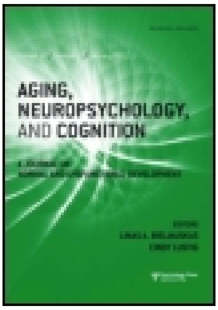

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Rehabilitation of reading in older individuals with macular degeneration: A review of effective training programs

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ABSTRACT

Macular degeneration (MD) is the most common cause of visual impairment among older adults. It severely affects reading performance. People with MD have to rely on peripheral vision for reading. In this review, we considered several training programs that aim to improve peripheral reading, with a focus on eccentric viewing, oculomotor control, or perceptual learning. There was no strong support in favor of one particular training method for rehabilitation of reading in MD, but there is evidence that older individuals with MD can be trained to improve reading performance, even within limited time.

Keywords: Reading; Rehabilitation; Low vision; (Age-related) macular degeneration; Central vision loss.

Macular degeneration (MD) involves a progressive loss of central vision due to damage of the macula. In later stages, it severely impairs visual acuity, and therefore, activities like reading, watching television, and driving become difficult or may even be impossible. Though central vision is affected, peripheral vision usually remains preserved in MD. The most common form of MD is age-related macular degeneration (AMD), but there is also a juvenile form in younger people (JMD).

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AMD is one of the leading causes of visual impairment among older individuals in developed countries (Congdon et al., 2004; Klaver, Wolfs, Vingerling, Hofman, & de Jong, 1998). Risk factors for developing AMD include aging, genetic heredity, smoking, and obesity (Jager, Mieler, & Miller, 2008). There are two major types of AMD: dry AMD ('atrophic') and wet AMD ('exudative' or 'neovascular'). Dry AMD is the most frequent type and accounts for most occurrences of AMD (Jager et al., 2008). It is typically characterized by a gradual loss of central vision over the course of months to years. Wet AMD is far less common than dry AMD, but can develop very fast with severe loss or distortion of vision within weeks or even days. People with AMD usually develop a central scotoma, which is an area of absent vision within the visual field (absolute scotoma) or of diminished light perception (relative scotoma).

Given that the population is aging in developed countries, the prevalence of AMD is expected to increase rapidly. It has been estimated that there will be more than 3 million people with AMD in Western Europe in 2020 (Friedman et al., 2004). Because up to now, there is a lack of effective medical treatment for most occurrences of AMD, it is important to focus rehabilitation efforts on compensatory mechanisms. In particular, rehabilitation programs are needed that allow persons with AMD to continue or resume daily living activities, such that independence of living can be maintained. Of these daily living activities, reading is often one of the primary rehabilitation goals (Owsley, McGwin, Lee, Wasserman, & Searcey, 2009). For rehabilitation purposes, it is important to know whether and how people with MD can compensate for their visual impairments when reading. Therefore, the main purpose of this review is to evaluate the available training programs that aim to improve reading in persons with MD. More specifically, we focus on training programs that aimed at learning to adapt to the loss of central vision (sometimes in combination with magnification) through eccentric viewing training, eye movement control or perceptual learning. We excluded studies that focus exclusively on the use of reading aids like magnifiers, telescopes, and electronic aids. For a systematic review on reading aids for low vision, see Virgili and Acosta (2006).

In order to understand the consequences of having central vision loss for reading and the possibilities for rehabilitation, we will first describe reading characteristics in individuals with MD (see Box 1 for characteristics of normal reading), and elaborate on a compensatory mechanism to central vision loss. Second, the available training programs that aim to improve reading in MD are presented, followed by a final section in which the available reading training programs will be evaluated and the implications for rehabilitation practice will be discussed.

Fixations and saccades

Reading is a complex skill that involves visual processing, oculomotor control and cognitive processing. As we read, our eyes do not move smoothly along a line of text, but move with a series of rapid eye movements (saccades) alternated by pauses (fixations). During a fixation the eyes remain relatively still for about 200–300 ms and visual information is extracted (Rayner, 1998, 2009). A fixation is followed by a saccade. Saccades are fast eye movements, which are necessary because of limitations in visual acuity outside the fovea (Rayner, 1998, 2009). Because reading requires high visual acuity for letter discrimination, saccades move the eyes so that a piece of text is placed on the fovea.

There are forward saccades in which the eyes move forward along a line of text, and regressions whereby the eyes move backwards. Most saccades are forward saccades. Only 10–15% of the saccades are regressions (Rayner, 1998, 2009). Regressions are usually related to difficulties in text processing (Rayner, 1998). Furthermore, at the end of a line of text, a large saccade (the return sweep) is made to the beginning of the next line. Finally, small corrective saccades are made to correct for oculomotor errors like overshoots or undershoots, or to maintain fixation stability.

Visual span and perceptual span (Figure 1)

Visual span is the number of letters in a line of text that can be recognized accurately without moving the eyes (Legge et al., 2007). Normally sighted readers can recognize up to 10 characters during a single fixation, depending on variables such as print size and contrast (Legge, Ahn, Klitz, & Luebker, 1997; Legge, Mansfield, & Chung, 2001). Visual span must be distinguished from perceptual span, which refers to the region from which readers extract useful information to guide saccades and fixation duration (Findlay & Gilchrist, 2003; Legge et al., 1997; Rayner, 1998).

The perceptual span is determined both by structural and attentional factors, and includes useful information about word boundaries, word length and word initial letters (Findlay & Gilchrist, 2003; Rayner, 1998). The perceptual span extends to 14–15 characters to the right of fixation, but only 3–4 characters to the left of fixation (Rayner, 1998), and is thus largely asymmetric to the right, at least in left-to-right printed language. For right-to-left printed languages (e.g., Arabic, Hebrew), the asymmetry is reversed. This asymmetry is functional, because it enables the reader to have a preview of the word adjacent to fixation. Such a preview guides saccade planning, that is, how far the eyes have to move for the next fixation. The size of perceptual span is not constant, but is influenced by several factors such as text difficulty, reading skill, and characteristics of the writing system (Findlay & Gilchrist, 2003; Rayner, 1998).

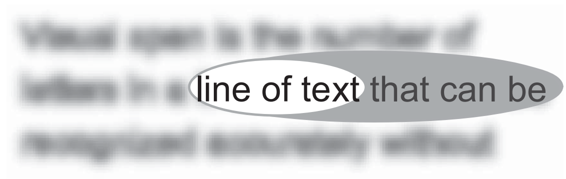
How to measure reading ability?

