Vision Research 155 (2019) 1–10

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The influence of word frequency on word reading speed when individuals with macular diseases read text

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ARTICLE INFO

No. of Reviewers: 2

Keywords:
Central field loss
Macular degeneration
Reading
Psycholinguistics
Word frequency
Lexical simplification

ABSTRACT

People with central field loss (CFL) use peripheral vision to identify words. Eccentric vision provides ambiguous visual inputs to the processes leading to lexical access. Our purpose was to explore the hypothesis that this ambiguity leads to strong influences of inferential processes, our prediction being that increasing word frequency would decrease word reading time. Individuals with bilateral CFL induced by macular diseases read French sentences displayed with a self-paced reading method. Reading time of the last word of each sentence (target word) was recorded. Each target word (in sentence n) was matched with a synonym word (in sentence n + 1) of the same length. When using absolute frequency value (Analysis 1), we found that reading time of target words decreased when word frequency increases, even when controlling for word length. The amplitude of this effect is larger than reported in previous investigations of reading with normal subjects. When comparing the effect of relative frequency (low vs. high) within each pair of synonyms (Analysis 2), results show the same pattern as the one observed in Analysis 1. Our results demonstrate clear-cut frequency effects on word reading time and suggest that inferential processes are stronger in CFL readers than in normally sighted observers. These results might also help design text simplification tools tailored for low-vision patients.

1. Introduction

Age-related Macular Degeneration (AMD) is one of the main causes of low vision in industrialized countries and affects about 20% of the population over 65 years (Klein, Klein, & Cruickshanks, 1999; Wong et al., 2014). Like other macular diseases such as Stargardt's disease, cone dystrophy or myopic maculopathy, AMD causes a central field loss (CFL) that severely impairs reading, an activity that is usually the main complaint of these patients (Brown et al., 2014; Elliott et al., 1997; Mangione et al., 1998; Wolffsohn & Cochrane, 1999).

Currently-available treatments for AMD cannot always restore central vision and, in that case, patients' support is mainly based on low-vision rehabilitation and the use of visual aids (Meyniel, Bodaghi, & Robert, 2017). However, the use of these visual aids, whose principles are essentially based on magnification, is not sufficient to restore reading performance in patients with AMD (Chung, Mansfield, & Legge, 1998; Legge, 2007; Li, Lin, Lin, & Lee, 2002). This is why many efforts have been made to improve reading speed in peripheral vision by manipulating other visual factors such as: (1) text presentation mode, e.g. static, scrolling or flashing one word at a time (Bowers, Woods, & Peli, 2004; Fine & Peli, 1998; Rubin & Turano, 1994); (2) characteristics of the text, e.g. font (Bernard, Aguilar, & Castet, 2016; Mansfield, Legge, & Bane, 1996), text orientation (Calabrèse, Liu, & Legge, 2017), letter, word or interline spacing (Bernard, Scherlen, & Castet, 2007; Blackmore-Wright, Georgeson, & Anderson, 2013; Calabrèse et al., 2010; Chung, 2002; Chung, Jarvis, Woo, Hanson, & Jose, 2008; Yu,

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https://doi.org/10.1016/j.visres.2018.12.002
Received 29 May 2018; Received in revised form 6 December 2018; Accepted 6 December 2018
Available online 04 January 2019
0042-6989/

Cheung, Legge, & Chung, 2007); (3) perceptual learning, i.e. the performance improvement that follows practice of a sensory task (Chung, 2011; Chung, Legge, & Cheung, 2004). Mixed results have been obtained in terms of the clinical efficiency of these manipulations.

In this paper, we explore another consequence for CFL patients of the necessity of using their eccentric vision. Words processed in the periphery provide a very ambiguous low-level visual input, due for instance to confusions between letters (Pelli, 2008), which should induce a high influence of lexical inference processes (Legge, Klitz, & Tjan, 1997; Legge, Ahn, Klitz, & Luebker, 1997). Basically, when faced with an ambiguous percept (say a three-letter string starting with "c" and ending with "r"), a patient would make a guess about the most likely word having induced this percept (probably "car"). Thus, word frequency is expected to influence the speed with which a guess would be made. This is consistent with a recent investigation of eye movements in AMD patients during short-sentences reading that reported clusters of fixations that significantly reduce reading speed (Calabrèse, Bernard, Faure, Hoffart, & Castet, 2016). The clusters in some parts of a sentence indicated that specific words required dozens of fixations before successful identification, while the other ones were read with fewer fixations. The presence/absence of clusters was a significant predictor of reading speed, independently of the perceptual span size (Calabrèse, Bernard, Faure, Hoffart, & Castet, 2014). Interestingly, these clusters were more likely to occur in sentences containing a low-frequency word. This new finding suggested that low-frequency words might cause a local slowing of reading speed (i.e. a dense cluster of fixations) due to more difficult lexical access. However, the authors were not able to quantify the strength of the word frequency effect because their protocol did not allow for a clear determination of which word was being processed when a cluster occurred.

