization for each individual while being effective in enhancing peripheral reading performance. These findings have important implications for reading rehabilitation of patients with central vision loss.
Acknowledgments

I would like to give my sincerest thanks to my advisor, Dr. Deyue Yu, for her guidance, patience, motivation and continued support throughout the last 4 years. I will be forever grateful for the knowledge she shared throughout all of our conversations and discussions. I would also like to thank my committee members, Dr. Thomas Raasch and Dr. Teng Leng, Ooi, for their thought provoking questions and recommendations.
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Fields of Study

Major Field: Vision Science
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Chapter 1: Introduction

Age-related macular degeneration (AMD) is a leading cause of vision loss in older adults in developed countries. In the United States, more than 2 million Americans, 50 years and older, suffer intermediate or advanced AMD (Prevent Blindness, 2008). The prevalence of AMD is expected to increase as the population ages. Research on AMD has provided a better understanding of the disease (see Appendix for a brief summary of pathogenesis, etiology, and current treatment options for AMD). However, there are still many unanswered questions, especially in the area of prevention and treatment. Due to the limited treatment options, many patients suffer irreversible and substantial visual loss.

AMD damages the central retina, leading to central vision loss. The damaged region often creates a scotoma. Patients with a central scotoma(s) must rely on their peripheral vision for everyday tasks, including reading. Following vision loss, most of the patients learn to adopt a healthy region of the eccentric retina, the preferred retinal locus (PRL), as a new oculomotor reference and for fixation. Despite so, reading is still difficult and slow for these patients (Fine & Peli, 1995; Legge, Rubin, Pelli, & Schleske, 1985). It has been suggested that reading difficulty is the most common reason that patients with central vision loss seek out vision rehabilitation (Owsley, McGwin, Lee, Wasserman, & Searcey,
Due to the severe impact of central vision loss on reading and other daily tasks, developing suitable visual rehabilitation is vital to patients with central vision loss.

Conventional low-vision rehabilitation often include prescribing assistive devices such as magnifiers and lighting aids to help with reading (Cheong, Lovie-Kitchin, Bowers, & Brown, 2005). Recent research studies have been focusing on developing various training methods to improve reading performance in patients with central vision loss. For instance, eccentric viewing training at the PRL has been shown to improve reading speeds for patients with central vision loss (Nilsson, Frennesson, & Nilsson, 2003). There is also training that targets improving oculomotor control in peripheral reading by practicing saccadic eye movements (Seiple, Grant, & Szlyk, 2011; Seiple, Szlyk, McMahon, Pulido, & Fishman, 2005). Other studies suggest that perceptual learning is another promising training method for improving reading performance in the periphery (e.g., Chung, Legge, & Cheung, 2004; Yu, Cheung, Legge, & Chung, 2010; Yu, Legge, Park, Gage, & Chung, 2010). Perceptual learning refers to the relatively long lasting modification of the perceptual system following practice of a sensory task (Gibson, 1963; Goldstone, 1998). Yu et al. (2010) examined several character-based tasks for perceptual learning and found that training directly on a reading task was the most effective in improving reading speed in normal peripheral vision. The same training method has also been found to be effective in patients with central field loss (S. T. Chung, 2011; Nguyen, Stockum, Hahn, & Trauzettel-Klosinski, 2011).

Ahissar and Hochstein (2004) suggested that perceptual learning occurs in a top-down guided process, known as the Reverse Hierarchy Theory. If training on a sensory
tasks modifies neurons at a higher level cortical areas, transfer of learning to untrained conditions or locations can more readily occur. More difficult visual tasks tend to be learned at lower cortical levels and therefore learning is more specific to the trained conditions and tasks. To achieve generalization of learning, training must not be too difficult and hence occur on a higher cortical level. If the task is too easy, it may lead to insufficient learning due to a ceiling effect. To maximize learning and its transfer, the optimal level of difficulty in the training task needs to be “just barely too difficult” (Green & Bavelier, 2006). Maintaining task difficulty at an intermediate level is also recommended for the purpose of keeping high motivation and persistence in trainees. Task difficulty can be controlled through adjusting a stimulus/task parameter. Adaptive training involves constant adjustment of stimulus/task parameter according to subject’s response to keep the performance level close to a pre-defined level. Adaptive training procedures have been mostly evaluated in working memory studies (Brehmer, Westerberg, & Backman, 2012; Metzler-Baddeley and Baddeley, 2009). It has been shown that adaptive training procedure can lead to larger gains in learning than practice on a constant low difficulty task (Brehmer, Westerberg, & Backman, 2012). In perceptual learning, learning seems to follow a cascade — the learning on easy conditions can facilitate learning of more difficult ones (Ahissar & Hochstein, 1997). Varying training difficulty certainly seems to be more beneficial than training on a difficult task alone.

