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The effect of normal aging and age-related macular degeneration on perceptual learning

Andrew T. Astle Visual Neuroscience Group, School of Psychology, University of Nottingham, Nottingham, UK

Alan J. Blighe Visual Neuroscience Group, School of Psychology, University of Nottingham, Nottingham, UK

Ben S. Webb Visual Neuroscience Group, School of Psychology, University of Nottingham, Nottingham, UK

Paul V. McGraw Visual Neuroscience Group, School of Psychology, University of Nottingham, Nottingham, UK

We investigated whether perceptual learning could be used to improve peripheral word identification speed. The relationship between the magnitude of learning and age was established in normal participants to determine whether perceptual learning effects are age invariant. We then investigated whether training could lead to improvements in patients with age-related macular degeneration (AMD). Twenty-eight participants with normal vision and five participants with AMD trained on a word identification task. They were required to identify three-letter words, presented 10° from fixation. To standardize crowding across each of the letters that made up the word, words were flanked laterally by randomly chosen letters. Word identification performance was measured psychophysically using a staircase procedure. Significant improvements in peripheral word identification speed were demonstrated following training (71% ± 18%). Initial task performance was correlated with age, with older participants having poorer performance. However, older adults learned more rapidly such that, following training, they reached the same level of performance as their younger counterparts. As a function of number of trials completed, patients with AMD learned at an equivalent rate as age-matched participants with normal vision. Improvements in word identification speed were maintained at least 6 months after training. We have demonstrated that temporal aspects of word recognition can be improved in peripheral vision with training across a range of ages and these learned improvements are relatively enduring. However, training targeted at other bottlenecks to peripheral reading ability, such as visual crowding, may need to be incorporated to optimize this approach.

Introduction

Perceptual performance can be improved significantly following periods of practice: this is known as perceptual learning (Gibson, 1963). Perceptual learning is thought to be mediated by cortical plasticity and has been demonstrated for a large variety of tasks (Fine & Jacobs, 2002) in different sensory modalities. Perceptual learning raises the prospect of using targeted, noninvasive, training protocols to improve perceptual performance and, in turn, reverse or compensate for sensory decline caused by aging and/or pathology (Deveau, Lovcik, & Seitz, 2014).

A number of studies have demonstrated perceptual learning in healthy older adults. For example, perceptual learning has been shown to lead to improvements in peripheral texture discrimination (Andersen, Ni, Bower, & Watanabe, 2010), motion discrimination (Ball & Sekuler, 1986; Bower & Andersen, 2012; Bower, Watanabe, & Andersen, 2013), contour integration (McKendrick & Battista, 2013), orientation discrimination (DeLoss, Watanabe, & Andersen, 2014), Vernier jump discrimination (Fahle & Daum, 1997), global shape discrimination (Mayhew & Kourtzi, 2013), multiple object tracking (Legault, Allard, & Faubert, 2013), and contrast sensitivity (DeLoss, Watanabe, & Andersen, 2015) in older adults. In fact,

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contrast sensitivity shows improvements from the age at which presbyopia starts (approximately 45 years of age) and onwards (Polat et al., 2012). Advances have also been made in relating perceptual learning in older adults to the underlying neuroanatomy, with one recent study showing the unexpected result that improvements in older adults are correlated with the size of a functionally defined cortical area (Chang et al., 2015) and another showing that perceptual learning in older adults is associated with white matter changes in early visual cortex (Yotsumoto et al., 2014).

Perceptual learning has also been demonstrated in patients with amblyopia (Astle, Webb, & McGraw, 2011; Levi, 2005; Levi & Li, 2009), a developmental visual anomaly that reduces vision in one eye, and in patients with age-related macular degeneration (AMD; Chung, 2011). AMD is characterized by a degeneration of the retinal photoreceptors and pigment epithelium, resulting in a reduction in the quality of central vision. It is one of the most common causes of blindness in the world, affecting 2.95 million people (Pascolini & Mariotti, 2011). The estimated prevalence of AMD is 12% in people over the age of 80 years (Owen et al., 2012) and is becoming increasingly common due to an aging population (Velez-Montoya et al., 2014). A method of improving functional vision in patients with AMD would be extremely valuable because there is no treatment available for the vast majority (90%) of patients with the disease (Amoaku, 2008), it often goes on to affect both eyes (Roy & Kaiser-Kupfer, 1990), and causes a profound decrease in quality of life (Brown et al., 2005). Where treatment is available, it is rarely able to reverse vision loss and is associated with a number of potential adverse side effects (Falavarjani & Nguyen, 2013). End-stage AMD results in loss of central vision and patients must instead rely on relatively healthy areas of neighboring *peripheral* retina to view objects, often developing an extrafoveal preferred retinal locus (PRL; Fletcher & Schuchard, 1997).

Compared to central vision, peripheral vision is limited in a number of ways. For example, luminance sensitivity, contrast sensitivity, orientation discrimination, letter acuity, grating acuity, Vernier acuity, stereoacuity, and word identification speed are reduced in the periphery compared to the central visual field (Strasburger, Rentschler, & Jüttner, 2011). It is also much more difficult to identify peripheral objects when they are surrounded by neighboring objects—a phenomenon known as visual crowding (Bouma, 1970). Studies aimed at improving visual function in patients with AMD must target peripheral visual function and the deficits, relative to central vision, associated with it. There is growing evidence that perceptual learning can be used to improve vision in the normal periphery. For example, practice improves peripheral resolution acuity (Beard, Levi, & Reich, 1995), hyperacuity (Fahle & Edelman, 1993), spatial localization (Crist, Kapadia, Westheimer, & Gilbert, 1997), orientation discrimination (Schoups, Vogels, & Orban, 1995), texture discrimination (Karni & Sagi, 1991), and letter recognition (Chung, Legge, & Cheung, 2004; Chung, Levi, & Tjan, 2005), A number of studies have also shown that crowding in the normal periphery can be reduced following training (Chung, 2007; Chung & Truong, 2012; Hussain, Webb, Astle, & McGraw, 2012).

The majority of patients with AMD have difficulties performing everyday tasks, especially reading (Crossland, Gould, Helman, Feely, & Rubin, 2007). Therefore, training on tasks that directly or indirectly lead to improvements in peripheral reading ability would be of particular value to patients with AMD. A number of studies have investigated whether perceptual learning can improve peripheral reading speed in normally sighted participants (Chung, 2010; Chung et al., 2004; Lee, Kwon, Legge, & Gefroh, 2010; Sommerhalder et al., 2004; Yu, Cheung, Legge, & Chung, 2010). However, one may expect less improvement in AMD patients if their age, which tends to be much older than those typically recruited to perceptual learning studies, results in reduced cortical plasticity. Retinal pathology may also influence results. The retina contains lateral connections, and it is not clear whether macular pathology affects peripheral regions of retina, which otherwise appear normal on ophthalmic examination. Additionally, there is some evidence of cortical reorganization in patients with AMD. Some studies have found that regions of visual cortex that were responsible for processing information from the macula may become reassigned to processing information from adjacent, peripheral retinal areas in cases of central vision loss. However, results are ambiguous and there is some debate over this issue in the literature (Baseler et al., 2011; Dilks, Baker, Peli, & Kanwisher, 2009).