The main goal of the present work is to investigate this question further and study the direct effect of word frequency on word reading speed in individuals with bilateral macular disease. For normally sighted readers, factors such as word familiarity or word frequency are known to affect reading performance at different perceptual levels. To the best of our knowledge, the quantitative relationship between word frequency and natural reading performance with CFL has not been investigated yet. This contrasts with the wealth of the literature for normally sighted observers (Clifton et al., 2016; Kliegl, Nuthmann, & Engbert, 2006; Rayner, 1998). The main goal of the present study is thus to test whether word frequency affects word reading speed in individuals with CFL: it is expected that high-frequency words would lead to shorter reading times than low-frequency words. Two distinct analyses were performed to test the effect of word frequency on reading performance: Analysis 1, using absolute values of frequency (in occurrences/million) and Analysis 2, using frequency categories (low vs. high).

We used a reading presentation mode, known as "self-paced reading", that has never been used before in low-vision reading studies. Self-paced reading has been extensively used in psycholinguistic studies as a proxy for natural reading (Aaronson & Scarborough, 1976; Just, Carpenter, & Woolley, 1982; Mitchell & Green, 1978). In this context, natural reading, also called eye-mediated reading, refers to the natural process of reading that is used in daily life and requires eye movements; this has to be contrasted with paradigms such as RSVP (Rapid Serial Visual Presentation) requiring few or no eye movements since all words are presented one at a time at the same position (Rubin & Turano, 1992). With the self-paced reading paradigm, sentences appear as a whole, with all words masked and revealed only one at a time. Compared to other sequential word presentation modes, the self-paced reading paradigm reduces the amount of meaningful text to a single word, while maintaining the overall spatial layout of the sentence. Given that only one word is available to the reader at any given time, this paradigm makes it possible to identify in real time which word is being read, and thus to accurately measure the actual time spent reading each word.

Our secondary goal was to introduce the technique of text simplification and its potential benefit to facilitate reading performance with CFL. Text simplification is the process of reducing the complexity of a text by modifying the vocabulary or the syntax, while preserving its informational content (Shardlow, 2014). The purpose of this technique is to transform a text into a different one, which will convey the same message, while being easier to read and understand by a broader audience (Saggion, 2017). Text simplification techniques have been applied to dyslexic and aphasic patients and have been shown to improve reading performance (Siddharthan, 2014). However, text simplification has not yet been considered for CFL patients. The present work constitutes a first step towards the investigation of the simplification significance for this specific population. By testing the effect of word frequency on individuals with CFL, we focused on a small part of text simplification: the lexical substitution. Our results on word frequency suggest that lexical simplification techniques in general could be used successfully as a new reading aid for individuals with CFL.

2. Methods

2.1. Participants

29 participants were recruited from December 2016 to June 2017 from the Low-Vision Clinic of the La Timone Hospital (Marseille, France). Recruited patients had to present a bilateral central scotoma, accompanied or not by an additional peripheral lesion and be fluent French readers. Patients with ophthalmologic disorders other than maculopathy (e.g. glaucoma) or cognitive disorders were not included. There was no minimal visual acuity threshold. Among the 29 patients recruited, 6 were excluded from the study because they could not read an entire block of text due to their low-functional vision. 23 participants (14 females) were included in the present work. They had different etiologies: atrophic AMD (n = 11), exudative AMD (n = 2), Stargardt's disease (n = 4), cone dystrophy (n = 1) and myopic retinopathy (n = 5) (Kumar, Chawla, Kumawat, & Pillay, 2017; Silva, 2012; Vongphanit, Mitchell, & Jin Wang, 2002). Mean age (± SD) was 72 ± 15 years and ranged from 32 to 88. Mean best-corrected visual acuity was 0.87 logMAR. Additional information was collected for each individual: lens status, duration of maculopathy, low-vision rehabilitation history and reading habits. The research was approved by the Ethics Committee of the French Society of Ophthalmology (IRB 00008855 Société Française d'Ophtalmologie IRB#1) and carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was obtained from all participants after complete explanation of the nature and possible consequences of the study. Table 1 summarizes the participants' demographic, visual and reading characteristics.

2.2. Apparatus and stimuli

Stimuli were displayed on an LCD HP LE2201W monitor with a 60 Hz screen refresh rate. Within the full display area of this monitor (47.4 × 29.6 cm; 1680 × 1050 pixels), a 1400 × 1050 pixel window was used to display our stimuli. At the viewing distance of 40 cm, this window subtended 56° × 42°. Stimuli were created with the PsychoPy library (Peirce, 2007, 2009). Characters were black on a white background. Sentences were aligned to the left and displayed in Courier (non proportional font). Print size was chosen optimally for each participant as the value of his/her Critical Print Size, measured before testing with a French computerized version of MNREAD (Calabrèse et al., 2014). Reading was monocular (eye with better visual acuity) with an appropriate correction for near vision (wide-field Metrovision lenses).