As shown in previous perceptual learning studies (e.g., Yu, Legge, et al., 2010), even in the normal periphery, the initial performance, the speed, and the total amount of learning can be quite variable across subjects. The similar inter-subject variability can be
observed in patients with central vision loss as well (Chung, S., 2011). In addition, there is a high degree of variability in the vision conditions across patients with central vision loss. Patients may have scotoma(s) of different shape, size, and density, covering different region of retina. It is possible that a more individualized training program may be more beneficial than a one size fits all training protocol (Chung S., 2011). Although perceptual learning has been proven useful in improving peripheral reading speeds, further development of training protocols are still required to improve their efficiency and effectiveness on an individual level.

Fluent reading requires accurate recognition of multiple letters simultaneously. The letter size required to recognize peripherally presented letters accurately increases with eccentricity (Anstis, 1974). Even with a letter size above the acuity limit, reading is still slow in the periphery. The size of the visual span, the number of neighboring characters that can be recognized in one fixation, has been suggested to be a sensory bottleneck on peripheral reading speed (Legge, 2007; Yu et al., 2010). Normal sighted individuals who use their central vision for reading have a visual-span size of 9 to 10 characters (Legge, 2007). Visual span shrinks in the normal periphery (Legge, Mansfield & Chung, 2001) and in patients with a central vision loss (Nguyen, Stockum, Hahn, & Trauzettel-Klosinski, 2011) (Cheong, Legge, Lawrence, Cheung, & Ruff, 2008). These findings indicate that enlarging peripheral visual span may lead to improved reading speed in the periphery. Indeed, several studies confirmed this hypothesis (e.g. Chung, S.L.T, et al., 2004; Yu, Cheung, Legge, & Chung, 2010; Yu, Legge, et al., 2010). These studies utilized the perceptual learning method and provided normally sighted subjects with extensive practice
on a letter-recognition task to achieve the expansion of the visual span. Typically, training consisted of four to five one-hour sessions on consecutive days. They found that training focusing on enlarging peripheral visual span is accompanied by an improvement in peripheral reading speed, and that learning can transfer to an untrained reading task and an untrained retinal location (Chung, Legge, & Cheung, 2004; He, Legge, & Yu, 2013; Yu, Legge, Park, Gage, & Chung, 2010). In addition, normally sighted observers were able to retain what they had learned for at least three months following training (Chung, Legge, & Cheung, 2004). Similar training effects have also been found in older individuals who have a more similar age range as those with AMD (Yu, Cheung, Legge, & Ghung, 2010).

Yu et al. (2014) demonstrated that the size of the visual span is determined by three sensory factors: decreasing resolution with eccentricity, uncertainty in the relative positions of letters within a stimulus, and crowding. Crowding refers to the increased difficulty in recognizing a target object due to the interference from flanking objects (Whitney & Levi, 2011). It is especially prominent in the periphery. The extent of crowding is dependent on target eccentricity (Bouma, 1970). Among the three sensory factors, crowding is the major factor limiting the size of the visual span (He et al., 2013; Yu et al., 2014), and is considered as the bottleneck to reading and object recognition in the periphery (Pelli et al., 2007; Whitney & Levi, 2011; Yu et al., 2014). For patients with central vision loss, the difficulty in peripheral reading can be accounted for by the shrunken visual span or increased crowding. Investigation on how the sensory factors are responsible for the improvement following training suggested that improvement in visual-span size and reading speed is primarily due to the reduction in crowding (He et al., 2013). Chung (2007)
examined whether training can reduce crowding in peripheral vision and whether the reduction of crowding is accompanied by an improvement in peripheral reading speed. The author found that performing a letter recognition task repetitively at a fixed retinal location can reduce crowding in the periphery. However, the reduced crowding did not lead to faster reading speed. A basis for the discrepancy may lie in differences in the total number of letter positions trained during training.