Reading ability is often assessed by measuring reading rate (i.e., the number of words or syllables read per minute). Reading rate is usually established by oral reading of sentences (e.g., MNREAD Charts, Radner Reading Charts), paragraphs or texts. Another method is Rapid Serial Visual Presentation (RSVP) of sentences. Here are the words of a sentence presented sequentially, one word at a time. The need for eye movements is minimal in RSVP and much higher levels of reading speed can be achieved. So far, there is a lack of standardized reading texts that are available in different languages, but currently the development of one standardized reading text is in progress (International Reading Speed Texts (IReST), see www.amd-read.net). Another method for investigating reading ability is eye tracking in which fixations and saccades during reading can be precisely registered.

Oral reading rate in normally sighted people depends on various factors like reading purpose, text characteristics, and reading skill (Findlay & Gilchrist, 2003; Whittaker & Lovie-Kitchin, 1993). The average reading rate of page mode reading is about 250–300 wpm, whereas RSVP text reading can be faster than 1000 wpm (Findlay & Gilchrist, 2003; Rubin & Turano, 1992).

Box 1. Characteristics of normal reading.

FIGURE 1. Schematic illustration of the visual span (white oval) and perceptual span (grey oval) in normal reading.



READING AND MACULAR DEGENERATION

Characteristics of Reading in Persons with Central Vision Loss

People with advanced MD often have a scotoma in their central vision, which can extend to a large area of the visual field. A central scotoma affects the fovea, which is the center of the macula, with highest visual acuity. Visual acuity decreases rapidly as the distance from the fovea increases. Reading with a central scotoma is very difficult, because the scotoma is constantly obscuring the characters to be read. Because people with advanced MD cannot longer use the fovea for reading, they must rely on a peripheral retinal area compensating for the damaged fovea. A major problem is that visual acuity and contrast sensitivity are largely reduced in the peripheral retina. To compensate for this acuity loss, magnification—large print size or a magnifier—is required for peripheral reading. However, even with sufficient magnification, peripheral reading remains difficult and slow (Chung, Mansfield, & Legge, 1998).

Several factors have been proposed that limit reading rate in peripheral vision, of which visual span size has been shown to be an important one (see Box 1; Legge et al., 2001, 2007). Even when appropriately compensated for differences in visual acuity, visual span appears to be smaller in peripheral vision, which has an adverse effect on letter and word recognition (Legge et al., 2001, 2007). There is evidence that a smaller visual span in peripheral vision is at least partly due to crowding,[1] which is stronger at higher eccentricity (Pelli et al., 2007; Sommerhalder et al., 2003). Furthermore, Cheong, Legge, Lawrence, Cheung, and Ruff (2007, 2008) showed that participants with AMD needed more time for letter and word recognition in comparison with participants with normal peripheral vision. They suggested that slow visual processing of letter recognition in combination with a smaller visual span is a limiting factor on reading rate in AMD. This slow visual

[1] Crowding (also called lateral masking) refers to the phenomenon that it is more difficult to recognize a letter that is flanked by other letters than one in isolation. It involves spatial interference between adjacent letters.

processing in AMD might be due to concomitant retinal pathology outside the central scotoma, or fixation instability (Cheong et al., 2007, 2008). Other research has indicated that a reduced perceptual span is limiting reading rate in peripheral reading (Bullimore & Bailey, 1995; Crossland & Rubin, 2006). As mentioned in Box 1, perceptual span is important for saccade planning. A smaller perceptual span will therefore adversely affect reading speed.

Another factor that is limiting reading rate in peripheral reading is poor oculomotor control. There is evidence that peripheral reading involves both adaptation of eccentric fixation and of saccadic control (Fornos, Sommerhalder, Rappaz, Pelizzone, & Safran, 2006; Safran & Landis, 1996; White & Bedell, 1990; Whittaker, Cummings, & Swieson, 1991). Adaptation to use the peripheral retina for fixation instead of the fovea, appears to take place relatively fast, for instance, people with a simulated central scotoma adapted to eccentric viewing within 5 hours reading practice without any instruction (Varsori, Perez-Fornos, Safran, & Whatham, 2004). However, adaptation of saccades to use a peripheral retinal area as reference point is more demanding, because the reflex to direct the eyes to the fovea ('foveating' saccades) has to be overcome (Fornos et al., 2006; White & Bedell, 1990; Whittaker et al., 1991). Moreover, 'nonfoveating' saccades are slow and less accurate than 'foveating' saccades (Fornos et al., 2006; Whittaker et al., 1991).

Research on oculomotor patterns in AMD have found that a reduced reading rate was associated with a decreased size of forward saccades, and an increased number of regressions (Bullimore & Bailey, 1995; Crossland & Rubin, 2006; Rubin & Feely, 2009). Fixation duration did not seem to be related to reading speed in AMD (Bullimore & Bailey, 1995; Crossland & Rubin, 2006; Rubin & Feely, 2009). Finally, there is evidence that there is a relationship between reading rate and fixation stability in AMD (Crossland, Culham, & Rubin, 2004; Rubin & Feely, 2009; Schuchard, 2005). Fixation stability refers to the ability to maintain a visual image in a discrete and stable retinal area during fixation: the larger that retinal area, the more unstable fixation. Though fixation instability seems disadvantageous for reading, Deruaz et al. (2004) suggest that it may have a functional advantage in terms of compensation for perceptual fading of eccentrically fixated letters or words, and thus may actually improve text perception.

Compensatory Mechanism: The Preferred Retinal Locus

As described above, people with central scotomas have to use an intact part of the peripheral retina for fixation instead of the damaged fovea. Such an eccentric location is commonly referred to as preferred retinal locus[2]

[2] In principle, the fovea can be considered as the PRL for normally sighted persons, but the term PRL is usually used to refer to the preferred eccentric retinal area for fixation in people with central scotoma.

(henceforth PRL). Because the PRL substitutes the damaged fovea, it is also called 'pseudo-fovea'. PRLs often develop spontaneously, though patients are not always aware that they use a peripheral retinal area for fixation (Crossland, Culham, Kabanarou, & Rubin, 2005; Fletcher, Schuchard, & Watson, 1999; Schuchard, 2005).

For rehabilitation purposes, it is important to know what retinal location is optimal for eccentric fixation. However, there is no decisive evidence about this issue so far. First, PRLs have been found in any direction around the central scotoma (Fletcher & Schuchard, 1997; Fletcher et al., 1999; Sunness, Applegate, Haselwood, & Rubin, 1996). Second, there are patients with central scotomas who use multiple, possibly task-specific PRLs (Deruaz, Whatham, Mermoud, & Safran, 2002; Duret, Issenhuth, & Safran, 1999; Timberlake, Sharma, Grose, & Maino, 2006). Finally, MD patients may not always choose an optimal PRL spontaneously.