A small number of studies suggest that perceptual learning leads to increased reading performance in patients with AMD (Chung, 2011; Tarita-Nistor, Brent, Steinbach, Markowitz, & González, 2014; but see Seiple, Grant, & Szlyk, 2011). Chung (2011) trained AMD patients using meaningful sentences. Words were presented in sequence, one word at a time (rapid serial visual presentation [RSVP] paradigm; Rubin & Turano, 1992), and training consisted of measuring the effect of word exposure duration on reading accuracy. It was found that reading speed improved by 53%, on average, following six training sessions. Another study showed that training on an RSVP task using relatively smaller words, near the reading acuity limit, increases reading speed and reading acuity in patients with AMD (Tarita-Nistor et al., 2014).

	Age (years)	Gender	AMD type	Years since diagnosis	Eye affected	Training location
AMD1	81	Female	Dry	13	Right	Right eye, lower field
AMD2	75	Female	Dry	10	Left	Left eye, upper field
AMD3	67	Male	Dry	3	Right	Right eye, lower field
AMD4	76	Male	Dry	4	Right	Right eye, upper field
AMD5	80	Female	Wet	18	Both	Left eye, upper field

Table 1. Details of participants with AMD.

The present study investigates perceptual learning of a peripheral word identification task in normal participants of different ages and compares improvements on the same task in participants with AMD. In doing so, the word identification task is used as a proxy to determine the effect of age and the effect of retinal pathology on learned improvements in peripheral visual performance. Peripheral sentence reading speed is influenced by both visual span (i.e., the number of letters that can be identified with no eye movements; Legge, Ahn, Klitz, & Luebker, 1997) and temporal thresholds for letter recognition (Cheong, Legge, Lawrence, Cheung, & Ruff, 2007). This implies that we could either increase exposure time or increase visual span size to achieve improvements in reading speed. Previous studies have investigated the effect of increasing visual span, via training on a trigram letter recognition task, on peripheral reading speed (Bernard, Arunkumar, & Chung, 2012; Chung et al., 2004; Yu, Cheung et al., 2010). In this study, we chose to target the temporal aspects of letter recognition, which has been shown to be amenable to improvements in the elderly for non–text-based tasks (Ball, Edwards, & Ross, 2007). We keep word length fixed, standardize crowding for each letter of each word (Latham & Whitaker, 1996), and explore the effect of changing stimulus duration.

Here we measure the effect of training younger and older aged participants with normal vision on a crowded peripheral word identification task. We also determine the extent of improvements that are possible in participants with AMD on the same task and the amount of training required to produce a given amount of improvement relative to age-matched participants with normal vision. In doing so, we provide important information on the utility of perceptual learning protocols in older adults with normal vision and with AMD.

Methods

Participants

Twenty-eight participants with normal or corrected-to-normal vision (17 to 73 years, mean 46 ± 19 years; 15 female, 13 male) and five participants with AMD (67 to 81 years, mean 76 ± 6 years; three female, two male) participated in the study. All participants scored within the normal range on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975), which screens for cognitive impairment. Details of the participants with AMD are shown in Table 1. Four participants had AMD in one eye and one had AMD in both eyes. Central visual acuity was 1.00 logMAR or worse in each eye with AMD. In each unaffected eye, central visual acuity was 0.28 logMAR or better. The eye used to carry out training for participants with AMD is indicated in Table 1. For participants with normal vision, the eye used for training was randomly selected. Participants wore the appropriate optical correction for the viewing distance. Informed consent was obtained from all participants. The experimental procedures adhered to the tenets of the Declaration of Helsinki and were approved by a local ethics committee at the School of Psychology, The University of Nottingham.

Apparatus

Stimuli were generated on a PC computer using custom software written in Python (Peirce, 2007) and presented on a CRT monitor (Belinea 10 80 35 CRT; Maxdata, Marl, Germany) with a frame-rate of 85 Hz, a display resolution of 1024 × 768, and pixel size of 0.4 mm. The monitor was photometrically calibrated using a Minolta CS-110 photometer (Konica Minolta, Mississauga, ON, Canada). A forehead and chin rest were used to hold the head of each observer in position and maintain a constant viewing distance of 57 cm. Testing was carried out in a darkened room.

Test stimuli and procedures

Stimuli were presented 10° from a fixation target for participants with normal vision and those with AMD (see below). Participants with AMD did not fixate on stimuli using an established PRL. We did this for a number of reasons. First, training normal participants and those with AMD at the same location allows easier comparison of results between the two groups in terms

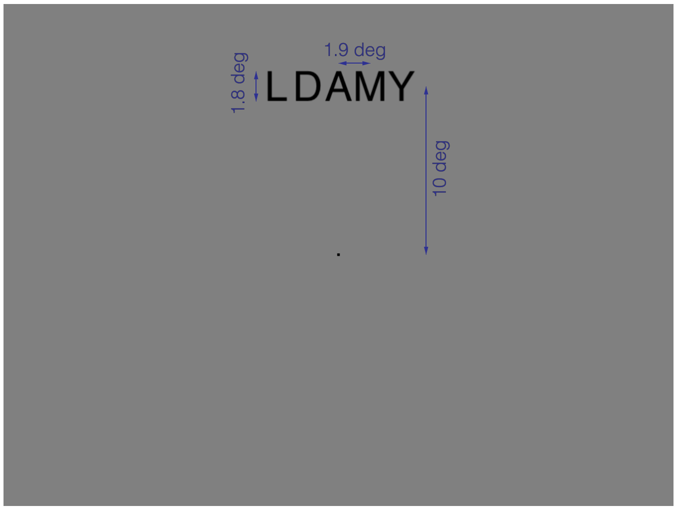

Figure 1. Example of stimulus used to test and train word identification in participants with normal vision. A random three-letter word (e.g., DAM) was displayed 10° above a fixation dot and flanked either side by a random letter. Arrows and labels in blue were not displayed during the experiment.