For low-vision reading rehabilitation, outcome effectiveness of the training method (the degree to which training is successful in enhancing reading performance by a clinically meaningful amount) is the predominant objective. Since patients with central vision loss have a high degree of variability in their vision conditions and potential learning curves, it is crucial to design a protocol that is effective on an individual level. Adaptive methods provide us a possible approach for a simple customization of the training method for each patient with a unique ocular condition. We aim to develop a perceptual learning paradigm that makes adaptive adjustment to the training task to maintain a certain level of task difficulty, based on patient’s performance. By using the adaptive method, we hope to improve learning efficiency while reducing the effort required from patients. Ultimately, our goal is to translate our research findings into an effective form of low-vision rehabilitation, and to help people with central vision loss improve their visual performance and their quality of life.
Chapter 2: Methods

Subjects

Twenty-one normally sighted adults aged 20-35 years participated in the study. Subjects were randomly assigned to three groups: a training group and a control group in the main experiment, and a group performing a supplementary experiment. Written informed consent was obtained from each subject prior to starting the study. Monetary compensation was given to subjects based on time of participation. The study protocol followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of The Ohio State University.

All subjects were native English speakers, had no history of ocular pathology, and had no difficulties with reading. Prior to the experiment, we obtained three visual measurements from each subject: near visual acuity, and high- and low-contrast visual acuities using the Bailey-Lovie charts. All subjects had high-contrast visual acuity of 20/20 or better in each eye and a binocular near acuity of 20/20 or better.

Apparatus and Stimuli

We used MATLAB R2010a and Psychtoolbox 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) to generate all the testing stimuli and to control the experiments. All stimuli were black text on a white background, displayed on a ViewSonic Graphics
Series G225f CRT monitor (size: 38.1cm×30.2 cm; resolution: 1280×1024; refresh rate: 85 Hz) in a dark room. Luminance was 136 cd/m² for the white background and 0.5 cd/m² for the black letters. Courier font, a fixed-width font, was used. To maintain a viewing distance of 40 cm, subjects sat with their chins in a chin rest and foreheads up against a forehead rest for all testing sessions.

**Experimental Design**

The control and training groups completed the same pre- and post-tests. The pre- and post-tests were separated by one week. During the pre- and post-testing, reading speeds and visual span profiles were measured at 10° eccentricity in both the upper and lower visual fields. The eccentricity of 10° was chosen based on a report from Schuchard, Naseer, and de Castro (1999) on the average size of a central scotoma (about 18°) for patients with exudative or atrophic AMD. If the scotoma is centered at the fovea, 10° eccentricity from the fovea would be just outside the scotoma. We can use 10° eccentricity to approximate the location used for reading by AMD patients with an average-size scotoma centered at the fovea. A print size (defined as x-height) of 2.5° was used because it is larger than the critical print size for reading at 10° eccentricity (S. T. Chung, Mansfield, & Legge, 1998). This letter size roughly correlates to a 20/600 letter size. In the pre-test, we measured reading speeds first and then visual span profiles. The testing order was reversed for the post-test.

The training group completed four consecutive days of training starting two days after the pre-test. The training involved identifying crowded letters at 10° eccentricity for about an hour. Pre- and post.measurements were taken in both the upper and lower visual
field, while training only took place in the lower visual field. This design allowed us to assess the transfer of learning from the trained lower visual field to the untrained upper visual field.

*Visual-span profile*

The size of the visual span is the number of letters that can be recognized reliably without moving the eyes (Legge et al. 2007), which can be derived from visual-span profile. As shown in Figure 1, visual-span profile refers to a plot of letter recognition accuracy as a function of letter position. It was measured using a trigram task. In the task, trigrams, strings of three lowercase letters randomly chosen from the 26 letters in the English alphabet, were presented at various positions to the left and right of midline, for an exposure duration of 188ms.

Subjects were asked to fixate on a green dot at the center of the display while identifying all three letters in the left-to-right order. There were eleven trigram positions included five positions to the left of the midline (positions -5 to -1), position directly below or above the fixation at 10 eccentricity (position 0), and five positions to the right of the midline (positions 1 to 5). There were four blocks of the trigram task, two for the upper and two for the lower visual field. During each block, the trigram was randomly presented five times at the eleven positions, for a total of 55 trials per block.
Figure 1: **Visual span plot.** Top diagram is an example of two different trigrams presented 10° above fixation. Trigram “ove” is presented at position -4 (to the left of 0; trigram “ltd” is presented at position +2 (to the right of position 0). The lower diagram is an example of a visual span profile which plots proportion correct as a function of letter position. The right vertical scale is a conversion from proportion correct to bits of information transmitted which is an indication of how many letters can be recognized in one fixation. The shaded area under the curve indicates the visual span size.