MD patients are likely to adopt a PRL close to the scotoma boundary, usually to the left of, or below the central scotoma (Crossland et al., 2005; Fletcher & Schuchard, 1997; Guez, Le Gargasson, Rigaudiere, & O'Regan, 1993; Sunness et al., 1996; Timberlake, Mainster, & Peli, 1986; White & Bedell, 1990). A left-field PRL (a PRL located in the visual field to left of the scotoma) has been argued to be disadvantageous for reading, as the upcoming text will fall into the scotoma (Guez et al., 1993; Sunness et al., 1996). Though unfavorable, a left-field PRL may be chosen that often because left-to-right readers need to monitor the landing position of the eyes relative to word on the left in the previous fixation (Guez et al., 1993).

It has been proposed that a PRL above or below the central scotoma is more favorable for peripheral reading. In that case, a line of text can be read without being obscured by the scotoma and the peripheral retinal area is wide enough to accommodate about 4–10 characters that are required for effective reading (Legge et al., 2008; Nilsson, Frennesson, & Nilsson, 1998, 2003). Still, these arguments are inconsistent with empirical findings obtained from people with simulated central scotoma. Both Fine and Rubin (1999) and Lingnau, Schwarzbach, and Vorberg (2008) found that a right-field PRL is most beneficial for reading with simulated central scotoma. Only in case of a right-field PRL, there is no conflict between eye movements in text direction and shifting attention to the PRL (Lingnau et al., 2008). Remarkably, the position of the PRL was shown not to affect reading rate in patients with central scotoma (Crossland & Rubin, 2006; Fletcher et al., 1999; Rubin & Feely, 2009). Other factors such as fixation stability and saccade control rather than PRL position were associated with reading rates (Fletcher et al., 1999; Rubin & Feely, 2009).

Though the choice for the PRL position is still unclear, there seems to be an interplay of several factors such as visual acuity, visual span size, oculomotor control, and attention that determines the position of the PRL (Cheung & Legge, 2005; Duret et al., 1999; Guez et al., 1993; Lingnau et al., 2008; Timberlake, Peli, Essock, & Augliere, 1987). With regard to rehabilitation, it is more relevant to find out how patients can be trained to use an eccentric retinal area for fixation. We will discuss this issue in more detail in the section entitled 'Eccentric Viewing Training'.

READING TRAINING PROGRAMS FOR MACULAR DEGENERATION

Review of Available Studies

In the following sections, we will review and evaluate available research on training programs that aimed to improve reading in MD. We grouped the training programs into three different categories based on their specific approach, namely training programs that focus on: (1) eccentric viewing; (2) eye movement control; and (3) perceptual learning. It is important to point out that these approaches are not completely independent from each other. For example, training eye movement control may also improve eccentric viewing, and vice versa, training eccentric viewing may improve eye movement control as well.

Relevant publications were identified by means of database searches and citation tracking. The databases PsychINFO, Medline and EMBASE were searched for publications in the period 1980–May 2011 using the following search terms: (*macular degeneration; central scotoma; macular disease; retina macula degeneration; retina maculopathy; retina macula age related degeneration*) and *reading*. Only publications that focused on reading training programs were included. In addition, references of the selected publications were checked for relevant publications that were not covered by the database searches. Publications about low vision reading aids only were excluded. In total, 18 studies were included.

Though the focus of this review is on MD in older individuals, about half of the patient studies included both participants with AMD and JMD. Because research on this topic is rather limited and all cases involved central vision loss, we did not exclude these studies. Moreover, only 2 patient studies reported an average age below 59 years old, and even 8 out of the 13 patient studies reported an average age over 70 years. Nonetheless, we should not disregard the role of age in rehabilitation effects.

For objective comparison of the different training programs, we will compare the included studies on one common outcome measure, namely reading speed, though most studies also reported other outcome measures such as reading acuity, fixation stability, and visual span size. Likewise, in order to make training effects comparable, studies that did not report reading rates are not included in the review. An overview of the 18 included studies and their characteristics can be found in Table 1. The main findings of these studies are reported in Table 2 and Figure 2. In the next sections, we will describe the training programs in detail.

TABLE 1. Characteristics of the included studies

Included study	Characteristics	
Chung et al. (2004)	*Participants*	$n = 12$ with normal vision Control group: $n = 6$ with normal vision Form: forced eccentric viewing at 10° below ($n = 6$) or above ($n = 6$) fixation Age: 24 [19–30] Visual acuity: ≥1.0
	Intervention	Perceptual learning using trigram letter-recognition (10° below or above fixation)
	Duration	6 hours over 4 sessions, 1300 trigram trials per session
	Measure	Sentences presented with RSVP, taken from novels
Chung (2011)	*Participants*	$n = 6$ Control group: no Form: AMD $n = 4$, JMD = 2 Age: 74 ± 12 [57–85] years Visual acuity: 0.23 ± 0.09 [0.08–0.33]
	Intervention	Perceptual learning using oral reading of single sentences (RSVP)
	Duration	6 sessions, 300 sentences per session
	Measure	Sentences presented with RSVP, taken from Visual Stimulus Generator
Frennesson et al. (1995)	*Participants*	$n = 10$ Control group: no Form: advanced bilateral AMD Age: 80 ± 6 [71–88] years Visual acuity: 0.035 ± 0.016 [0.015–0.07]
	Intervention	Stepwise eccentric viewing training
	Duration	2.6 ± 0.7 hours
	Measure	Paragraphs from non-fiction book
Gustafsson et al. (2004)	*Participants*	$n = 9$ Control group: no Form: AMD $n = 2$, JMD $n = 3$, $n = 4$ other etiology for central scotoma Age: 46 [33–81] years Visual acuity: 0.03–0.16
	Intervention	Eccentric viewing training; scrolled text
	Duration	3 hours + 10 hours [0–30] home training
	Measure	3-minutes text reading
Hall and Ciuffreda (2001)	*Participants*	$n = 10$ Control group: $n = 5$ with normal vision Form: wet AMD $n = 3$, dry AMD $n = 3$, JMD $n = 4$ Age MD: 65 ± 15 [43–84] years; age controls: 71 ± 10 [62–81] Visual acuity: 0.19 ± 0.13 [0.08–0.5]
	Intervention	Eye movement control by auditory oculomotor feedback
	Duration	1.5 hours over 6 sessions
	Measure	Standardized 100-word paragraphs

