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REVIEW ARTICLE

Reading performance and central field loss

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Abstract

Age-related macular degeneration is a major cause of blindness in Europe and the U.S. and a leading cause of significant loss of visual acuity in elderly patients. Reading is a key visual task in everyday living involving a synthesis of a number of different motor, sensory and cognitive functions. When the centre of a reader's visual field is obscured, reading speed declines and oculomotor pattern differs, compared to normal reading. Improvement in the generation of visual stimuli using computer-generated images and projection/display systems as well as advances in eye movement recording techniques, including infrared pupil tracking and magnetic search coils, have contributed greatly to our understanding of these sensorimotor abnormalities. The developed reading strategies have been thoroughly investigated in individuals with central field loss either induced artificially or related to eye pathology.

The following review aims at presenting the contemporary literature regarding the sensory and oculomotor deficits in reading ability, resulting from central field loss and should contribute to a greater understanding of the functional visual deficit caused by this visual impairment. Hippokratia 2011; 15 (2): 103-108

Key words: reading; age-related macular degeneration; central field loss, review

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Age-related macular degeneration (AMD) is a major cause of blindness in Europe and the U.S. and a leading cause of significant loss of visual acuity in elderly patients[1-3]. The incidence of AMD increases with age[4].

AMD in its early stages can be defined as the presence of soft drusen or any type of drusen combined with changes in the pigment epithelium or increased pigmentation in the macular region[5]. Blindness in AMD is caused by the degeneration of pigment epithelium[6]. The cause of blindness may also be the impairment of the photoreceptors. AMD causes localized macular degeneration, with destruction of rods and cones, either with presence of vascular damage and serum extravasation (wet AMD) or without (dry AMD). Although only 10% of patients have wet AMD, more than 85% of blindness is attributed to this form of AMD[7].

Reading is an extraordinarily sophisticated task involving a synthesis of a number of different motor, sensory and cognitive functions. Reading ability is dependent on macular function and eye movements show a clearly defined strategy during reading (Figure 1). When reading English text, eye movements consist of short and rapid movements called saccades, that typically move the eyes forward about 6-9 character spaces equal to 1-2°. Saccades take 20-50 ms to complete, depending upon the length of the movement and virtually no visual information is extracted during saccadic eye movements[8-10]. Between saccades, the eyes remain stationary for brief periods of time (typically 200-250 ms) called fixations. Visual information is only extracted from the printed page during fixations. A small number of saccades are in the opposite direction to the reading order of text (i.e. right to left in English reading), where the reader reprocesses a previously read word. These are called regressions and usually account for about 10-15% of the saccades made. Regressions are probably caused by problems with linguistic processing as well as oculomotor errors[8-10].

Since reading ability relates to macular function, the frequency of saccades is attributed to acuity restrictions[8,9,11]. Visual acuity attains its maximal function at the centre of the retina, sharply decreasing as we move

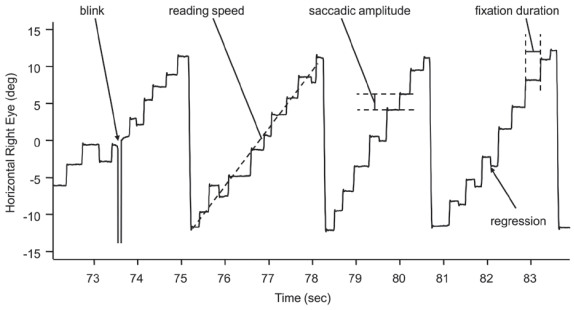

Figure 1: Original recordings of eye-movement patterns of a normally sighted individual observed during reading. The reading parameters, namely saccades, fixations and regressions are highlighted. When reading English text a series of short saccades and fixations are used to scan text across a line from left to right followed by a longer forward saccade to bring the gaze to the beginning of the next line. A small number of saccades called regressions are in the opposite direction to the reading order of the text (i.e. right to left in English reading) where the reader reprocesses a previously read word. A blink as recorded in eye movement patterns derived is also illustrated.

towards the periphery and hence subtle discrimination is only possible in the region of the fovea, or the central 2° of vision[11]. Furthermore, there is an inverse relation holding between the capacity for word recognition and the angular disparity between the fovea and the retinal image of the word[12]. In practice, this means that a reader needs to fixate most words so that they can be identified[8,9,11].