The visual span profile was constructed by examining the accuracy of letter identification at each letter slot between positions -4 and 4. Only these positions were included because the left, middle and right letters of trigrams were equally presented at each of these locations. The plot of identification accuracy versus letter position was fit
with an asymmetric Gaussian function. As shown in Figure 1, proportion correct of letter identification can be converted to bit of information transmitted (Beckmann and Legge, 2002). An accuracy of 100% corresponds to 4.7 bits of information (i.e. \( \log_2(26) = 4.7 \)). An accuracy of 3.8% or 1/26 corresponds to 0 bits of information. The total amount of information transmitted through the visual-span profile (i.e., area under the curve) indicates the size of the visual span expressed in bits.

**RSVP reading speed**

Reading speed was measure using the rapid serial visual presentation (RSVP) method. The RSVP method presents words one at a time at the same, left justified, starting position in either the upper or lower visual field. Each trial started with a row of x’s to indicate where words would be presented and ended with a row of x’s to indicate the end of the sentence. Sentences were presented at various speeds. Six exposure durations of word presentation were used: (76ms, 159ms, 241ms, 406ms, 735ms, 1312ms). All subjects were able to reach 80% reading accuracy at the longest duration. Each trial was initiated by the subject left-clicking a computer mouse. Subjects were instructed to fixate on a horizontal line while reading aloud a sentence. Only horizontal eye movements along the fixation line were allowed. For any vertical eye movement, the trial was cancelled and replaced. The number of words read correctly was recorded.

For each testing condition, there were two blocks and a total of 36 sentences, six for each of the six exposure durations. Sentences were randomly selected, without replacement, from over 2000 sentences. We plotted word recognition accuracy as a
function of exposure duration (Figure 2). Reading speed in words per minute was derived based on the duration corresponding to 80% reading accuracy.

![Reading curve](image)

**Figure 2**: Reading curve. An example of a reading curve which plots proportion correct as a function of exposure duration. The criterion of 80% accuracy was used to derive reading speed.

**Training**

Training consisted of four daily one-hour sessions of identifying the middle letters of trigrams presented at various positions 10° below fixation. The trigram presentation was similar to that used in the pre- and post-tests with the following exceptions. The training stimuli were presented only in the lower visual field. The subjects were required to report only the middle letter of the trigram. To maintain the task difficulty at a constant level for middle letter recognition during training, jitter motion was applied to the middle letter of the trigram and adaptive adjustment of jitter amplitude was made on block-by-block basis. Jitter motion is defined as a rapid displacement (2 cycles during the total presentation duration of 188ms) along the vertical direction with a specific magnitude. As shown in the supplementary experiment, performance level, an indicator of task
difficulty, changes with jitter amplitude. The reason we choose to use motion instead of varying other parameters (e.g., letter spacing or contrast) of stimuli is that motion can leave the spatial properties of reading stimulus largely unchanged (Husk & Yu, 2015). Based on the findings of the supplementary experiment, we chose to use seven jitter amplitudes, ranging from 0% (static) to 10.8% of $x$-height (corresponding to 0 to 6 pixels on the display with an increment step of one pixel), for training. Each training session consisted of 16 blocks with 55 trials in each block. The amplitude of the motion was dependent on the performance level of the previous block and changed adaptively on to maintain a roughly 80% accuracy of letter recognition. Specifically, after completing each training block, letter recognition accuracy averaged across all letter positions was calculated. If the percent correct of letter recognition was above 80%, jitter amplitude would decrease for the next block by one step size (i.e. 1 pixel or 1.8% of $x$-height). Otherwise, if the percent correct was 80% or less, an increase of amplitude would occur. There were also occasions that amplitude of jitter motion stayed unchanged for two or more consecutive blocks. For example, amplitude would remain at the minimal if the performance is beyond 80% accuracy at the static condition (0% of $x$-height), and would be kept at the maximum level if the performance is equal or below 80% at the amplitude of 10.8% of $x$-height. The beginning of the next day of training started at the level where the previous day had finished, regardless of performance on the final block of the previous day.
Data Analysis

Repeated measures ANOVA was used to analyze the post-pre ratio in reading speed and the post-pre difference in visual-span size. The within-subject factor was visual field (lower visual field and upper visual field). The between-subject factor was group (control group and training group). The effectiveness of the training protocol was evaluated based on comparisons between the two groups. Transfer of learning was evaluated by comparing upper (untrained) and lower (trained) visual fields in the training group.