(*Continued*)

Table 1. (Continued)

Included study	Characteristics	
Kasten et al. (2010)	*Participants*	$n = 14$ Control group: no Form: bilateral central scotoma (dry AMD, wet AMD, JMD, other) Age: 59 ± 23 [22–86] Visual acuity: 0.09 ± 0.07 [0.01–0.25]
	Intervention	Eccentric viewing training; computer training for at home
	Duration	–
	Measure	Sentences (Radner Reading Charts)
Lee et al. (2010)	*Participants*	$n = 10$ with normal vision Control group: $n = 10$ with normal vision Form: forced eccentric viewing at 10° below or above fixation Age: 23 [18–41] Visual acuity: 1.5 [0.56–2]
	Intervention	Perceptual learning using trigram letter-recognition (10° below or above fixation)
	Duration	10 hours over 4 sessions, 1300 trigram trials per session
	Measure	Sentences presented with RSVP, taken from novels
Nguyen et al. (2011)	*Participants*	$n = 36$ Control group: no Form: JMD Age: 31 [23–40] Visual acuity: 0.1 [0.1 – 0.25]
	Intervention	1. RSVP; 2. sensomotoric training (both home-based computer training)
	Duration	10 hours over 20 sessions
	Measure	100-word text passages
Nilsson et al. (1998)	*Participants*	$n = 6$ Control group: no Form: unilateral AMD Age: 71 (median) [61–79] years Visual acuity: 0.06 (median) [0.002–0.07]
	Intervention	Stepwise eccentric viewing training
	Duration	4–5 hours + home training
	Measure	3-minutes reading of novel text
Nilsson et al. (2003)	*Participants*	$n = 20$ Control group: no Form: advanced wet AMD Age: 77 ± 6 [64–86] Visual acuity: 0.042 ± 0.016 [0.02–0.08]
	Intervention	Stepwise eccentric viewing training
	Duration	5.2 ± 1.2 hours + home training
	Measure	3-minutes reading of novel text
Palmer et al. (2010)	*Participants*	$n = 242$ Control group: no Form: AMD Age: 75 ± 12 Visual acuity: –
	Intervention	Eccentric viewing training; manually moved text
	Duration	3.8 ± 1.6 hours + home training

(*Continued*)

Table 1. (Continued)

Included study	Characteristics	
	Measure	1-minute reading of text
Seiple et al. (2005)	*Participants*	$n = 16$ Control group: no Form: wet and dry AMD Age: 77 ± 6 [65–87] years Visual acuity: 0.18 [0.05–0.36]
	Intervention	Eye movement control training
	Duration	–
	Measures	Sentences (Woodcock Johnson II Exercises of achievement: reading fluency)
Seiple et al. (2011)	*Participants*	$n = 30$ Control group: $n = 6$ (no training) Form: dry AMD Age: 76 ± 8 [54–89] Visual acuity: 0.20 ± 0.18 [0.05–0.79]
	Intervention	1. Eccentric viewing training; 2. eye movement control; 3. reading practice
	Duration	12 hours over 6 sessions per training (36 hours in total)
	Measures	Sentences (adapted from Woodcock Johnson III Test: reading fluency)
Sommerhalder et al. (2004)	*Participants*	$n = 3$ with normal vision Control group: no, but same task for central reading with 10°×7° viewing window Form: forced eccentric viewing at 15° with 10°×7° viewing window Age: 26 ± 4 [23–30] years Visual acuity: 15° eccentricity ≈0.16
	Intervention	Perceptual learning of eccentric text reading
	Duration	±28–34 hours over 55–68 sessions
	Measure	100-word paragraphs from newspaper
Tarita-Nistor et al. (2009)	*Participants*	$n = 6$ Control group: no Form: advanced wet and dry AMD Age: 81 ± 5 [76–89] Visual acuity: 0.16 [0.06–0.25]
	Intervention	Eye movement control by auditory oculomotor feedback
	Duration	5 hours + home training
	Measures	Sentences (MNRead Test)
Vingolo et al. (2007)	*Participants*	$n = 15$ Control group: no Form: AMD Age: [64–85] Visual acuity: –
	Intervention	Eye movement control by auditory oculomotor feedback
	Duration	± 3 hours over 10 sessions
	Measures	Sentences
Yu, Cheung, et al. (2010)	*Participants*	$n = 9$ with normal vision

(*Continued*)

Table 1. (Continued)

Included study	Characteristics	
		Control group: $n = 9$ with normal vision
		Form: forced eccentric viewing at 10° below or above fixation
		Age: 65 ± 8 [55–76]
		Visual acuity: ≥1.0
	Intervention	Perceptual learning using trigram letter-recognition (10° below or above fixation)
	Duration	7 hours over 4 sessions, 880 trigram trials per session
	Measures	Sentences presented with RSVP, taken from novels
Yu, Legge, et al. (2010)	*Participants*	$n = 21$ with normal vision (3 types of training, $n = 7$ per group)
		Control group: $n = 7$ with normal vision
		Form: forced eccentric viewing at 10° below fixation
		Age: 20
		Visual acuity: ≥1.0
	Intervention	Perceptual learning using trigram letter-recognition, lexical decision, and RSVP
	Duration	4 hours over 4 sessions
	Measures	Sentences presented with RSVP, taken from novels

Notes: For age and (corrected) visual acuity, mean ± standard deviation are reported, unless otherwise mentioned. The range is denoted in brackets [ ]. Visual acuity is reported in Snellen decimals. If visual acuity was reported in logMAR, it was converted to Snellen decimals. The total duration of the training is reported.

Eccentric Viewing Training

Eccentric viewing training was one of the first available methods for reading rehabilitation in AMD (Bäckman & Inde, 1979; Holcomb & Goodrich, 1976). The purpose of eccentric viewing training is to learn to use a (new) eccentric location for reading. Training techniques for eccentric viewing aim to enhance the patient's awareness of the location of the PRL. One of the first investigations of eccentric viewing training was performed by Frennesson, Jakobsson, and Nilsson (1995), and followed up by Nilsson et al. (1998, 2003). These studies investigated a more or less similar eccentric viewing training that involves four steps. The first step was to establish the degree of eccentricity in the upper or lower visual field at which the patient could recognize letters. The degree of eccentricity (PRL) was determined by presenting a cross on a computer screen with a letter in its center. The horizontal line of the cross moved upwards or downwards step by step, whereas the letter remained at its position. The participant had to follow the moving horizontal line until the letter in the center was no longer obscured by the scotoma and became visible. The rationale is that the horizontal line functions as a 'peripheral landmark' for fixation, facilitating to find the letter, and thus supporting eccentric viewing. The second step involves the training of