When the centre of a reader's visual field is obscured, reading speed declines and oculomotor pattern differs, compared to normal reading[11]. Improvement in the generation of visual stimuli using computer-generated images and projection/display systems as well as advances in eye movement recording techniques, including infrared pupil tracking and magnetic search coils, have contributed greatly to our understanding of these sensorimotor abnormalities. The developed reading strategies have been thoroughly investigated in individuals with central field loss either induced artificially or related to eye pathology.

Reading performance in normal subjects with simulated foveal scotomas

Rayner et al[8,9,13] investigated the effects of artificial scotomas on reading performance in normal subjects and highlighted the importance of the foveal vision capabilities during reading. In their foveal masking paradigm, central scotomas were simulated using the eye-contingent display change technique to create foveal masks, subtending between 1 and 17 characters size. The masks moved across the presenting text in synchrony with the reader's eye movements, which were recorded using the Dual-Purkinje eye-tracking system. The authors noted the strong negative relationship between the number of centrally masked characters and reading rate and concluded that reading speed deteriorates strikingly with increasing mask size. It was interesting to observe that even a single letter size foveal mask caused a reduction in reading speed to one-half its normal value.

Furthermore, increasing the mask size resulted in a change in oculomotor parameters, such as an increase in the mean fixation duration, the number of progressive/forward saccades and the number of regressive/backward saccades. These changes were also associated with difficulties in comprehension of the presented reading material indicated by the dramatic reduction in the number of correctly reported sentences. It should be noted however, that the reading material was presented in a fixed print size, so increasing the mask size would have resulted in a reduced perceptibility of the reading text.

In an attempt to extend Rayner's investigation, Fine et al[14] tried to determine whether the number of letters masked or the size of the mask in degrees was the main component resulting in decreased reading rates. By varying the number of letters masked in reading text, across several mask sizes and recording the eye movements using a dual-Purkinje-image eyetracker, the authors found that the number of letters masked was the predominant factor affecting reading behavior until mask size was 7.5° and the number of letters masked more than seven.

Thus, an increased font size may adequately compensate for the reduced reading rates observed in patients suffering from central scotomas.

Reading performance in patients with foveal scotomas

Extensive research has been undertaken in eye movement characteristics during reading with the use of infrared gazetrackers and more recently, with the employment of the scanning laser ophthalmoscope in patients suffering from central field loss. One of the characteristic features of macular degenerations, such as age-related macular degeneration and Stargardt's disease, is the development of an absolute central scotoma[11]. In almost all of the affected individuals, the loss of foveal vision is followed by Preferred Retinal Loci (PRL) in order to fixate steadily on objects of interest using one or more extra-foveal areas. A number of studies have highlighted the importance of preferred retinal loci awareness during reading, as well as the number and location of the preferred retinal loci used while performing a reading task.

Crossland et al[15] investigated the significance of preferred retinal locus development during reading in patients with central scotomas due to macular disease. The authors recorded fixational eye movements using a scanning laser ophthalmoscope and infrared gaze-traker and evaluated reading rates using "MN-Read" style sentences as reading material. They concluded that reading speed was not significantly associated with PRL location or the presence of multiple PRLs. However, patients who lack consciousness of employing a non-central retinal area for fixation but still adjust their oculomotor behavior to use consistent repeatable PRLs while reading, actually exhibit higher reading rates.