Supplemental Experiment

During the training, task difficulty was manipulated through adding various amount of jitter motion. To investigate how performance level changes with motion amplitude, the supplemental experiment was performed before carrying out the main experiment. The findings of the experiment also help further confirm the use of motion being an appropriate option for adaptive change in task difficulty, and help determine the appropriate range of motion amplitude to use throughout training.

Subjects participated in a single experimental session on a crowded letter recognition task. The stimuli were trigrams presented at positions -3 and 3 at 10° below fixation. The jitter motion was applied to the middle letter only. Five amplitudes were tested: 0, 2, 4, 6, and 8 pixels (corresponding to 0%, 3.6%, 7.2%, 10.8%, and 14.4% of x-height). The subjects’ task was to identify the middle letter while maintaining stable fixation. The order of testing sequence of amplitudes were randomized for each subject.
There were 40 trials per letter position and amplitude. Based on the data, we constructed a plot of percent correct of letter recognition versus jitter amplitude.

During all experiments, subjects’ eye movements were monitored by the experimenter. The experimenter sat next to the subject and observed eye movements in profile. Prior to the start of the experiment, the experimenter trained on detecting eye movements, and was able to reliably detect an eye movement of 1.5°. Detection of any deviation away from the fixation triggered cancelation and replacement of the trial. Prior to the administration of each task, subjects were given a practice block for each testing condition. Data from practice blocks were recorded but not taken into consideration for data analysis.
Chapter 3: Results

Visual-span size

Figure 3 shows the pre and post visual span profiles for one of the training subjects. The visual-span profiles show an upward shift. The upward shift is observed in both the trained lower and untrained upper visual field, although the shift is greater in the trained field. The size of the visual span was calculated using the method described in the Method section. Compared to the control group, the size of the visual span increased following the training in both the trained and untrained visual fields (F(1,12) = 20.71, p = 0.001). Table 1 lists the pre- and post- visual span sizes as well as change in visual span size for both the control group and the training group. The enlargement of the visual span was greater in the trained lower visual field (5.0 bits of information transmitted) compared with the untrained upper visual field (2.5 bits), indicating a substantial but not complete transfer of learning from the trained to the untrained field (F(1,12) = 13.14, p=0.003). Figure 4 shows changes in visual span for the training group (4a), the control group (4b) and the overall average (4c).
Figure 3: **Enlargement in visual span.** Pre- and post-measurements of visual-span profile for both the trained lower visual field and untrained upper visual field. The data are from one training subject. Red circles represent the data collected in the pre-test. Black circles represent the data collected in the post-test.

<table>
<thead>
<tr>
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<th>Pre-test</th>
<th>Post-test</th>
<th>Post-pre difference</th>
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<tbody>
<tr>
<td></td>
<td>Lower VF</td>
<td>Upper VF</td>
<td>Lower VF</td>
</tr>
<tr>
<td><strong>Visual-span size (bits)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>32.5 ± 1.4</td>
<td>29.9 ± 1.5</td>
<td>33.5 ± 1.3</td>
</tr>
<tr>
<td>Training</td>
<td>30.4 ± 1.3</td>
<td>27.8 ± 1.0</td>
<td>35.4 ± 0.7</td>
</tr>
<tr>
<td><strong>Reading speed (wpm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>184 ± 23</td>
<td>145 ± 19</td>
<td>210 ± 28</td>
</tr>
<tr>
<td>Training</td>
<td>152 ± 15</td>
<td>104 ± 11</td>
<td>224 ± 24</td>
</tr>
</tbody>
</table>

Table 1: **Pre-test, post-test, and post-pre difference.** Pre-test performance, post-test performance, and post-pre change for the two groups (mean improvement ± standard error).
Figure 4: **Training group, control group, and group average for visual span.** Post-pre change in the size of the visual span. (A) Seven training subjects. (B) Seven control subjects. (C) Group average. The horizontal line corresponds to zero change in the visual-span size. Bar above the line indicates an enlargement of the visual span. Bar falling below the line indicates a constriction of the visual span. Error bars indicate standard errors.