TABLE 2. Training effects of the included studies

Intervention	No.	Study	Reading speed before (wpm)	Reading speed after (wpm)	Effect in wpm	[%]	*p*-value
Eccentric viewing	1	Frennesson et al. (1995)	12 ± 5 [6–19]	59 ± 20 [34–84]	47	[412%]	<.001
	2	Gustafsson et al. (2004)	46 ± 39 [0–100]	80 ± 41 [10–126]	34	[72%]	.012
	3	Kasten et al. (2010)	58 ± 33 [19–115]	77 ± 52 [17–193]	20	[34%]	<.05
	4	Nilsson et al. (1998)	[0–12]	Median = 71 [62–76]	n.a.	[n.a.]	n.a.
	5	Nilsson et al. (2003)	9 ± 6 [3–26]	68 ± 19 [28–115][1]	59	[656%]	<.001
	6	Palmer et al. (2010)	48 ± 35	72 ± 31	24	[50%]	<.001
	7	Seiple et al. (2011)	n.a.	n.a.	−8	[n.a.]	*ns*
Oculomotor control	8a	Hall and Ciuffreda (2001)	MD: 83 ± 77 [22–242]	MD: 96 ± 85 [23–258]	14	[17%]	<.01
	8b		CON: 227 ± 56 [175–321]	CON: 219 ± 95 [160–386]	−8	[−4%]	*ns*
	9	Nguyen et al. (2011)	SM: median = 102 [IQR 63–126]	SM: median = 122 [IQR 102–137]	20	[20%]	.006
	10	Seiple et al. (2005)	91 [51–121]	116	25	[27%]	<.001
	11a	Seiple et al. (2011)	EM: n.a.	EM: n.a.	27	[n.a.]	<.001
	11b		CON: n.a.	CON: n.a.	1	[n.a.]	*ns*
	12	Tarita-Nistor et al. (2009)	93 ± 62 [30–171]	119 ± 65 [32–200]	26	[28%]	n.a.[2]
	13	Vingolo et al. (2007)	25	45	20	[80%]	.031
	14a	Chung et al. (2004)	EXP-trained: n.a.	EXP-trained: n.a.	n.a.	[41%]	n.a.
	14b		EXP-untrained: n.a.	EXP-untrained: n.a.	n.a.	[31%]	n.a.
Perceptual learning	15	Chung (2011)	n.a.	n.a.	n.a.	[53%	<0.001
	16a	Lee et al. (2010)	EXP-L/L: 167 ± 70 [68–262]	EXP-L/L: 229 ± 73 [146–334]	62	[37%	.006
	16b		EXP-L/U: 169 ± 64 [80–231]	EXP-L/U: 221 ± 92 [128–345]	52	[31%]	.041
	16c		EXP-U/U: 132 ± 31 [99–183]	EXP-U/U: 281 ± 41 [237–337]	149	[113%]	.009
	16d		EXP-U/L: 178 ± 16 [152–189]	EXP-U/L: 283 ± 49 [249–365]	105	[59%]	.006
	16e		CON-C/L: 127 ± 78 [45–239]	CON-C/L: 149 ± 93 [50–251]	23	[18%]	*ns*
	16f		CON-C/U: 93 ± 48 [40–163]	CON-C/U: 123 ± 67 [52–194]	31	[33%]	*ns*
	16g		CON-no/L: 236 ± 58 [183–321]	CON-no/L: 269 ± 104 [186–448]	33	[14%]	*ns*
	16h		CON-no/U: 214 ± 45 [179–289]	CON-no/U: 244 ± 67 [198–360]	30	[14%]	*ns*

17	Nguyen et al. (2011)	RSVP: median = 83 [IQR 74–105]	RSVP: median = 104 [IQR 81–124]	21	[25%]	.01
18	Seiple et al. (2011)	RP: n.a.	RP: n.a.	−10	[n.a.]	*ns*
19	Sommerhalder et al. (2004)	3 ± 2 [1–5]	23 ± 8 [14–28]	20	[657%]	n.a.[3]
20a	Yu, Cheung, et al. (2010)	EXP: n.a.	EXP: n.a.	n.a.	[60%]	n.a.
20b		CON: n.a.	CON: n.a.	n.a.	[16%]	n.a.
21a	Yu, Legge, et al. (2010)	EXP-lexical decision: n.a.	EXP-lexical decision: n.a.	n.a.	[39%]	<.05
21b		EXP-trigram: n.a.	EXP-trigram: n.a.	n.a.	[54%]	<.05
21c		EXP-RSVP: n.a.	EXP-RSVP: n.a.	n.a.	[72%]	<.05

Notes: The size of the effects in wpm or percent are based on unrounded numbers. In columns 4 and 5, result figures are reported as the mean ± standard deviation [range] if available.

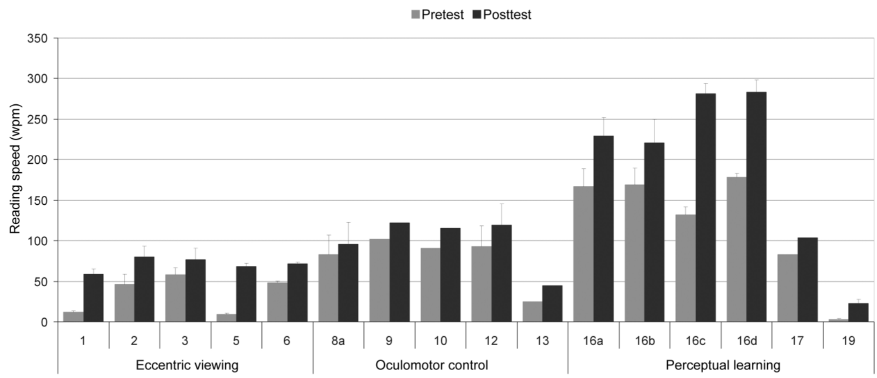
(A)MD, (age-related) macular degeneration group; CON, control group; C/L, trained center-group on untrained lower-field text; C/U, trained center-group on untrained upper-field text; EM, eye movement training group; EV, eccentric viewing training group; EXP, experimental group (no macular degeneration, but normal vision with forced eccentric viewing); IQR, interquartile range; L/L, trained lower-group on trained lower-field text; L/U, trained lower-group on untrained upper-field text; n.a., not available; *ns*, non-significant; no/L, no-training group on untrained lower-field text; no/U, no-training group on untrained upper-field text; RP, reading practice group; RSVP, RSVP training group; SM, sensomotoric training group; (un)trained, (un)trained eccentric position; U/L, trained upper-group on untrained lower-field text; U/U, trained upper-group on trained upper-field text.

