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The relationship between word length and threshold character size in patients with central scotoma and eccentric fixation

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Abstract *Background:* Understanding limitations on text reading with eccentric fixation is of major concern in low vision research. Our objective was to determine, in patients with a central scotoma, whether threshold character size is similar for different word lengths and paragraphed texts. *Methods:* In 19 patients, we retrospectively analyzed the relationship between minimum readable character size for isolated words and text. Isolated letters, two, five, and ten-letter words and a paragraphed text were presented randomly through a scanning laser ophthalmoscope in eight different character sizes. *Results:* Threshold character size varied according to the text stimulus ($p<0.05$). Threshold character sizes for single letters and two-letter words were matched ($p>0.99$), as were those for five-letter words, ten-letter words, and paragraphed text ($p>0.99$). Threshold character size for single letters and two-letter words was significantly lower than that measured with other text stimuli. *Discussion:* Reading performance is influenced by a variety of factors such as crowding, contextual effects, visual span, degree of oculomotor adaptation needed, and frequency of a defined word. Globally, when reading with a central scotoma, it appears that within word characteristics have more impact than inter-word parameters on threshold character size.

Keywords Reading · Low vison · Central scotoma · Age-related macular degeneration · Rehabilitation

Introduction

Loss of, or reduction in, the ability to read is a leading complaint of patients with central scotomas associated with macular disorders, such as age-related macular degeneration (AMD) [40]. Generally, reading rates in patients with central field loss are low, around 25 words/minute, while rates for normal individuals in the same age range are at least around 130 words/minute [13, 20, 47, 48, 55]. Therefore, attempting to improve reading through training is a major consideration in low-vision rehabilitation. As part of this process, determination of the minimum level of magnification required to read continuous text and training technique for eccentric viewing are essential.

To define the minimum magnification needed, several methods have been proposed [42]. Based on reading speed measurements, the minimum print size at which the maximum reading rate is attained is referred to as the critical print size. As a rule, patients with central scotomas require magnification to reach a critical print size. Most often, two to four times magnification of the minimum angle of resolution for single letters is needed [7, 40]. In clinical practice and research, critical print size is usually determined over short duration tasks such as reading single sentences in Rapid Serial Visual Presentation (RSVP) [41], MNRead [26], Sloan reading cards [44] or the Pepper test [4, 46, 54]. The Pepper test has specifically been designed to assess the visual components of the reading process in low-vision individuals and to indicate the kinds of reading recognition mistakes the subject might make [4]. All these methods are of value in understanding the minimum magnification requirements for fluent reading performance and to inform about the ease of reading in normal and low vision. Additionally, other methods such as the Bailey reading chart [3] and the Radner Reading (RR) chart [35, 36, 47] allow the simultaneous measurement of reading speed and reading acuity. The RR chart also takes into account the word length, the position of words in the sentence, and lexical difficulty [35, 36, 47]. The relationship between word acuity and reading speed has already been extensively investigated (reviewed in [55]).

However, it should be emphasized that in daily life reading at the maximum possible rate is not in itself a priority. Additionally, sufficient understanding can be obtained on a wide range of reading speeds, including low reading rates [27].

Reading rate appears to be much more sensitive to scotoma size and depth than reading accuracy. Cummings et al. [11] have shown that, in contrast to a steady decrease in reading rate with increasing size of central scotoma, word recognition can remain accurate but slow with central scotomas up to about 20° in diameter. Moreover, Ergun et al., showed that reading speed and acuity were correlated with the size of the absolute scotoma in AMD, but not with the size of the relative scotoma [14]. Reading accuracy might then be an important initial goal during reading training for patients with a central scotoma, before maximizing reading speed [45].

In addition to single letter acuity and reading speed measures, word acuity is an important parameter for the assessment of an individual's ability to read accurately. It is unclear whether word recognition varies as a function of word length in normal subjects and in low-vision patients. It is not clearly established whether single letter acuity is a good predictor of text threshold print size [1, 2, 6, 25, 28]. Here we investigated the relationship between threshold character size for different word lengths and for paragraphed text in patients with central scotomas.