**RSVP reading speed**

Although training was on a letter recognition task and took place only in the lower visual field, learning was generalized to RSVP reading task in both trained and untrained visual fields. Figure 5 shows the pre and post RSVP reading performance for one training subject. Proportion correct of word recognition increases a substantial amount across most of the tested exposure durations. RSVP reading speed showed significant increase for the training group compared to the control group ($F(1,12) = 10.43$, $p = 0.007$). No main and interaction effects of visual field were found, indicating a complete transfer of
learning from the trained to the untrained visual field. The training group showed an average improvement in reading speed of 49% in the trained lower visual field and 50% in the untrained upper visual field. Table 1 lists the group average of pre and post-test reading speeds as well as post/pre ratio indicating change between pre- and post-tests. Figure 6 shows individual changes in reading speed for the trained and the untrained control subjects, and the group average.

Figure 5: **Increase in reading speed.** Pre- and post-measurements of RSVP reading performance for both the trained lower visual field and untrained upper visual field. The data are from one training subject. Red circles represent the data collected in the pre-test. Black circles represent the data collected in the post-test. The criterion of 80% accuracy is used to derive reading speed.
Figure 6: **Training group, control group, and group average for reading speed.** Post-pre change in RSVP reading speed. (A) Seven training subjects. (B) Seven control subjects. (C) group average. The horizontal line corresponds to the post/pre ratio of 1 and represents no change. Bar above the line indicates an increase in reading speed. Bar falling below the line indicates a decrease in reading speed. Error bars indicate standard errors.

*Supplementary Experiment*

As shown in Figure 7, accuracy at identifying the middle letter of the trigram varies with the amplitude of motion applied to the middle letter, F(4,12)-26.4; p<0.0005. Specifically, averaged across subjects, letter identification accuracy improved from 53% to 76% as the amplitude increasing from 0 (static) to 4 pixels (7.2% of x-height), ps<0.05, and then leveled off for larger amplitudes, ps>0.05. The findings from the supplementary experiment confirmed the use of motion as an appropriate option for varying task difficulty. Based on the findings (both group and individual levels), a range
of motion amplitudes (0% to 10.8% of x-height corresponding to 0 to 6 pixels) were selected to be used in the training. In addition, large individual variation observed in the data further supports the need for individualized training.

Figure 7: Change in letter identification vs jitter amplitude. Accuracy of letter identification plotted against amplitude motion applied to the middle letters of the trigrams for the seven subjects and the group average. (A). Normalized performance (normalizing the performance accuracy by the identification accuracy for the static condition). (B). Raw performance accuracy. Open circles are the individual data (different colors represent different subjects). The filled black dots represent the group average, which were fitted with an exponential function. The black curve represents the best fitted curve. Error bars indicate standard errors.

Training

Seven levels of motion amplitude, 0, 1, 2, 3, 4, 5, and 6 pixels, were used during the training. Figure 8 shows individual block-by-block selection of motion amplitude and the group average. All subjects started training at the maximum motion amplitude (6 pixels). The large range of variation in learning pattern among subjects, as shown in
Figure 8a, indicates the individual differences in the combination of initial performance, learning speed, and the effect of motion on letter recognition performance. Some subjects quickly dropped to smaller amplitudes (e.g., subject T4), others stayed at larger amplitudes for numerous blocks (e.g., subject T2). Some subject (e.g., T3) showed substantial amount of fluctuations within almost each training day. However, as a group, there is a clear trend of gradual reduction in motion amplitude across training, as shown in Figure 8b. Figure 9 shows the block-by-block change of letter recognition accuracy for the group average. Most of the time, especially after the first few blocks on the first day of training, letter recognition performance was successfully maintained around roughly 80% accuracy. Consistent with previous learning studies (e.g. Yu, et al., 2010), we also observed lapses in the training effects from the last block of one training day to the first block the next training day (Figure 10; one-tailed t-test, \( p < 0.05 \)). The average lapse is 7% across subjects and training days. The lapses introduce a local peak of motion amplitude in the learning data at the beginning of each training day.
Figure 8: **Individual and group average training data.** 8a: Block-by-block selection of motion amplitude (pixels) is shown for the seven trained subjects. Each panel shows amplitude of motion used in the pre- and post-tests (solid dots), and also day-by-day training amplitudes (open circles). There are 16 blocks in each of the four training days. The data for different days were plotted in different colors. Vertical dashed lines indicate the boundaries between days. 8b: Group average for block by block performance over four days of training.
Figure 9: **Letter recognition accuracy**. Block-by-block change of letter recognition accuracy for the group average. The solid dots represent the performance measured in the pre- and post-tests. The open circles represent training data. There are 16 blocks in each of the four training days. The data for different days were plotted in different colors. Vertical dashed lines indicate the boundaries between days. The horizontal line represents the 80% accuracy.