[1]Two persons who failed to learn a new PRL were excluded.

[2]We applied a two-sided paired t-test on the reported individual outcomes, which revealed no significant effect.

[3]We applied a two-sided paired t-test on the reported individual outcomes, which revealed $p = .052$.

FIGURE 2. Reading rates (in wpm) before and after the different reading trainings. The numbers below the boxes refer to the studies listed in Table 2. Error bars represent 1 standard error of the means.



the new PRL. Reading of single words, sentences and text was trained at the new eccentricity, using the horizontal line as landmark. Text was displayed as scrolled text, that is, a single line of text moving from right to left over the computer screen. The next step was to read text without the computer screen. In combination with high magnification (often 10–15×), patients had to read single words or text with fixation lines above or below the text, which indicated the correct eccentricity and helped the patient to hold the scotoma above or below the text. Because reading distance was very short, patients were taught to manually move the text from right to left instead of scanning the text. Finally, patients had to read without the fixation lines, just remembering the established eccentric position for fixation.

A similar eccentric viewing training was described by Gustafsson and Inde (2004), who trained patients to read scrolled text at a new eccentricity in combination with fixation lines, before optical devices were employed. For scrolling the text on a computer screen, they used a module from the commercially available software ZoomText. Instead of scrolled text on a computer screen, Palmer, Logan, Nabili, and Dutton (2010) trained participants to manually move the text from right to left while reading at short distance. The participants were instructed to keep the eye and head steady while moving the text slowly in front of their eyes from right to left (called ‘steady eye strategy’). Moreover, fixation lines above or below the text helped the patient to keep fixation at the right eccentricity, which was determined before the training. Finally, Kasten, Haschke, Meinhold, and Oertel-Verweyen (2010) developed a computer-based training program on eccentric viewing. First, the best position of eccentricity was determined by displaying a word on a computer screen at different positions relative to a cross at the center of the screen. Next, participants were trained to read words at this eccentricity, whereby the words were scrolled from right to left at the computer screen, while the participants had to hold their eyes steady by looking at the cross. This training was partly practiced at home. After the computer training, they learned to move printed text from right to left while reading.

As is evident from Table 2, all included studies with eccentric viewing training paradigms were successful in improving reading performance of patients with central scotomas. Though the effect of the training varied over the studies, all trainings resulted into average reading speed levels up to 60–80 words per minute (wpm). A couple of studies used advanced techniques like microperimetry to establish the new PRL and to examine whether the new PRL was used after training, or to continuously monitor the fixation position during the training (Nilsson et al., 1998, 2003). Microperimeters, like the SLO[3] or MP1, have the advantage that the retinal image is made visible, and hence the scotoma boundaries and the new PRL can be determined exactly. Moreover, it allows instructing the patient very precisely where to fixate. Yet microperimeters are expensive and often not available for rehabilitation practice. However, microperimetry is not necessary for learning to use a new PRL successfully, as has been shown by several studies (Gustafsson & Inde, 2004; Kasten et al., 2010; Palmer et al., 2010).

One severe limitation in all studies is that eccentric viewing training was accompanied by the provision of optical devices. This makes it hard to disentangle whether improvement in reading is due to the optical device, the eccentric viewing training or a combination of both. Moreover, Nillson et al. (2003) excluded two participants who failed to learn a new PRL, and hence outcomes may be positively biased. Another issue that should be noted here is that the studies by Nilsson et al. (1998, 2003) only provided training to the eye with worst visual acuity in order to avoid previous experience with eccentric viewing. However, from a rehabilitation perspective, it makes more sense to train the least affected eye, as this eye is most likely to be used for reading.

Controlling Eye Movements

Oculomotor control is crucial for efficient reading. Because there is evidence that oculomotor control is poor in MD, a number of training programs have been developed that aim to improve eye movement control in MD. Some of these training programs use auditory oculomotor feedback. In the training by Hall and Ciuffreda (2001), changes in horizontal eye position were accompanied by changes in tone (pitch), such that patients could 'hear their eyes move'. When the eyes moved from left to right across a line of text, the tone

[3] The scanning laser ophthalmoscope (SLO) is no longer available on the market, but a comparable instrument has been developed, namely the Micro Perimeter 1 (MP1).

increased from a low to a high pitch. Patients were instructed to move their eyes in a regular, rhythmical manner. Moreover, patients were trained in fixation stability by keeping the tone steady while fixating a target. The rationale is that the auditory feedback will enhance awareness of one's eye movements, in turn leading to increased intentional oculomotor control, which will ultimately become automatic through associative learning. Moreover, Hall and Ciuffreda (2001) suggest that the oculomotor training is likely to facilitate the optimal placement of text on the PRL, and thus improving eccentric viewing.

In another oculomotor training, a tone indicated whether the eyes were approaching the PRL (Vingolo, Cavarretta, Domanico, Parisi, & Malagola, 2007). Thus here it was the PRL that was made audible. A similar technique was used by Tarista-Nistor et al. (2009), who employed auditory oculomotor feedback to train a new PRL and to maintain fixation at that PRL. The auditory feedback was meant to help the patients align the PRL with a fixation target and keep it at that position for some period. The idea is that the auditory oculomotor feedback will lead to increased fixation stability and re-reference of the oculomotor system to the PRL.

There are some studies in which eye movements are trained without any auditory oculomotor feedback. For example, Seiple, Szlyk, McMahon, Pulido, and Fishman (2005) developed a training program that consisted of a series of exercises in which eye movements were practiced. These exercises consisted of visual tasks like visual search, fixation stability, and saccadic and pursuit tracking. In a recent study, Seiple, Grant, and Szlyk (2011) used saccadic training (i.e., making saccades to dots, letters, letter pairs, and words) to improve oculomotor control. In addition, the efficacy of this type of training was compared with eccentric viewing training and reading practice using a cross-over design. Finally, Nguyen, Stockum, Hahn, and Trauzettel-Klosinski (2011) used what they termed a sensomotoric training to optimize reading eye movements in a group of only JMD patients, and compared this with a training to read with RSVP. For the sensomotoric training, participants had to read texts that moved from left to right on a computer screen (moving-window technique), whereby the text was split up into different components. According to Nguyen et al. (2011), this moving-window technique could optimize eye movements during reading because it acts as a guide for eye movements. However, they failed to explain how this might actually work.