Table 1
Participants' demographic, visual and reading characteristics. Visual acuity and lens status are given for the tested eye only. Participants with central scotoma only are highlighted in yellow. Participants with central scotoma and peripheral lesions are highlighted in blue. Participants with a reading time different from 0 were considered as "still reading" (cf Analyses 1 and 2). Missing values are represented by the symbol NA.

Participants	Gender	Age *(years)*	Etiology	Disease onset *(years)*	Low-vision rehabilitation	Visual acuity *(logMAR)*	Lens status	Daily reading time *(min/day)*
1	M	69	Atrophic AMD	9	Yes	0.5	Phakic	0
2	M	76	Atrophic AMD	2	No	1	Phakic	0
3	F	76	Atrophic AMD	16	Yes	1	Phakic	0
4	F	77	Atrophic AMD	7	No	*NA*	Pseudophakic	45
5	F	79	Atrophic AMD	5	Yes	0.8	Phakic	5
6	F	80	Atrophic AMD	6	Yes	1	Phakic	25
7	M	81	Atrophic AMD	2	Yes	0.8	Pseudophakic	15
8	F	82	Atrophic AMD	12	Yes	0.5	Phakic	10
9	F	83	Atrophic AMD	1	Yes	0.7	Pseudophakic	0
10	F	85	Atrophic AMD	15	No	0.7	Pseudophakic	60
11	M	88	Atrophic AMD	22	Yes	0.6	Phakic	*NA*
12	M	85	Exudative AMD	5	Yes	0.7	Pseudophakic	60
13	F	87	Exudative AMD	1.5	Yes	0.5	Pseudophakic	20
14	M	47	Stargardt's disease	24	No	1.2	Phakic	360
15	F	48	Stargardt's disease	35	Yes	1.3	Phakic	20
16	M	51	Stargardt's disease	37	No	1.2	Phakic	60
17	F	72	Stargardt's disease	16	No	1	Phakic	120
18	F	32	Cone dystrophy	30	No	1	Phakic	*NA*
19	M	59	Myopic retinopathy	15	Yes	1	Phakic	3
20	F	69	Myopic retinopathy	21	Yes	1.3	Pseudophakic	120
21	F	70	Myopic retinopathy	62	Yes	0.8	Pseudophakic	12
22	M	78	Myopic retinopathy + AMD	6	Yes	0.6	Pseudophakic	5
23	F	82	Myopic retinopathy + AMD	41	Yes	1	Pseudophakic	30

2.3. Reading material

Reading material was created in French using ReSyf, a French graded lexicon (Billami, François, & Gala, 2018) and Lexique3, a French lexical database (New, Brysbaert, Veronis, & Pallier, 2007). First, we created hundreds of pairs of synonyms by selecting a word of any frequency along with its higher frequency synonym. We used the frequency of the lemma, which includes all the inflexional variants of a word (e.g. gender, number, tense, etc.). Lemma frequency (in occurrences/million) was estimated from a corpus of French film subtitles. Among the synonym pairs created, we then selected the ones that met the following criteria: (1) same number of characters within a pair (ranging from 5 to 10 characters); (2) frequency ratio between a high-frequency word and its low-frequency synonym comprised between 5 and 10. A total of 32 pairs of synonyms were selected (Fig. 1 – Step 1).

From these 32 pairs of target words, we then created 32 pairs of matching sentences so that each word from a pair could fit at the end of either sentence of the corresponding sentence pair. To this end, pairs of sentences were specifically designed to fit the single common sense of a synonym pair. An example is given in Fig. 1, with the polysemic word 'records', that means both 'documentation' and 'discs', and its synonym 'archive'. In the sentence "This is probably one of my favorite records", records and archive convey different senses and cannot be considered interchangeable synonyms anymore. Therefore, acceptable sentences for this synonym pair must refer to the meaning 'documentation' only. Apart from this context constraint, all sentences were created similar in length (41–65 characters), with a maximum difference of 5 characters within a pair (Fig. 1 – Step 2). Lastly, we created our final reading material by combining these sentence pairs with their matching pairs of synonyms (Fig. 1 – Step 3). In Condition 1, the first word of a pair was assigned to the first sentence of the corresponding pair, while the second word was assigned to the second sentence, thus creating 64 full sentences. In Condition 2, the "sentence – word" matching was reversed to create a different set of 64 full sentences. These two experimental conditions allowed us to counterbalance any potential effect of the sentence itself (structure, complexity, predictability) by randomly assigning participants to Condition 1 or 2 (Steen-Baker et al., 2017). Fig. 1 illustrates the full creation process.