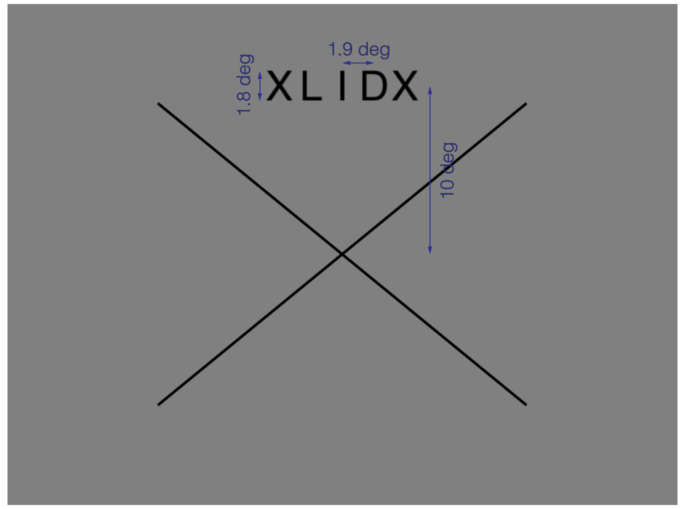

Figure 2. Example of stimulus used to test and train word identification in participants with AMD. A random three-letter word (e.g., LID) was displayed 10° above or below a fixation cross and flanked either side by a random letter. Arrows and labels in blue were not displayed during the experiment.

of amount and rate of any improvements because they share a common eccentricity. Second, the majority of our participants have AMD in one eye only and are unlikely to have an established PRL. Third, not all individuals with AMD select the optimal location for the PRL for performing visual tasks (Fine & Rubin, 1999; Petre, Hazel, Fine, & Rubin, 2000) and the location of the PRL may need to change as the disease progresses. We already know it is possible to train AMD patients to use a different retinal location (trained retinal location, or TRL; Nilsson, Frennesson, & Nilsson, 2003). Here we want to know if the performance on the trained task can be improved at a location other than the PRL, providing proof of plasticity of the peripheral visual field (at a point other than the PRL) in patients with AMD. We chose a location 10° above or below the fovea as scotomas are rarely more than 20° in diameter (Chung & Legge, 2005). Since visual performance tends to decrease with increasing eccentricity (e.g., acuity [Johnson, Keltner, & Balestrery, 1978] and reading speed [Latham & Whitaker, 1996]), this is likely to represent a worst-case scenario for the placement of any potential new PRL.

Word identification

Word identification speed was measured using a method adapted from a previous study (Latham & Whitaker, 1996). Three-letter words were presented on a 45 cdm^{-2} luminance background with a letter height of 1.8° and a center-to-center letter spacing of 1.9° (Figure 1), which was measured to be above the resolution limit for participants during pilot testing. Words were selected from a list of the most common words in the English language (Kilgarriff, 1997). Two randomly selected letters (any letter of the alphabet) were presented either side of the three-letter word with the same interletter spacing. All letters were rendered in uppercase Arial font. This task was chosen because uppercase letters are less variable in size than lowercase letters, and because placing letters either side of each word standardized crowding for each letter of each word. Standardizing crowding across each letter in the word reduces the probability of participants employing a strategy of guessing words based on the first and final letter of the word.

Participants with normal vision were asked to fixate on a central fixation dot and letters were presented 10° above the fixation dot. For participants with AMD, letters were presented 10° either above or below (see Table 1) a large (26° across by 18° high) diagonal fixation-cross presented at the center of the screen (see Figure 2). The stroke width of the diagonals was 0.25°. Participants were asked to fixate the center of the fixation cross so that the end of the limbs appeared to extend equal distances into the peripheral visual field, even though the center of the fixation cross itself was not visible to any of the participants (i.e., it fell within the scotoma). The experimenter sat to the side of the monitor and monitored fixation by observing participants' eye movements directly at a distance of 38 cm. Participants who were unable to maintain fixation during a practice run of 30 trials were excluded from the study. During the experiment, on the very rare occasions when there was a fixation loss, the trial was

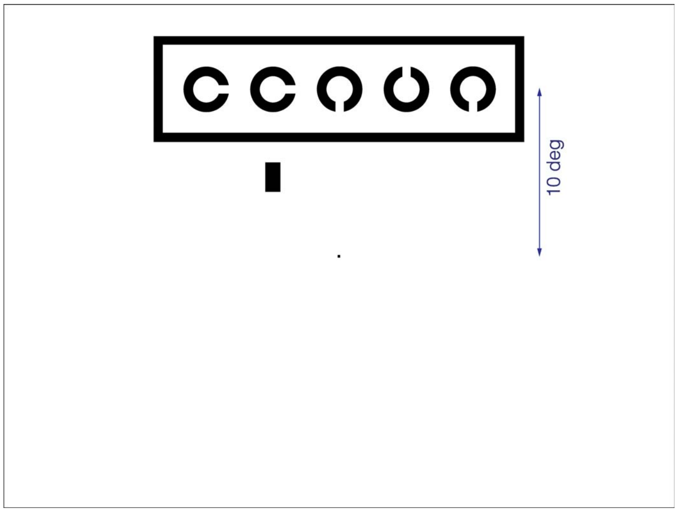

Figure 3. Example of stimuli used to test visual acuity. Participants were required to identify the gap in a Landolt C, which was presented in a line of five Landolt Cs positioned 10° above fixation and randomly set to one of the four cardinal directions. Arrows and labels in blue were not displayed during the experiment.

scored as incorrect. Eye movements of 1.5° can be reliably detected, even by relatively inexperienced observers (Fogt, Baughman, & Good, 2000). Since stimuli were presented 10° from fixation, we can be confident that the experimenter detected eye movements made to the stimulus. Participants with AMD were assessed using an Amsler chart and a Central 10-2 Threshold test on a Humphrey Field Analyser II (Carl Zeiss Meditec, Inc., Dublin, CA). If there was any field loss or metamorphopsia present 10° above fixation, participants were instead trained at 10° below fixation (see Table 1), where there was no field loss or metamorphopsia in each of these participants.

Participants were required to read each three-letter word aloud. The experimenter recorded correct and incorrect responses via a keyboard. For feedback, the experimenter read the correct word aloud after each participant response. Stimulus duration was varied in 0.15 log steps. Trials were blocked into groups of five: five correct responses in a block lead to a decrease in presentation duration while one or more errors in any block caused the duration to increase (converges to 84% accuracy level). Staircases terminated after eight reversals.

Crowded visual acuity

A computer-based visual acuity test was used to measure peripheral visual acuity in participants with normal vision. A line of five Landolt Cs was presented 10° above fixation on a 90 cdm^{-2} luminance background (Figure 3). Landolt Cs were 5×5 sans serif letter Cs with stroke width equal to gap width and one fifth of the letter size. The Landolt Cs were spaced half a letter width away from each other (edge-to-edge). The Landolt C targets were displayed within a rectangular box with stroke width equal to the stroke width of the Landolt C targets and spaced half a letter width away from the letters (edge-to-edge).