Materials and methods

Determination of threshold character size

We retrospectively analyzed data collected during the investigation of reading strategies in patients with central scotomas. Nineteen patients were studied (Table 1). They included 13 patients with age-related macular degeneration (AMD) and 6 with Stargardt's disease. In AMD patients ages ranged from 72 to 95 years (mean 80 years), and in Stargardt's patients ages ranged from 22 to 62 years (mean 39 years). All patients were fluent in French. They were investigated using a Scanning Laser Ophthalmoscope (SLO, Rodenstock, Germany). In each subject, the eye with the best visual acuity was investigated. The area of the scotoma was delineated using the scotometry program of the SLO. None of the patients had a residual island of vision within the scotomatous area. The scotoma diameter was calculated by averaging the values of its horizontal and vertical extents. Participants gave their informed consent to procedures and testing methods, all of which were in accordance with the declaration of Helsinki and had been accepted by the local ethical committee for human experimentation.

Stimuli were projected onto the retina through the SLO. The luminance level of the instrument was kept at 38 μW. Stimuli were of maximum contrast. Patients were asked to read aloud series of common French isolated words of 1, 2, 5, and 10 letters. The following eight character sizes were used: 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5 logMAR. All words were in lower case Times New Roman font, and were projected in a random order. Next, pages of a paragraphed text with the same range of character size were presented in decreasing order from 1.5 to 0.8 logMAR. At least 11 words were shown in each character size. Mean word length was 4.8±0.17 (SE) characters. Text reading was assessed using texts from school handbooks to equalize familiarity between patients with the subject of the text. Presentation time of visual stimuli was not restricted.

The threshold character size was considered as the smallest size at which a correct verbal report of the word could be made at the first attempt, all words of smaller size being read incorrectly. For paragraphed text, threshold character size was the smallest size that patients could read and understand (even if they got some words wrong). Patients stopped reading when they could no longer understand the text. Presentation time of the stimuli was not limited and patients were not requested to read as fast as possible. Statistical analyses were carried out using SPSS software (version 11.5).

Word-length distribution in newspaper articles

To assess possible influences of word-length frequencies on the threshold character size for text, we analyzed the distribution of word lengths in 16 articles of the four most read French newspapers in Switzerland. We selected four articles from each newspaper. Each article contained around 500 words (range 448–653). We removed all the numerical information, leaving a total of 8,774 words, then plotted word-length distribution. Word-length distribution in the newspaper articles was skewed, with two-letter words being the most common. This was similar to the word-length distribution in the texts used in the experiment. For the newspaper articles the mean word length was 4.7±2.89 (SD) characters. For the text used in the study the mean was 4.8±2.64 (SD) characters per word. Both distributions did not differ significantly (p=0.59, chi-squared test). It appears that the largest category is that of two-letter words. However, when adding up on one hand the total number of two-letter words and on the other hand the total number of words of five letters or more, it appears that the latter are more frequently represented.

Table 1 Clinical data and investigation results concerning the 19 patients examined