As evident from Table 2 and Figure 2, most training programs that focused on oculomotor control only lead to modest improvements in reading rate, with the exception of Vingolo et al. (2007) and Seiple et al. (2011) who both found a relatively large improvement. However, we should notice that the other oculomotor training programs (Hall & Ciuffreda, 2001; Seiple et al., 2005; Tarita-Nistor, Gonzalez, Markowitz, & Steinbach, 2009) had relatively high average baseline reading rates of about 80–100 wpm, and hence effects might be at ceiling here. Nonetheless, despite these modest effects, the findings have an important implication. That is, given that we are normally not aware of the kind of eye movements we make while reading (i.e., we have no voluntary control over our eye movements), these findings suggest that both eye movements and eye position can be practiced.

Perceptual Learning

Several recent studies used perceptual learning to improve peripheral vision for reading (Chung, 2011; Chung, Legge, & Cheung, 2004; Lee, Kwon, Legge, & Gefroh, 2010; Sommerhalder et al., 2004; Yu, Cheung, Legge, & Chung, 2010; Yu, Legge, Park, Gage, & Chung, 2010). Perceptual learning refers to the process of long-term improvement in performing perceptual tasks induced by extensive practice (Goldstone, 1998). It involves discrimination or detection of perceptual stimuli by repeated exposure to these stimuli, which is supposed to result into neural changes in perceptual pathways rather than learning task specific strategies (Legge et al., 2008).

Chung et al. (2004) and Lee et al. (2010) used a perceptual learning paradigm to investigate whether normally sighted participants could adapt to peripheral vision. Participants had to recognize random strings of three letters ('trigrams'), which were presented at 10° in the lower or upper visual field at different vertical positions. During practice participants did not receive any feedback. Both Chung et al. (2004) and Lee et al. (2010) found that after extensive practice, reading speed and visual span size had significantly been increased.

In order to investigate whether similar learning effects could be achieved with other perceptual learning tasks, Yu, Legge, et al. (2010) compared three different tasks: trigram letter recognition, lexical decision,[4] and RSVP. All three training tasks resulted into significant improvements of reading speed, but the RSVP task was most effective. However, we should keep in mind that the outcome measure was also assessed through RSVP reading. More importantly, the other two training methods that did not train RSVP had improved RSVP reading as consequence as well, and thus generalized to untrained tasks. Yu, Legge, et al. (2010) suggest that a lexical decision task is perhaps more suitable for home-based training, because errors can be tracked, it is much simpler because of the two-choice response, and word recognition is presumably more appealing than recognition of meaningless letter strings. Another kind of task was used by Sommerhalder et al. (2004). In this study, normally sighted participants had to read aloud newspaper texts using a very restricted eccentric area of the retina, thus simulating

[4] In the lexical-decision training, participants were presented with strings of three letters. Participants had to indicate whether the string was a word or a non-word.

retinal implants.[5] After intense daily training, all three participants showed remarkable improvements in reading rates and accuracy.

The studies described above all included young and normally sighted participants. Still, for rehabilitation of AMD it is a crucial issue to find out if perceptual learning leads up to improvement in reading by older people, especially those with MD. For a group of normally sighted older people, Yu, Cheung, et al. (2010) found similar effects of perceptual learning of peripheral vision as in young people, though the effects were less strong than found in younger people. Weaker training effects might be explained by the fact that older people had more difficulty to retain training benefits between sessions, possibly due to age-related reduced cortical plasticity. Nonetheless, the findings by Yu, Cheung, et al. (2010) demonstrated that normally sighted older people still benefit from perceptual learning and are able to improve peripheral reading. Moreover, in a recent study by Chung (2011) it was shown that older people with longstanding MD improved on RSVP sentence reading after perceptual learning of RSVP reading, while visual acuity, fixation stability, and PRL location did not change substantially.

Finally, both Seiple et al. (2011) and Nguyen et al. (2011) had extensive practice of RSVP reading as part of their training protocol, which can be regarded as a type of perceptual learning. Remarkably, Seiple et al. (2011) failed to find any effects for RSVP training in a group of older individuals with MD, while Nguyen et al. (2011) found that young people with MD improved on reading speed after RSVP training.

To sum up, there is evidence that perceptual learning of peripheral vision can improve reading speed, both in normally sighted people and in people with central vision loss (Table 2, Figure 2). More importantly, after training a specific retinal location, learning effects were transferred from the trained eccentricity to an untrained eccentricity (Chung et al., 2004; Lee et al., 2010; Yu, Legge, et al., 2010), and from the trained eye to the untrained eye (Sommerhalder et al., 2004), at least in young people. Moreover, training effects were retained for a period of several months after completion of the training (Chung et al., 2004; Sommerhalder et al., 2004).

One question that arises is how perceptual learning actually contributes to peripheral reading. There is evidence that perceptual learning results into larger visual span size (Chung, 2010; Chung et al., 2004; Lee et al., 2010; Yu, Cheung, et al., 2010), which in turn has a positive effect on reading speed (see the earlier section entitled 'Characteristics of Reading in Persons with Central Vision Loss'). Possible explanations for the increased visual span are a reduction of spatial uncertainty about letter position, a reduction of

[5] Because retinal implants can only be placed outside the fovea, people with retinal implants also have to rely on a peripheral retinal area for reading. However, in case of central scotoma larger parts of the retina can be used for reading compared to retinal implants.

crowding, or better allocation of attention (Sommerhalder et al., 2004; Yu, Cheung, et al., 2010). The latter explanation, however, is not supported by Lee et al. (2010), who demonstrated that perceptual learning effects were not associated with enhanced ability to allocate attention to eccentric stimuli. Another explanation is put forward by Sommerhalder et al. (2004), who suggest that it is in particular the adaptation of eye movements to a non-foveal, eccentric location that contributes to the learning process.

Though perceptual learning is a promising method for improving reading in case of central vision loss, thus far, only two studies have actually scrutinized perceptual learning in a group of older MD patients, and findings are still inconsistent (Chung, 2011; Seiple et al., 2011). As Chung (2010) noted in a review of her research, perceptual learning might be less effective for people with AMD, because of reduced plasticity of the visual system, and because of practical problems like limited mobility. Because the kind of perceptual learning that was used for reading training can be considered as extensive reading practice, the question arises whether extensive page mode reading would result into similar improvements in reading speed as perceptual learning. To provide a conclusive answer, a study should be carried out in which perceptual learning and extensive practice of page mode reading are combined in one experimental design.