A marker (0.3×0.6 letter widths in size) was placed below each letter to indicate the target letter for a given trial. Participants were required to verbally report the gap location in each Landolt C, which were randomly set to one of the four cardinal directions. The examiner recorded responses via a keyboard. An auditory tone was played to indicate an incorrect response. Following five trials, letter size was reduced in 0.1 logMAR steps. Each letter was scored 0.02 logMAR and a letter-by-letter (complete line) termination rule of four errors was used (Carkeet, 2001).

Training procedure

Twenty participants with normal vision and five participants with AMD trained for up to 14 sessions (approximately 30 min/session) on the word identification task. Testing and training was carried out with one eye while the other was occluded. All training sessions took place on different days, separated by no more than 3 days.

Five separate estimates of crowded visual acuity at 10° above fixation were obtained before and after training for a random subset of eight participants with normal vision who underwent training. Peripheral crowded visual acuity was also assessed on two sessions separated by 2–3 weeks in eight control participants with normal vision who did not undergo word identification training.

Data analysis

The mean exposure duration for each session was calculated from the geometric mean of the final four reversals of up to five staircases (see below).

An exponential one-phase decay function of the form:

$$D = s \times 10^{(-kx)} + p, \quad (1)$$

was fitted to the mean learning curve data, where D is duration in seconds, s is duration on session 1, k is the rate constant, x is session number, and p is the plateau.

ANOVAs, Sidak's multiple comparisons tests, and Student's t tests were used to assess the statistical significance of mean threshold differences before and after training and between different groups. Linear

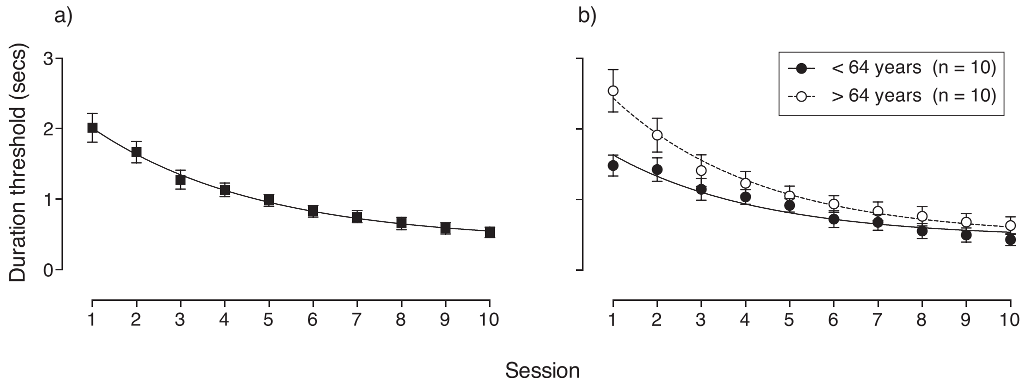

Figure 4. (a) Mean peripheral word identification duration as a function of training session for all participants with normal vision. (b) Mean peripheral word identification duration for younger (<median age of 64 years) and older (>median age of 64 years) participants with normal vision as a function of training session. Smooth curves through the data points are best fittings solutions of Equation 1. Error bars show 1 standard error of the mean (*SEM*).

regression analysis and an extra sum-of-squares F test were used to analyze individual data at the start and end of training. All estimates of variability provided in the Results section in parentheses are standard deviation, unless otherwise stated.

Results

Improvements in peripheral word identification are greater in older participants with normal vision

Participants with normal vision were trained on the crowded word identification task at 10° in the upper visual field for 10 sessions, completing 3–5 staircases/runs per training session. Participants completed an average of 323 trials (±71) per session. Figure 4a shows mean duration thresholds for word identification for each session. Mean word identification speed was 2.012 (±0.91) s on session 1. There was a statistically significant improvement in performance from session 1 to session 10, $t(38) = 6.82$, $p < 0.0001$. Participants improved by an average of 1.48 (±0.90) s between session 1 and session 10, and the mean word identification speed on session 10 was 0.53 (±0.34) s.

Participants were divided into two groups according to their age: participants who were younger ($n = 10$) and older ($n = 10$) than the median age of 64 years. Figure 4b shows mean duration thresholds for word identification for each group as a function of session. We conducted a two-way ANOVA on mean performance in the two groups on sessions 1 and 10 (repeated measures for session). This analysis revealed whether there was a difference in duration thresholds between the two groups at the start and end of training and whether there was a difference in the amount of improvement in the two groups. There were main effects of session, $F(1, 18) = 68.04$, $p < 0.0001$, and age, $F(1, 18) = 11.33$, $p = 0.0034$, as well as a significant interaction effect between age and session, $F(1, 18) = 5.70$, $p = 0.028$. Post hoc analysis (Sidak multiple comparisons test) revealed that word identification duration on session 1 was significantly shorter for the younger group (1.48 ± 0.47) than the older group (2.54 ± 0.95; $p = 0.0005$). However, by session 10 there was no statistical difference ($p = 0.69$) between the younger (0.43 ± 0.26) and older groups (0.63 ± 0.39). The change in mean word identification duration between session 1 and session 10 was significant for both the younger ($p = 0.0012$) and older ($p < 0.0001$) groups. The improvement was significantly greater in the older group (a difference of 1.91 ± 1.07 s) compared to the younger group (a difference of 1.05 ± 0.39 s), $t(18) = 2.39$, $p = 0.028$.

Differences in the amount or rate of learning between younger and older aged groups cannot be explained by differences in the amount of training completed by participants in each group: Participants in the younger group completed an average of 4.87 (±0.51) runs per session, compared to the older group, which completed an average of 4.90 (±0.39) runs per session, and there was no significant difference in the number of runs, $t(196) = 0.47$, $p = 0.64$, completed per session between the two groups. Younger participants completed an average of 3,082 (±620) trials, while older participants completed 3,393 (±825) trials in total. There was also no significant difference in the total number of trials completed between the two groups, $t(18) = 0.95$, $p = 0.35$.

These data suggest that, although older participants are initially slower at identifying words presented in the periphery compared to younger participants, they learn more as a result of practice and reach the same level of performance as younger participants after 10 sessions.