In order to evaluate the importance of using more than one multiple preferred retinal loci during reading, Deruaz et al[16] studied the eye movement patterns in patients with central scotomas and multiple preferred retinal loci. The authors used a scanning laser ophthalmoscope to record fixational eye movements. They concluded that patients with foveal loss tended to use at least two PRLs during reading in order to acquire a global view of the text with the use of the one PRL and to obtain further detail with the use of the other PRL.

The choice of the exact position for the PRL development has not been fully understood yet, especially for tasks requiring fixation such as reading. Alpeter et al[17] have shown that, apart from the obstructive aspect of the foveal scotoma and the developed correspondence in binocular visual function, the topographical variations in attentional performance may play a key role.

Sunccess et al[18] investigated the location of the ec-

centric PRL for fixation, as well as the fixation patterns during reading in patients with central scotomas, due to age-related macular degeneration, using a scanning laser ophthalmoscope. They noted that there was a preference for fixation with the scotoma placed to the right in the majority of the participants, which resulted in faster reading rates, compared to patients who fixated with the scotoma to the left of fixation. In particular, in patients fixating with the scotoma to the right, a reading rate of ≥50 words/min was achieved in 38%-100% of the eyes, depending on the extent of the retinal lesion. In patients who fixated with the scotoma to the left, none of the eyes demonstrated a reading rate of ≥50 words/min. The authors suggested, therefore, that this arrangement of PRL and scotoma might be advantageous for reading because it indicated where the fixation has landed, with respect to the previous word. This would allow readers to integrate the previously acquired information with the currently fixated information and to programme the subsequent saccadic eye movements. In contrast to this, Fine et al[19] monitored eye movement patterns during reading using a dual-Purkinje-image eyetracker in normally sighted individuals with the left or right of their visual field masked from view with simulated hemifield scotomas. They observed that letter identification, word identification and reading rates were improved in the participants fixing with the scotoma to the left, compared to the participants fixing with the scotoma to the right. Consequently, they suggested that when the information to the right visual field was obscured by the scotoma, reading rates decline primarily due to the increased number of saccades performed to successfully read the stimuli. In addition, Rayner et al[8,9] investigated the importance of the available information to the left and to the right of the fixation in reading with normal vision employing the moving window technique. By varying the size and location of the window that moved across the reading text in synchrony with the reader's fixational eye movements, the authors assessed reading behavior in relation to information available in the parafoveal vision. They concluded that it was the text available to the right of the current fixation, guiding the subsequent eye movements, that was the most important for efficient reading. Therefore, when patients with central field loss use a PRL on the left to place their scotoma to the right of fixation in visual space, the information that has not yet been fixated would be masked from view, resulting in reduced reading rates.

Research has been undertaken regarding the strength of association between fixational stability and reading performance. Crossland et al[20] investigated the relationship between reading speed and fixational stability in patients with newly developed macular disease using a scanning laser ophthalmoscope and an infrared gazetracker to evaluate the fixational eye movements. The authors noticed that 54% of the variance in the oculomotor patterns could be attributed to changes in fixational stability, even though stability of fixation was not significantly associated with clinical features such as visual acuity, contrast sensitivity or scotoma size. Therefore, the reading deficit in patients with macular disease may partially be ascribed to impairments in fixational stability.

The findings of Crossland et al[20] were in conflict with Deruaz et al[21] observations, who also studied the fixation behavior and the oculomotor patterns in patients with central scotomas from age-related macular degeneration (AMD) or Stargardt's disease with the use of a scanning laser ophthalmoscope. The authors attributed the fixational instability observed during eccentric viewing to perceptual fading or Troxler's phenomenon, a condition probably related to the local adaptation effects in the retina. In particular, they suggested that the saccades performed while alternating between PRLs resulted in greater clarity of the perceived image since this prevented the fading of small targets presented in the peripheral visual field. Therefore, intentional changes in fixational eye movements, while attempting to decode letters or words, could facilitate the perception of reading text in individuals with central scotoma and eccentric viewing. In addition, Safran et al[22] investigated the eye movement patterns during reading in a patient with a central scotoma using several PRL while text material was projected on his retina with the use of a scanning laser ophthalmoscope. The authors concluded that the observed changes in fixation position and the associated oculomotor adaptations comprising of backward saccades and unexpected line losses could probably improve the perception of the eccentrically fixated text stimulus, even though they resulted in reduced reading rates.