Figure 10: **Day-to-day lapse**. Day-to-day lapse (change in proportion correct; Mean ± SE) averaged over seven training subjects.
Chapter 4: Discussion

In the present study, we developed a training paradigm that individualizes training by adaptively adjusting a testing parameter to maintain the task difficulty at a constant level. We found that following four days of adaptive training on a letter-recognition task, the training group showed substantial enlargement in the visual-span size (increase in the number of letters recognized without moving the eyes) in the periphery compared to the control group. The training benefit was generalized to an untrained task – RSVP reading. For both performance measures, learning was also successfully transferred to an untrained retinal location. The important indication of our findings is that a simple customization of training for each individual can be achieved while maintaining effectiveness of training in enhancing peripheral reading performance.

Following the adaptive training, the mean improvement in reading speed was about 50% which is similar to the improvement reported in other non-adaptive learning studies that also aim at improving peripheral reading speed (Chung et al., 2004; Yu et al., 2010; Lee et al., 2010; He et al., 2013). In terms of training procedure, the only other differences between the current study and the previous ones are that our subjects reported the middle letter only instead of all three letters of the trigram, and that there are 3520 training trials instead of 5200 trials in some studies (Chung et al., 2004; Lee et al., 2010).
Transfer of learning is an important aspect to consider when developing a training protocol targeting peripheral reading for patients with AMD. First, AMD is a progressive disease. Central scotoma(s) and PRL(s) may change as the disease progresses. Second, even if the disease and vision condition is stable, it would still be useful to have the improvement obtained at one location transfer to new locations for efficiency purpose especially when the patient has more than one PRL. It has been suggested that generalization of learning is determined by the cortical location where learning happens (Fahle & Poggio, 2002). When learning happens in the early visual processing, learning may be more specific. If learning activates the neurons in high-level area, it would be more likely for learning to generalize. Task performance (an indicator of task difficulty) has been a factor influencing where learning occurs in the visual pathway (Ahissar & Hochstein, 1993). Easier task tends to be learned at higher cortical areas and modify neurons at the higher level of processing, and therefore likely induce generalization of learning. Vice versa. In the present study, we tried to control the task performance (difficulty) at an intermediate level by adaptively adjusting a task parameter. We observed learning transfers from the trained to the untrained task and retinal location, implying that the neural location(s) for the occurrence of learning includes non-retinotopic cortical area(s). Since we also found a partial transfer of learning from the trained to the untrained retinal location for visual-span size, there must be some learning occurring at the retinotopic level. In other words, the learning found in the present study may be due to the combination of changes on both the low- and higher-levels of visual processing. For RSVP reading speed, our result of complete transfer of learning across
visual fields is different from the partial transfer found in the previous non-adaptive learning studies (Chung et al., 2004; Yu et al., 2010; Lee et al., 2010; He et al., 2013). This seems to suggest that maintaining the task difficulty at an intermediate level may allow better transfer of learning, although replication of the data may be required before firmly drawing this conclusion.

He et al. (2013) performed a similar perceptual learning study on peripheral reading using trigram task and static stimuli for training. Their findings showed that the training-related improvement in reading speed is mainly accounted for by the reduction in crowding, which indicated that training focusing on decreasing crowding, may be beneficial for peripheral reading. Chung (2007) conducted a study to develop such a training protocol but did not find evidence supporting the link between the change in crowding and the change in reading speed. The author found that a decrease in spatial extent of crowding was not associated with statistically significant improvement in reading speed. In the training, the stimuli was presented with a smaller-than-standard letter spacing at a fixed location (directly below the fixation). In the pre- and post-test, crowding was evaluated only at the trained retinal location instead of various letter locations covered by reading task. Due to these specific design factors in the study, it is reasonable that the reduction of crowding for the conditions tested by Chung (2007) does not generalize to the testing conditions in our study and the study by He et al. (2013). In the present study, we use standard letter spacing between letters and ask subjects to identify the most crowded (middle) letter at various locations where reading stimuli are presented. Through introducing motion to the middle letter, the amount of crowding and
the difficulty of the task was manipulated adaptively to facilitate learning. Although we did not measure spatial extent of crowding, our results showed that the amplitude of crowding was significantly reduced for the standard letter spacing used in reading, which is what we were most concerned about.