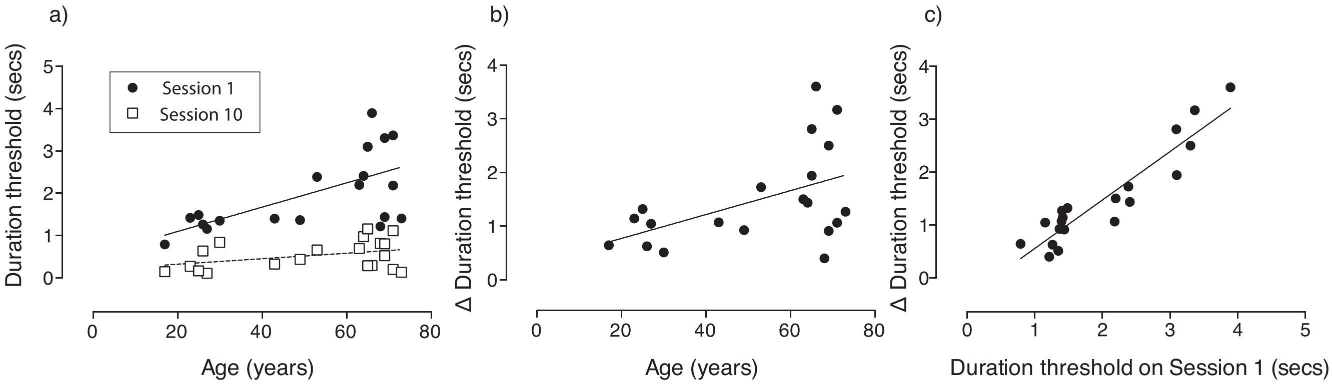

Figure 5. (a) Peripheral word identification speed on session 1 and session 10 as a function of age. Solid and dashed lines show linear regression curves fitted through the duration threshold data for session 1 and session 10, respectively. (b) Change in word identification threshold (threshold on session 10 − threshold on session 1) as a function of age. The line shows a linear regression curve fitted through the data. (c) Change in peripheral word identification threshold (threshold on session 10 − threshold on session 1) as a function of threshold on session 1, including linear regression curve fit.

This inference is reinforced by analyses on the individual participant data.

Magnitude of learned improvements are related to participant age and performance at the start of training

The median age may be considered to be on the older end of the age range and does not adequately divide participants into what would be classed as "young" and "old" groups. However, this approach has the desirable outcome that the age of the older group corresponds better with the age of those likely to have AMD. It should also be borne in mind that any age chosen to divide the data is somewhat arbitrary. Analyzing the individual data circumvents this limitation.

Figure 5a shows peripheral word identification thresholds for each participant on sessions 1 and 10 as a function of age. The effect of age on peripheral word recognition prior to training (session 1) can be seen, while avoiding the somewhat arbitrary division of participants according to the median age of the group. The slope of the linear regression function fitted to the data on session 1 was 0.029 and significantly different from zero, $R^2 = 0.39$, $F(1, 18) = 11.57$, $p = 0.003$, indicating that word identification speed varied significantly with age at the start of training. However, at the end of training (session 10), the slope of the linear regression curve fitted through the data was shallower (0.006), significantly flatter than on session 1, $F(1, 18) = 5.80$, $p = 0.021$, and did not significantly differ from zero, $R^2 = 0.14$, $F(1, 18) = 3.00$, $p = 0.10$. This adds further evidence that training removes the difference in performance between different ages at the start of training, and that this is caused by the fact that older individuals improve more on the task compared to younger individuals.

This can be seen clearly in Figure 5b, which shows the change in word identification speed from session 1 to session 10. As participant age increased, the amount of improvement in word identification speed increased significantly, $R^2 = 0.24$, $F(1, 18) = 5.73$, $p = 0.028$. Note, however, when improvements were quantified in terms of a ratio or a percentage, there was no significant change in improvement with age, $R^2 = 0.002$, $F(1, 18) = 0.038$, $p = 0.85$, which is consistent with the fact that the percentage change in performance in the younger and older groups in Figure 4a was approximately the same: 71.4% (±21) in the older group and 71.1% (±17%) in the younger group.

The amount of improvement on the task was associated with individual performance on the first session. Figure 5c shows how word identification speed changes relative to threshold on session 1. The slope of the linear regression function is 0.92 ($R^2 = 0.86$) and significantly different from zero $F(1, 18) = 114.0$, $p < 0.0001$. Improvements in word identification speed increased significantly with word identification duration thresholds on session 1. In other words, people who initially perform worse on the task improve more.

The change in performance over time during perceptual training has been shown to follow an exponential progression (Chung, 2011; Dosher & Lu, 2007). A one-phase exponential decay function (see Equation 1) was fitted to the mean data shown in Figure 4. Rate of learning was quantified by taking the rate constant (k) from the functions. A higher k-value signifies that learning was faster. The rate constant (±*SEM*) for the young and old groups was 0.11 (±0.086) and 0.31 (±0.080), respectively. The half-life of a process, corresponding to the time taken for a quantity to halve in value, is a more intuitive measure,

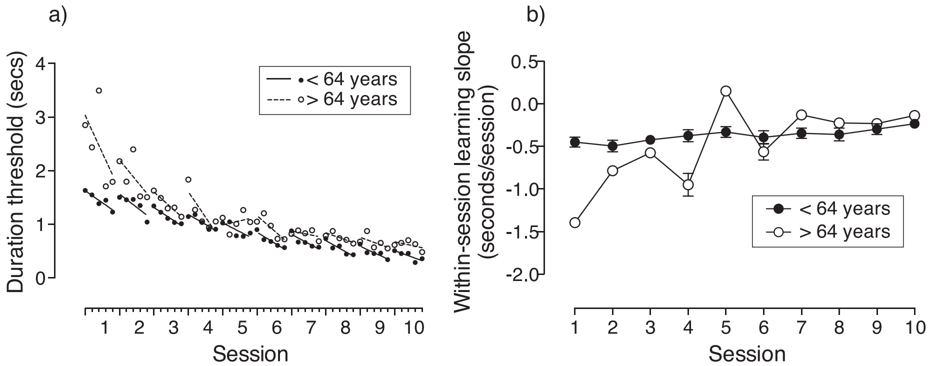

Figure 6. (a) Mean peripheral word identification speed for younger (<median age of 64 years) and older (>median age of 64 years) participants with normal vision as a function of training session. Circular points represent mean peripheral word identification speed on each run. Solid and dashed lines show linear regression curves fitted through the word identification data for each session for the younger and older groups, respectively. (b) Within-session learning rate as a function of session. A negative slope corresponds to a within-session improvement in performance, whereas a positive slope indicates that participants got worse on the task during the session. Error bars show R^2 of linear regression curves fitted to mean threshold data for each run on individual sessions (see lines in panel a).

and can be calculated from the rate constant as follows: $\ln(2)/k$. Word identification duration thresholds halved in 6.10 sessions for the younger group and 2.25 sessions for the older group, indicating that word identification speed improved more rapidly in the older group.