In order to elucidate the efficacy of the residual retina for achieving visually demanding tasks in patients with macular scotomas, Timberlake et al[23] examined the eye movement patterns for fixating, inspecting acuity targets, scanning simple text and reading. They also used a scanning laser ophthalmoscope to map retinal lesions resulting from macular scotomas and identify PRL. The authors observed a discrepancy between the PRL used in each of these tasks, indicating that different PRLs were employed to achieve fixating, inspecting acuity targets, scanning simple, non-sense-syllable text and reading.

The processes related to oculomotor adaptations to eccentric viewing have also been evaluated. Whittaker et al[24] studied the characteristics of foveating and non-foveating saccadic response to salient visual targets presented in the peripheral visual field in patients with long-standing macular scotomas using a 2-dimensional search coil. They found that the tested individuals tended to suppress foveating saccadic mechanisms and directed presented peripheral stimuli to the preferred retinal locus used for fixation. However, these fixational eye movements were characterized by longer latencies and lower gains compared to the foveating saccades of normal individuals.

Fornos et al[25] investigated the oculomotor adaptations to eccentric viewing during reading in normally sighted observers using an eye-tracking system to record eye movements. The authors noticed that, in order to achieve

effective reading, the participants initially suppressed the reflexive vertical foveating saccades. Subsequently, they tended to adjust the horizontal eye movement patterns by gradually increasing the number of the progressive/forward saccades and minimising the number of the regressive/backward saccades.

The effect of font size on reading performance in normal subjects with simulated foveal scotomas and in patients with foveal scotomas

The effect of print size on reading rates and the associated eye movement parameters have been evaluated in individuals with central field loss either induced artificially or related to eye pathology.

Fine et al[26] monitored the reading eye movement patterns in normal subjects with simulated central scotomas using a dual-Purkinje-image eyetracker. The authors noticed that reading rates were reduced in all the print sizes tested compared to normal central reading and suggested that the decreased reading speed was primarily related to an increase in the number of saccades and extended fixation durations. This was considered to be caused by the visual span shrinkage resulting from the simulated central visual field loss.

McMahon et al[27] investigated the strength of the relationship between saccadic frequency and reading rates, in patients with macular degeneration, using an electro-oculogram/saccadic velocity recording instrument. They noticed that there was a strong negative correlation between the eye movement parameters under investigation, with higher saccadic frequencies associated with reduced reading rates. The authors speculated that the increase in the number of saccades resulted from the poor saccadic accuracy observed in patients with central field loss, presumably being related to a reduced visual span.

Bullimore et al[28] investigated reading strategies as a function of print size, in patients with age related maculopathy, with an infrared scleral reflection device. They observed that the reduced reading rates were highly associated with an increased number of saccades and prolonged fixation duration. These oculomotor abnormalities during reading were suggested to be related either to the subjects' inability to obtain the desired information from a fixation or an existing inefficacy to integrate the perceived information across saccades.

In order to determine the contribution of the oculomotor patterns in the reduced reading rates in patients with central field loss, Rubin et al[29] evaluated reading performance for rapid serial visual text presentation to conventional text presentation in individuals with and without scotomas in the central part of their visual field. The rapid serial visual presentation technique minimizes the need for eye movements as the visual stimuli are presented sequentially at the same retinal area location. Reading rates with the use of the rapid serial visual presentation paradigm versus static text were increased less in patients with central field loss compared to normal controls. Low vision patients, with a macular scotoma, exhibited an improvement by a factor of 1.5±0.41 with the Rapid Serial Visual Presentation (RSVP) while normally sighted observers showed an improvement by a factor of 2.1±0.38 on their maximum reading rates. The results indicate that controlling for the contribution of eye movements in reading performance in patients with central field loss had little effect on the recorded reading rates.