DISCUSSION

MD is the most common cause of visual impairment among older individuals, which severely affects reading performance. Due to central scotoma, people with MD have to rely on peripheral vision for reading. Peripheral reading has been shown to be very difficult, and rehabilitation programs are required to teach people with MD how to read with peripheral vision. In this article, we described how people with MD could learn peripheral reading. We considered three types of reading training: eccentric viewing training, oculomotor control training, and perceptual learning. The question is which kind of training is most effective for improving reading in MD.

Taking all studies into consideration, there appears to be no strong evidence in favor of one particular training program for rehabilitation of reading in MD. Most training studies lead up to significant improvements in reading rate, though training eye movements seems less effective than eccentric viewing and perceptual learning, with the exception of the oculomotor control training by Vingolo et al. (2007) and Seiple et al. (2011). The cross-over design by Seiple et al. (2011) even provides support for the effectiveness of eye movement training, in contrast to RSVP training or eccentric viewing training.

We should note that—though inevitable—direct comparison of the effects from different studies is not entirely straightforward, because of differences in participant groups between studies. Factors like age, visual acuity, scotoma size, type of MD (wet or dry, unilateral or bilateral), and time since disease onset may have influenced the outcomes significantly. Moreover, reading rates were established with different reading tests, varying from RSVP sentences to reading newspaper texts, and baseline reading rates diverged from 0 to 93 wpm in the patient groups. Regardless of this, and more importantly, there is clear evidence that older people with MD can be trained to improve reading performance, even within limited time (often 4–6 hours total training time). Moreover, we would like to emphasize that we should not underestimate the value of a modest improvement in reading performance for daily life. Even a reading speed increase of 15–20 wpm could be of value in daily life functioning.

All included studies focused on improving reading rate, while the ultimate goal of reading is comprehension. However, there is evidence that comprehension is not impeded by slow reading, and good comprehension is possible at low reading speeds (Legge, Ross, Maxwell, & Luebker, 1989; Whittaker & Lovie-Kitchin, 1993).

We like to underline that it is important to realize that many participants in the described patient studies are elderly, who are over 70 years old. Therefore, other factors besides visual impairment such as a compromised mental or physical condition may have played a role as well. In effect, these ‘comorbidities’ may have caused the large inter-individual variation in training effects. Besides, about half of the patient studies included both patients with AMD and JMD, and hence age may have played a role in training outcomes. Although most individuals did benefit from reading training, the extent to which this was the case varied among individuals. Only a minority of participants showed no benefit at all. For rehabilitation purposes, it is important to unravel the variables that contribute to, and predict the outcome of reading training in elderly with MD.

Though reading training appears to have effects with respect to improving reading in MD, there are several reasons why the studies performed thus far do not allow for conclusive answers. First, in several studies, in particular for the eccentric viewing programs, reading training was combined with the provision of magnification devices. This makes it hard to dissociate the effects of reading training from facilitative effects due to the magnification device. Second, most studies have small sample sizes. In 13 out of 18 studies the number of participants was less than 20 participants. Clearly, it is difficult to include a significant number of patients in this type of research, but these promising findings warrant further research with larger sample sizes. A third limitation of the existing studies is the lack of a control group in almost all patient studies. It is remarkable that despite randomized controlled research (RCT) being common practice nowadays, only 2 out of 13 patient studies included a control group. According to Gustafsson and Inde (2004), it is impossible to find a control group comparable to the experimental MD group, that is, matched on variables like visual acuity, scotoma size, and onset of disease. Nonetheless, it is exactly the added benefit of randomized research that such differences are random and cancelled out.

This draws an important issue: What kind of control group can be used to investigate the effectiveness of reading training programs for MD? One possibility that has been used in research is a control group consisting of normally sighted persons. However, they have not any need for using peripheral vision, and hence they are likely to be less motivated to practice intensively. Hall and Ciuffreda (2001) even found a (non-significant) reduction of reading speed for the normally sighted control group after oculomotor training. One possible explanation that they put forward is that when fixation is already optimal, auditory information about eye movements is just distracting attention. A second problem is that in case of MD there might be concomitant retinal pathology beyond the central scotoma, affecting visual processing (see the earlier section entitled 'Characteristics of Reading in Persons with Central Vision Loss'). In this perspective, it is important to point to the fact that the normally sighted persons in the perceptual learning studies had much higher baseline reading rates than the persons with MD in the other studies, despite that the normally sighted persons had to use peripheral vision to perform the task. It is therefore questionable to what extent a normally sighted control group which is forced to use peripheral vision is entirely comparable to an MD group.

Another possibility is to include a control group of MD patients that receive pre- and post-tests, but without any training in between. In this way, spontaneous adaptation and learning effects can be controlled for. Another method that might be well suitable to investigate the effectiveness of different treatments is a cross-over design. In such a design participants receive different treatments in sequential order. Owing to this set-up, each participant serves as his own control. As an example, half of the participants may receive reading practice followed by oculomotor training; whereas the other half receive the same treatments but now in reversed order. Similar to a RCT, participants are randomly assigned to treatment order. Until present, only Seiple et al. (2011) used a cross-over design. One reason for a lack of studies using a cross-over or controlled designs may be due to the effort and time it takes to include a patient group of a considerable size. This, in turn, may be due to a lack of motivation for extensive practice, limited mobility because of low-vision, and other factors related to logistics and participant recruitment.

Thus far, the focus was on the efficacy of training programs for improving reading rate in MD. Obviously, this is a first entry point for a new rehabilitation protocol to be used, but successful implementation of such a protocol faces several additional criteria. First, if it is to be used in clinical practice, training effects must generalize to everyday reading and must persist over time. Unfortunately, generalization of training effects over tasks and time is often not measured. Second, training programs should be cost-effective in producing the desired outcome. Here, home-based training has an added value, because they are usually associated with relatively low costs. As an example, training programs such as the eccentric viewing training by Gustafsson and Inde (2004) and Kasten et al. (2010) may be suitable for home-based computer training. In addition, perceptual learning based on lexical decision could be easily practiced at home as well (Yu, Legge, et al., 2010). Finally, the amount of effort and motivation needed for practice are both factors that may contribute to the efficacy of a reading training in clinical practice.

Finally, this review has shown that older people with MD can be trained to improve peripheral reading performance within only limited time. Despite a growing body of evidence, there remain many questions yet to be answered. For example, what is the minimal amount of training that is needed to achieve any beneficial effects? What is the optimal task? Does a combination of the described training programs have added value? How are training effects consolidated? These questions should be addressed in future research in order to develop better reading training programs that are effective as well as feasible for people with MD.

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