Within-session improvements in peripheral word identification speed are greater in older adults

Figure 6a shows mean word identification duration thresholds on each run for younger and older participants as a function of session. Up to five runs were completed per training session. A linear regression curve was fitted through the mean threshold for individual runs on each session. The slope of the linear regression curves fitted to data for each session provides a measure of the within-session learning. A negative slope corresponds to a within-session improvement in performance, while a positive slope indicates participants got worse on the task during the session. Figure 6b shows the slope of the linear regression fits for each session (in Figure 6a) as a function of session for younger and older participants. The within-session learning slope is negative in the younger and older groups for all sessions apart from one (on session 5 it was positive in the older group). This suggests that overall improvements in peripheral word identification speed were associated with within-session improvements. The within-session rate of learning was more negative for the older participants compared to the younger participants for the first four sessions. Therefore, for the first few sessions, older participants improved at a greater rate within each session relative to younger participants. The rate of within-session improvements was slower for later sessions compared to earlier sessions, consistent with the fact that the improvements in threshold are greatest toward the start of training and reduce exponentially for subsequent sessions (Figure 4).

Although there was learning within sessions, Figure 6a indicates there was often a reduction, or lapse, in performance between the final run of one session and the first run of the next session. Aging has previously been shown to increase the size of lapses between training sessions for a trigram letter-recognition task (Chung et al., 2004; Yu, Cheung et al., 2010), contributing to less learning in older participants over the course of training. To examine whether lapses in performance between sessions could explain the differences in the amount of learning between the younger and older participants, we calculated the difference in threshold between the final run on one session and the first run on the next session. A positive lapse corresponds to an increase in duration threshold from one session to the next (i.e., the participant got worse at the task between sessions), while a negative lapse indicates the reverse. The mean lapse size for younger and older participants across sessions was 0.13 ($\pm$0.15) and 0.09 ($\pm$0.32), respectively, and there was no significant difference in the mean lapse size between the younger and older participants, $t(18) = 0.37$, $p = 0.72$. In addition, there was no significant relationship between the lapse size and participant age, $R^2 = 0.0074$, $F(1, 18) = 4.42$, $p = 0.037$. This indicates that differences in the amount of learning found between different aged participants was not due to differences in the lapse in performance between sessions.

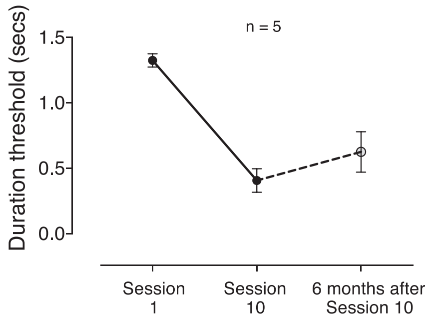

Figure 7. Peripheral word identification speed on session 1, session 10, and 6 months following training in five participants with normal vision (48 ± 18 years of age). Error bars show *SEM*.

Changes in peripheral word identification speed are not associated with changes in crowded visual acuity

Crowded visual acuity was measured at 10° above fixation in eight participants with normal vision who underwent word identification training and in eight control participants with normal vision who did not undergo any training. Crowded visual acuity in normal participants who underwent training was 1.36 (±0.07) on session 1 and 1.14 logMAR (±0.15) on session 10. In the control group, crowded visual acuity was 1.22 (±0.09) on initial measurement and 1.07 logMAR (±0.09) when measured 2–3 weeks later. The change in visual acuity in the trained group was not significantly different to that in the control group, $t(14) = 1.81$, $p = 0.091$. The change in visual acuity in the trained group can therefore be explained by the test–retest variability and is unlikely to be related to improvements in word identification speed.

Improvements in peripheral word identification speed endure for at least 6 months

Word identification speed was measured 6 months after training in five participants with normal vision who underwent training. Figure 7 shows word identification speed for these five participants on session 1, session 10, and 6 months after training. A one-way repeated measures ANOVA was used to compare mean word identification for each time point. There was a significant change in word identification speed, $F(2, 8) = 47.67$, $p < 0.0001$, with post hoc analysis indicating that there was a difference between word identification speed on session 1 and session 10 ($p < 0.0001$), but no difference between session 10 and 6 months after training ($p = 0.16$). Therefore, improvements in word identification speed were maintained at least 6 months after the training period.

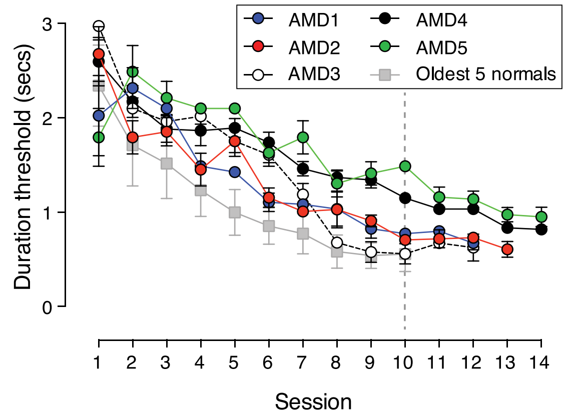

Figure 8. Word identification threshold as a function of training session for each participant with AMD (76 ± 6 years of age) and five age-matched participants (71 ± 2 years of age) with normal vision. Error bars show *SEM*.

Peripheral word identification speed improves in participants with AMD following training

Five participants with AMD were trained with the same word identification task as normal participants, completing three to five staircases per session, to determine whether similar improvements could be achieved in a group likely to benefit from better peripheral reading ability. Figure 8 shows word identification duration thresholds as a function of session for each participant with AMD. There was significant improvement in mean word identification speed from session 1 (2.41 ± 0.49 seconds) to session 10 (0.93 ± 0.38 seconds), $t(4) = 4.14$, $p = 0.007$. Participants continued to train for up to four additional sessions.

Peripheral word identification speed in participants with AMD compared to age-matched participants with normal vision

Average word identification duration thresholds were not significantly different for the older group of 10 participants with normal vision (2.54 ± 0.95 s; i.e., those over 64 years of age and shown in Figure 4b and Figure 6), and participants with AMD (2.41 ± 0.49 s) on session 1, $t(13) = 0.29$, $p = 0.78$. However, the mean age of the participants with AMD (76 ± 6 years) was greater than the mean age of the oldest group of 10 participants with normal vision (68 ± 3 years), $t(13) = 3.53$, $p = 0.004$.