Participants	Diagnosis	Age (years)	Number of PRLs	Position of PRLs	Disease duration (years)	Mean scotoma diameter (°)	Threshold character size (logMAR)				
							Single letter	Two-letter words	Five-letter words	Ten-letter words	Text
1	AMD	78	2	Up left, up right	Unknown	2.8	1.1	0.9	1.2	1.1	1.1
2	AMD	79	1	Left	1	Not defined	1.1	1.0	1.4	1.3	1.3
3	AMD	78	1	Left	12	Not defined	0.8	0.9	0.9	1.1	1.0
4	SD	37	3	Up left, up, right	18	7.8	0.9	1.0	1.0	1.1	1.0
5	AMD	88	1	Left	1	8.2	1.0	0.9	1.4	1.3	1.2
6	SD	33	3	Left, up, right	19	9.4	1.0	0.9	1.0	0.9	1.0
7	AMD	72	1	Down left	Unknown	15.8	1.1	1.0	1.1	1.2	1.3
8	AMD	80	1	Up	10	29.3	1.1	1.1	1.3	1.3	1.2
9	SD	62	1	Up	17	12.5	1.1	1.3	1.3	1.1	1.3
10	SD	22	1	Up	10	9.9	1.0	0.9	1.0	1.0	1.0
11	SD	37	1	Up	19	15.4	1.0	1.0	1.1	1.1	1.1
12	SD	44	2	Left, up	24	Not defined	0.8	0.8	1.1	1.3	1.1
13	AMD	73	1	Left	2	13.5	1.0	1.0	1.5	1.5	1.5
14	AMD	89	1	Up	2	9.9	1.0	1.0	1.0	1.2	1.2
15	AMD	95	1	Up	2	14.6	1.0	0.9	1.2	1.1	1.1
16	AMD	76	1	Right	4	16.5	1.2	0.9	1.2	1.5	1.5
17	AMD	81	1	Right	Unknown	17.2	1.0	1.0	1.5	1.5	1.5
18	AMD	77	1	Down right	4	12.7	1.0	1.0	0.9	1.0	1.2
19	AMD	79	4	Left, up, right, down	4	10.4	0.8	1.0	1.0	1.1	1.0
							Threshold character size (mean and standard error)				
							1.0 (0.03)	0.97 (0.02)	1.16 (0.04)	1.20 (0.04)	1.19 (0.04)

SD Stargardt's disease, *AMD* age-related macular degeneration, *PRL* preferred retinal locus
The disease duration is the time since the diagnosis

Results

All patients showed one (14 patients) or multiple (5 patients) spontaneously established preferred retinal loci (PRL) for reading (Table 1). They used the same area(s) to read single letters, isolated words, and the paragraphed text.

Threshold character size

For the largest character size, text reading times ranged from 9 to 87 s (mean 28 s). The threshold character size varied for isolated words of different lengths and paragraphed text. The threshold character size for isolated words was reduced with an increased number of letters: it was on average 0.1– 0.2 logMAR better for single letters and two-letter words than for five- and ten-letter words, and paragraphed text (Fig. 1). Differences in threshold size according to word length were significant ($p<0.05$, repeated measures ANOVA test).

We determined the minimum word length showing a threshold character size similar to that found for text reading using a one-way ANOVA design, and the Bonferroni test adjusted for multiple comparisons. Threshold character sizes for different word lengths and paragraphed text were matched to test for possible equivalences. The results are presented in Tables 2 and 3. Threshold character size for isolated letters and two-letter words were matched ($p=1.0$, one-way ANOVA) as were threshold character sizes for five- and ten-letter words and paragraphed text ($p=1.0$, one way ANOVA). In contrast, threshold character sizes for isolated letters and two-letter words were statisti-

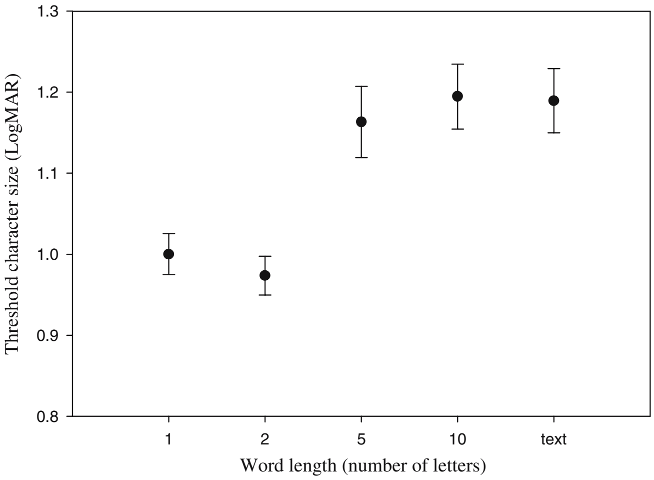

Fig. 1 Distribution of mean threshold character size (±SE) as a function of word length for all tested patients. Threshold character sizes for one- and two-letter words and that for five- and ten-letter words and text were not equivalent

cally different from those determined for the remaining categories.