Discussion

A wealth of literature exists concerning the eye movement strategies used during reading[8,9,30]. Earlier studies using eye movement recordings were impeded by the technological limitations of the equipment available. Electro-oculograms (EOG) initially employed to record eye movements, while performing a reading task used electrodes on the skin adjacent to the orbit which create eyelid artefact and therefore, gave rise to recording errors and inaccurate measurements[8,9]. More recent development of infrared pupil tracking techniques and magnetic search coil techniques has reduced recording error and artefact[24,31]. Generation of target stimuli has also improved over the years and, with the development of computers, stimuli could be produced more simply and conveniently on a computer monitor or projection screen. The use of the scanning laser ophthalmoscope has also substantially expanded the existing knowlegde with regard to the eye movement characteristics during reading[15,20,32]. Finally, functional magnetic resonance imaging techniques (fMRI) have contributed greatly in exploring and illustrating neural changes in humans during reading[33-36].

Extensive low vision research has demonstrated the significant effects of the acuity reserve, the contrast reserve, the field of view and, in cases of maculopathy, the size of the central scotome on reading rates[37]. Therefore, when the centre of the visual field is obscured, reading speed declines and eye movement pattern changes.

In addition, patients with central visual field defects, due to macular disease, may presumably use an eccentric or more than one refered retinal loci to serve fixation. However, normal peripheral vision is regarded as degraded visual system compared to normal central vision. Despite enlargement of letter size to compensate for decreased acuity with eccentric viewing, peripheral reading speed did not approach that achieved!!! using the fovea in normal vision. Similar results were also derived while accounting for the contribution of the eye movements in reading rates using the RSVP technique and the crowing effect using reading material presented with increasing letter spacing.

Chung et al[11,38] investigated the effect of print size on reading speed at different eccentricities using the RSVP Technique. The authors concluded that, even though the rate of change in reading speed as a function of print size remained invariant in both central and peripheral vision, maximum reading speeds were still lower in peripheral vision compared to central vision. Furthermore, Latham

et al[12] with the effects of eye-movements eliminated using the RSVP paradigm, have similarly shown that, reading rate of meaningful sentences could not be equated across the visual field by simple magnification, even though the word recognition rates could be equated across the visual field by appropriate magnification of the stimulus.

The crowding effect may significantly contribute to the reduced reading rates observed in normal individuals with simulated central scotomas and in patients with central field loss. Crowding has been suggested to affect reading in normal peripheral vision resulting in reduced reading speeds compared to normal central vision. Chung et al[11,29,40] argued that increasing letter spacing had beneficial effect on reading rates in both central and peripheral vision in normally sighted individuals. The author[39] studied whether reading speed could be improved in normal central and peripheral vision by increasing letter spacing, in both small and large print, using the RSVP technique. They concluded that even when character size was not a restricting factor and oculomotor demands were minimized with the RSVP technique, increased horizontal letter spacing beyond the standard size did not lead to an increase in reading rates in normal central or peripheral vision. The same author[40], on the contrary, observed that increased vertical word spacing seemed to be advantageous in reading performance, resulting in higher reading rates. This benefit proved to be greater in the peripheral than the central normal vision.

These results will lay the groundwork for determining the sensory and oculomotor deficits in reading ability, resulting from central field loss and they should contribute to a greater understanding of the functional visual deficit caused by this visual impairment. Despite the use of magnification, reducing the need of eye movements or modyfying print, reading rates in normal peripheral vision are still reduced compared to normal central vision. Further research is needed for a better undertstanding of the visual characteristics as a function of eccentricity to improve visual rehabilitation strategies and trainning methods in patients with central visual field defects.

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