To make a fairer comparison between learning in participants with AMD and those with normal vision, the results for the participants with AMD were compared to results for the five oldest participants with normal vision. The mean age of the five oldest

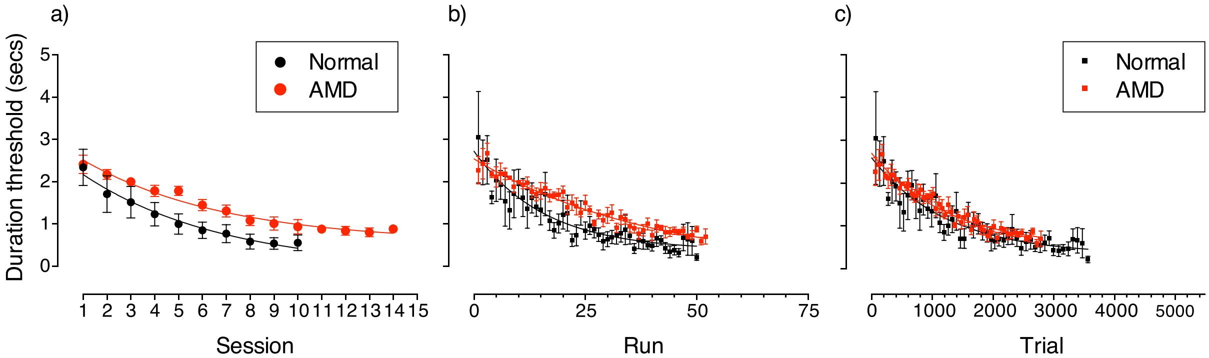

Figure 9. Word identification duration thresholds for participants with AMD ($n = 5$, 76 ± 6 years of age) and age-matched participants with normal vision ($n = 5$, 71 ± 2 years of age) as a function of (a) training session, (b) number of runs/staircases completed, and (c) number of trials completed. Error bars show *SEM*.

participants with normal vision (71 ± 2 years) was matched with the mean age for the participants with AMD (76 ± 6 years), $t(8) = 2.009$, $p = 0.079$. In addition, there was no significant difference in mean duration thresholds on session 1 between five oldest participants with normal vision (2.34 ± 0.96 s) and the participants with AMD (2.41 ± 0.49 s), $t(8) = 0.89$, $p = 0.15$. Figure 8 shows the mean word identification duration thresholds on each session for the five oldest participants with normal vision and each participant with AMD.

Figure 9a shows word identification duration thresholds as a function of training session for the two groups (i.e., the participants with AMD and the five oldest participants with normal vision). Rate of improvement was faster in the normal participants, halving in 2.49 sessions compared to 5.67 sessions in the participants with AMD. On session 10, the mean duration threshold for the participants with AMD was 0.93 (±0.38) compared to 0.56 (±0.41) for the participants with normal vision.

Could the differences in the amount and rate of learning in participants with AMD and those with normal vision be due to differences in the amount of training completed by each group? Participants with AMD found the task more difficult and became tired more quickly than the participants with normal vision. Consequently, participants with AMD completed fewer staircases (runs) per session (3.94 ± 0.70) compared to age-matched participants with normal vision (4.96 ± 0.20), $t(113) = 9.95$, $p < 0.0001$. Therefore, differences in the amount and rate of improvement between participants with normal vision and those with AMD might be due to differences in the amount of training in terms of runs completed by each group. Figure 9b shows mean word identification duration thresholds as a function of run. Even when analyzed on an equivalent run-by-run basis, participants with AMD improved at a slower rate compared to normal participants.

Staircases terminated after eight reversals and, therefore, the number of trials per run varied. The average number of trials per run for participants with AMD was lower (211 ± 28) compared to that for age-matched controls (357 ± 25), $t(99) = 10.61$, $p < 0.0001$. Figure 9c shows mean word identification duration thresholds as a function of trial. When performance is considered as a function of trial number, learning curves for participants with AMD and age-matched normal participants appear relatively similar. Therefore, performance on the trained task and the rate and magnitude of improvement appears to be closely related to the amount of training in terms of the number of trials completed.

Discussion

We have shown that the speed at which participants with normal vision identify crowded words presented in the peripheral visual field improves significantly following training. At the start of the training period, older participants were slower at identifying words. Improvements on the task were associated with age and word identification speed at the start of training. Larger, more rapid improvements were found in older participants. Participants were as good as each other at identifying words at the end of training, regardless of their age or how good they were at the start of the training period. In addition, improvements in performance were maintained for at least 6 months. These results are consistent with those of previous studies (Andersen et al., 2010; Chung et al., 2004; Richards, Bennett, & Sekuler, 2006), which showed that improvements following training were retained when participants were retested 3 months after cessation of training.

In addition to addressing age-related differences in perceptual learning, our results are relevant to work that has investigated perceptual learning in different clinical groups. For example, the results are of relevance to studies investigating perceptual learning in amblyopia, since there are a number of similarities between the normal periphery and a subtype of amblyopia (Levi, Klein, & Yen Lee, 1987) and in patients with AMD, as this condition results in loss of central vision in elderly individuals who then rely on their peripheral visual field to perform everyday tasks. We tested directly whether the approach can benefit individuals with AMD and found significant improvements in word identification performance in these participants. Our findings suggest that perceptual learning can be used to improve peripheral word identification irrespective of patient age or presence of AMD.

Like many visual functions (Andersen, 2012; Faubert, 2002; Owsley, 2011), word identification speed slowed with increasing age. Since we used a crowded word identification task, differences in word identification speed between individuals could have been due to differences in crowded visual acuity. However, crowded letter recognition in the peripheral visual field of normal participants does not change significantly with age (Astle, Blighe, Webb, & McGraw, 2014) and, thus, differences in word identification speed are more likely to reflect differences in temporal processing. Temporal processing speed for identifying strings of random letters has been shown to be slower in the peripheral visual field compared to central vision (Cheong et al., 2007). Previous studies have shown reductions in processing speed as part of normal aging (Salthouse, 1996) and, therefore, it is feasible that temporal processing speed for word identification in the peripheral visual field may reduce with age.

Differences in learning found between individuals were associated with differences in performance at the start of training. We previously investigated the effect of performance prior to training on a peripheral Vernier alignment task. Equating performance before training by scaling the stimuli or by modifying the amount of crowding exerted by changing the spatial separation between the targets and flanking objects lead to equivalent amounts of improvements on the trained task and transfer to nontrained task conditions (Astle, Li, Webb, Levi, & McGraw, 2013). Therefore, the fact that those with worse performance at the start of training improved more than those with better performance is consistent with our previous findings and those of others (Astle et al., 2013; Fahle & Henke-Fahle, 1996). The results suggest that age has a similar effect on threshold and subsequent learning as modifications made at the level of the stimulus.