Both Yu et al (2010) and Chung et al (2004) found that 3 days of consecutive training is adequate to reach an asymptotic level of learning. In Figure 8, our training data showed a similar trend – slowly reaching a plateau and having minimal change in average motion amplitude after day three. Consistent with previous findings (Dosher & Lu, 2007), the average performance improvement versus training time follows an exponential function form where learning is fastest at the beginning and then slows down over time. However, despite the observed plateau, we cannot be certain that learning has reached its maximal potential. One study extended the learning period beyond the initial plateau and found that further substantial improvement is possible especially for patients with severe vision impairment (Li, Klein, & Levi, 2008). When examining the effectiveness of the current training in low-vision patients, prolonged training may be necessary before concluding on the ultimate benefit of the training.

The adaptive training method developed in this study provides simple customization for each individual while being effective in enhancing peripheral reading performance. These findings have important implications for reading rehabilitation of patients with central vision loss. Each patient with central vision loss is unique. They can be different in stage of scotoma-induced disease, vision loss, capacity of learning, and speed of learning. The adaptive method developed here reduces effort required from
subjects in terms of task difficulty and response made in each trial (reporting one letter instead of all three letters). Ultimately, our goal is to translate our research findings into an effective form of low-vision rehabilitation, and to help people with central vision loss improve their visual performance and their quality of life. The next steps are to determine if similar results would be obtained in subjects in an older age range and those with central vision loss. We would also want to evaluate the transfer of the learning to daily page reading.
References


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Appendix: Pathogenesis, Etiology, and Current Treatment options for Age Related Macular Degeneration

Age-related macular degeneration is a degenerative disease which affects the retina and choroid, specifically the outer neural retina, the retinal pigmented epithelium (RPE), Bruch’s membrane and choroidal vasculature (Jonasson, et al., 2014). Degeneration is believed to start in the RPE which then causes the degeneration of the photoreceptors and choriocapillaris (Young, 1987). Major characteristics of the disease include thickening of Bruch’s membrane due to accumulation of drusen, and areas of hyper and hypo pigmentation from RPE cell death, referred to as mottling. There are two types of AMD: dry AMD and wet AMD. Dry AMD is characterized by pigmentation changes, drusen, and geographic atrophy leading to a gradual loss of vision (Curcio, 1996). Wet AMD shares many similar characteristics as dry AMD but includes choroid neovascularization which can lead to a more rapid and severe loss in vision (Curcio, 1996).

Many studies have been conducted to better understand risk factors that may lead to AMD or to an increased rate of progression and severity of AMD. Age and cigarette smoking have been consistently identified as two risk factors in development and progression of AMD (Jonasson, et al., 2014). It has been shown that the highest prevalence of this eye disease occurs among individuals older than 85 years (Young, 1987). Other risk factors for developing AMD include higher body mass index, higher levels of plasma HDL
cholesterol (Jonasson, et al., 2014), and a family history (Ambati, Ambati, Yoo, Ianchulev, & Adamis, 2003).

Since the etiology of AMD is unknown, creating an effective treatment is extremely challenging. There are very few treatment options for dry AMD. The majority of treatments target the hypothesis that oxidative stress plays a major role in the development of AMD. The rationale behind the The Age Related Eye Disease Study (AREDS) was the thought that macular carotendoid pigments: lutein and zeaxanthin would be protective in the development of AMD by limiting oxidative stress. The study found that patients with intermediate or advanced stages of AMD can benefit from an antioxidant supplement. However for all others the best route to receive these carotenoids is through a diet rich in dark green leafy vegetables.

Other treatment options for dry AMD include laser to break up large soft drusen, and apheresis to improve blood flow which may slow the process of degeneration that leads to drusen formation and degradation of Bruch’s membrane and the RPE (Comer, Ciulla, Criswell, & Tolentino, 2004).

Current treatment options for wet AMD target the choroidal neovascularization. The most common treatment is the use of anti-VEGF to decrease the stimulus for neovascularization. Other treatments include thermal laser destruction of blood vessels, Photodynamic Therapy (PDT), and Transpupillary thermotherapy.

Research on AMD has provided a better understanding of the disease. However, there are still many unanswered questions, especially in the area of prevention and
treatment. Due to the limited treatment options, many patients suffer irreversible and substantial visual loss.