Based on these results, two homogeneous subsets of data could be determined (Tables 2, 3). The first one included isolated letters and two-letter words whereas the second one contained five-letter words, ten-letter words, and paragraphed text.

Discussion

Our analysis showed that, in patients with a macular scotoma and a visual acuity worse than 0.8 logMAR, threshold character size for five- and ten-letter words was identical to that for paragraphed text. In contrast, threshold character size for single letter and two-letter words were significantly lower than that observed for paragraphed text.

Similar results were observed in patients with choroidal neovascularization and a visual acuity between 0.2 and 0.7 logMAR [39]. A key point in low-vision rehabilitation is to know the general reading characteristics of patients with macular scotoma, independently of the size of their lesion and their number or position of PRLs for the design of reading rehabilitation procedures.

Table 2 Results of the one-way ANOVA test using the Bonferroni correction factor

	Two-letter words	Five-letter words	Ten-letter words	Text
Single letter	>0.99	0.017	0.002	0.003
Two-letter words	–	0.003	<0.0001	<0.0001
Five-letter words	–	–	>0.99	>0.09
Ten-letter words	–	–	–	>0.09

Data showed that threshold character size for isolated letters and for two-letter words were similar, as were threshold character size for five-letter words, for ten-letter words, and for the paragraphed text

Table 3 Based on the results in Table 2, homogeneous subset tests using the Student–Newman–Keuls correction factor were conducted

Word length (number of letters)	*N*	Subset 1	Subset 2
1	19	0.974	
2	19	1.0	
5	19		1.163
10	19		1.189
Text	19		1.195
Significance		0.603	0.806

Measured threshold character sizes can be divided into two homogeneous subsets. Within each subset, no significant difference was found in the distribution of the data

We consider a variety of factors that could influence our results including: crowding effects, a restricted visual span in eccentric areas, the role of context in paragraphed text reading, word length distribution in paragraphed text, and adaptation in eye movement control when using peripheral vision. Each of these factors is now considered in more detail.

Crowding effect

Differences observed in words and paragraphed text threshold character sizes might be due to the crowding effect. This perceptual phenomenon, also known as contour or spatial interaction, results in better acuity for single isolated letters than for words in which letters are in close proximity [5, 33, 53]. Accordingly, long words would be more difficult to identify than short words. In normal readers, the crowding effect induces an underestimation of the length of small, closely packed letter strings [32].

Eccentric retinal areas are more susceptible to crowding effects than central areas due to increased spatial interactions [21, 23, 24, 52]. This difference has been studied during reading tasks and three main observations have been reported. Firstly, whereas in central areas contour interaction occurs only with the most proximal edge of the surrounding letters, in eccentric vision, the effect also involves more distant influences [24]. Similar findings were reported in individuals suffering from central field loss and using eccentric fixation [5, 18, 21, 31]. Secondly, spatial interactions depend on letter spacing [32]. In visually normal subjects, at all eccentricities, reading speed increases with letter spacing up to a critical value, close to that regularly used [8]. Wider letter spacing appears to be detrimental to reading, presumably as a result of the disruption of word characteristics, such as word shape [8].

Thirdly, the extent of spatial interactions do not scale with target size [24, 51].

Thus, in patients with a central scotoma, an increased crowding effect in eccentric fixation might explain the higher threshold character size observed for five- or ten-letter words than that for isolated letters or two-letter words. In paragraphed texts, an additional crowding effect might result from vertical interactions between successive lines and further interfere with reading [9], at least in subjects with normal vision unadapted to eccentric fixation.