Differences in the amount of improvement between individuals could be explained by age differences. Indeed, previous studies have found differences in the amount of perceptual learning that may be associated with the age of the participants. For example, a study that trained visual span in elderly participants with normal vision (Yu, Cheung et al., 2010) found an improvement that was smaller than that found in a study that trained younger participants with normal vision on a similar training task (Chung et al., 2004). This would suggest smaller improvements in the magnitude of perceptual learning would be expected in older participants in the present study. In contrast, improvements in reading speed found in AMD patients (Chung, 2011) following RSVP training were larger (53%) than those found in a group of younger patients with juvenile macular degeneration who underwent RSVP training (25%; Nguyen, Stockum, Hahn, & Trauzettel-Klosinski, 2011), suggesting the reverse. Caution should be taken in comparing the amount of learning found between different studies. Aside from methodological differences associated with the tasks trained, improvements following training may vary from study to study depending on the criterion level of accuracy chosen: larger improvements are expected for higher compared to lower criterion levels of accuracy (Coates & Chung, 2014).

We determined the effect of age on the amount of learning on a word identification task that lead to improvements in participants with AMD in a single study, which avoids the problems associated with comparing results between studies. Our results provide strong evidence for significant visual plasticity in older adults. Indeed, improvements were linked to participant age with older participants improving more than younger participants. A number of other studies have investigated the effect of age on perceptual learning within a single study. Studies in which performance on the trained task was the same at the start of training, decoupling the relationship between age and initial task performance, found similar amounts of improvements between younger and older participants (Andersen et al., 2010; Ball & Sekuler, 1986; McKendrick & Battista, 2013) also suggesting that significant visual plasticity is retained in older individuals.

We trained participants with normal vision and those with AMD at an equivalent retinal eccentricity. This may explain why we found relatively consistent levels of improvement and rates of learning. If we were to have trained participants at their PRLs, which would have been located in different regions of the visual field, we are likely to have found much more variability between improvements for the participants with AMD (Chung, 2011). Having trained normal participants at the same location, it is easier to compare improvements with participants with AMD. Our results demonstrate that the peripheral visual field in individuals with AMD behaves in a similar way to the normal periphery with performance on visual tasks improving with practice.

The differences in learning found between the AMD patients and age-matched controls appear to be quantitative rather than qualitative; therefore, in principle, using age-matched participants with normal vision to investigate improvements in patients with AMD seems valid. Differences in the rate and amount of improvement in participants with AMD compared to age-matched normals cannot be explained by age or performance at the start of training. However, performance appears to be determined by the amount of training in terms of number of trials is received.

It is useful to know that a location other than a patient's PRL can be improved with training as AMD patients rarely select the optimum location for the PRL (Fine & Rubin, 1999; Petre et al., 2000). Our results provide evidence that visual performance at a new location can be improved, which would be useful in cases in which disease progress means that patients must adopt a new PRL. Participants were trained at 10° from the fovea. Since most scotomas do not extend further than 10° from the fovea (Chung & Legge, 2005), and visual acuity and reading speed decrease with increasing eccentricity, the location trained represents (a) a worse-case scenario in which PRLs are likely to be closer to the fovea and offer better levels of vision and (b) a location that is less likely to be affected by AMD than more central locations.

A number of studies have shown that perceptual learning can lead to improved peripheral reading speed in normally sighted participants (for a review see Pijnacker, Verstraten, van Damme, Vandermeulen, & Steenbergen, 2011). These studies employed a range of different training protocols including training to recognize random strings of letters (Chung et al., 2004; Lee et al., 2010; Yu, Cheung et al., 2010; Yu, Legge, Park, Gage, & Chung, 2010), whether a presented string of letters formed a word or nonword (Yu, Legge et al., 2010), and RSVP training (Yu, Legge et al., 2010). In contrast, the present study trained participants on a crowded word identification task, in which participants were required to identify a three-letter word flanked either side by a random letter. Following on from this study, we aim to investigate whether a similar training task results in improvements for more traditional reading of sentences of lowercase words surrounded by other words in the normal periphery and at the PRL of AMD patients. Sentence reading differs from identification of single words. For example, unlike peripheral word identification, reading of sentences in the periphery cannot be matched to foveal performance by scaling the size of letters (Chung, Mansfield, & Legge, 1998; Latham & Whitaker, 1996).

In principle, the improvements we found could be due to changes in the magnitude of visual crowding. The three-letter words were displayed between two random letters to control for crowding effects on each of the three letters that made up each word. A number of studies have demonstrated that visual crowding in the peripheral visual field can be improved with practice (Chung, 2007; Chung et al., 2004; Hussain et al., 2012). However, the improvements in word identification in the present study are unlikely to be due to changes in crowding, since changes in crowded visual acuity could be explained by test–retest variability in a sample of participants with normal vision who underwent training.

A previous study reported improvements in reading ability in patients with AMD were not related to changes in the fixation location or fixation stability (Chung, 2011). Because the majority of participants with AMD in the present study had AMD in only one eye and were therefore unlikely to have an established PRL, their fixation stability is probably worse than that found in the previous study (Chung, 2011). Therefore, we cannot fully rule out the possibility that the improvements observed are not associated with changes in fixation stability or fixation location. However, in the present study, performance on the first session and the size of improvements found for participants with AMD were similar to those found for participants with normal vision, for whom fixation is normal. Therefore, we believe improvements in performance found in participants with AMD are unlikely to be due to changes in eye movements. We aim to explore whether training on the crowded word identification task affects eye movements and, if so, if training contributes to changes in page-mode reading and other measures of functional vision. Other factors that might affect learning in AMD patients on this task that could be investigated in the future include time since onset of AMD, and AMD subtype.

Furthermore, improvements in peripheral reading speed have been shown to be independent of allocation of attentional resources (Lee et al., 2010). Therefore, improvements are likely to reflect enduring cortical plasticity in elderly patients. Indeed, a recent study has shown that perceptual learning in AMD patients is accompanied by a change in the blood oxygen level dependent (BOLD) response in early visual cortex (Plank et al., 2014).

Conclusions

Word identification speed can be improved significantly in younger and older participants with normal vision and these improvements are relatively long lasting. Even though older participants are initially slower at identifying words, they improve more rapidly than younger participants, such that their performance reaches that of their younger counterparts. Our results provide strong evidence for significant levels of plasticity in older adults. Peripheral word identification can also be improved in patients with an age-related visual disorder using the same task. For a given number of trials, the amount of learning is similar in AMD patients and normal participants. Our results highlight the potential utility of perceptual learning protocols to improve sensory decline that results from normal aging and in patients with age-related pathologies.

Keywords: perceptual learning, aging, age-related macular degeneration, reading

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Corresponding author: Andrew T. Astle.
Email: andrew.astle@nottingham.ac.uk.
Address: Visual Neuroscience Group, School of Psychology, University Park, University of Nottingham, Nottingham, UK.

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