Visual span in eccentric fixation

During the reading process several letters are deciphered in a fixation. In regular foveal reading of high contrast texts, saccades cover 6–8 characters on average [38]. In addition to forward saccades, regressive eye movements are also observed [37]. The pattern of fixations along a line probably depends upon the extent of the visual span, the region around the point of fixation within which characters can be resolved [34]. For normal readers, one model predicts a visual span including about fifteen characters of 0.4° [34], but experimental data showed that readers with normal vision use a visual span of 7–11 letters [16].

The shortening of forward saccades observed in readers with central scotomas is consistent with their having a restricted visual span [6, 22, 29, 43]. Legge et al. [29] estimated that in normal subjects the visual span decreases from ten letters in central vision to less than four letters at 10° in the lower visual field. This reduction qualitatively parallels the decrease in reading speed. Additionally, in AMD patients the scotoma often partially blocks the visual field and may limit the extent of the visual span.

Context in paragraphed text

Context facilitates word recognition when words are included in a paragraphed text, because the general meaning helps the deduction [30]. This effect was not found in patients with a central scotoma when reading with the inferior part of the retina [15], but was well marked in a simulation study in which participants read with the nasal part of the retina [17]. It is conceivable that the benefits of contextual effect counteract to a certain extent limitations resulting from crowding effects, reduced visual span and eye movement problems.

Word length distribution in paragraphed text

Differences in threshold character sizes observed between two-letter words and longer words can be related to frequency effects of both individual word repetition and word length. Firstly, most of the two-letter words in texts are very frequently used, as French articles and prepositions, and therefore are extremely familiar to the participants. As a result, two-letter words might be more easily predicted than longer words. Secondly, the number of existing two-letter words is lower than that of longer words. Participants could then easily guess such words even if they decipher only one of the two letters. For longer words, the probability of correctly guessing words, at the first attempt, decreases as the number of characters in a word increases because mistakes can theoretically occur on any letter. Thirdly, considering the word-length distribution in texts, the most represented category is that of two-letter words. However, in full texts, the total number of words longer than five letters exceeds the total number of one- and two-letter words.

Adaptation in eye movement control when using peripheral fixation

Eye movement control is critical for reading tasks, particularly when several saccades along a word or line of text are needed. Adaptation to a central scotoma must involve a remapping of the oculomotor control system to position and stabilize projected letters at extra-foveal locations [12, 19], referred to as preferred retinal loci (PRL) [19, 50]. Eccentric fixation improves with practice [10, 50], as well as non-foveated refixational saccades [11] until people are able to directly fixate using their PRL. Eye movement control and scotoma size appear to be related in patients with macular lesions. A more extended retinal lesion generally results in less precise eye movements [11, 14, 49, 56].

This study focused on the analysis of threshold character size, and did not include other factors involved in eccentric reading, such as return sweeps. Performing accurate return sweeps may be important in the development of eccentric reading strategies and relies upon precise eye movement control. Considering this, reading a paragraphed text needs a more complex adaptation of eye movements than reading isolated words. SLO characteristics may affect reading assessment, as the viewing posture is unnatural, the target luminance and background color do not conform to ideal testing, and the range of available target sizes is small.

A variety of factors, including character size, word length, context, central or eccentric fixation and integrity of the visual field affect reading performance. The higher frequency of short words and the context effect tend to facilitate reading whereas restriction in the visual field, crowding effects and the adaptation in control of eye movements would limit it. This underlines the importance of using adapted test to evaluate reading in different situations. For example, the Pepper VSTR is of particular interest to evaluate reading in people with a macular scotoma.

Other tests, adapted to low-vision reading evaluation in general, such as the Bailey Near Vision chart or the Radner Reading chart, have the advantage of using optotypes and are logarithmically scaled to allow simultaneous reading acuity and reading speed evaluation. Additionally, the Radner Reading chart also counts for lexical difficulty, syntactical complexity, word length, and position of words [35, 36].

Globally, when reading with central scotoma, it appears that within-word characteristics have more impact than inter-word parameters on threshold character size.

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