2.4. Reading procedure and experimental design

Sentences were presented within 4 blocks of 16 trials (8 pairs of sentences) each. Participants were randomly assigned to Condition 1 or 2 and read between two and four blocks, depending on their individual reading speed and level of fatigue. Sentences were displayed with the self-paced reading paradigm and presented randomly within each block (Fig. 2). Participants were instructed to read aloud as quickly and accurately as possible as soon as the sentence appeared. At the beginning of each trial, the experimenter triggered the display of a sentence, which appeared on the screen with the first word unmasked and all other words masked by strings of "x". Participants were in charge of revealing the whole sentence, one word at a time, using a keyboard in front of them. They could either unmask forward or backward (to reveal again words they already read) as many times as they wanted. When participants considered they had finished reading the sentence accurately (no matter which word was unmasked at that moment), they said the word "stop" and the experimenter stopped the trial. A preliminary training phase with short sentences (French proverbs) was performed to familiarize the participant with the task and protocol. When the participant was comfortable with the keys and instructions, the test phase began and the blocks of sentences were presented.

Reading time (in seconds) was programmatically recorded for each

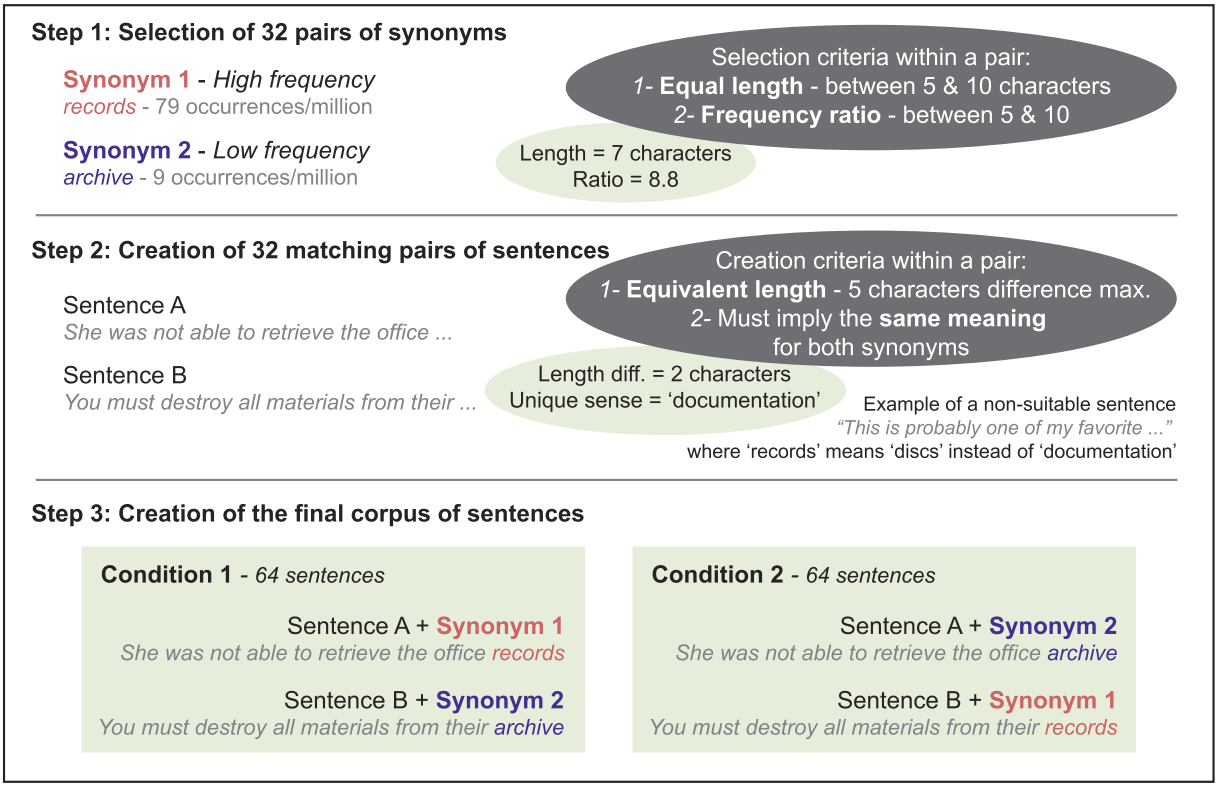

Fig. 1. Creation of the reading material Illustration of the reading material creation using the synonym pair "*records/archive*". Both words in this example contain 7 characters and have a frequency ratio (in French) of 79/9 = 8.8. Sentences A and B were created so that either word of this synonym pair can fit at the end of both sentences. In Condition 1, sentence A contains the target word 1 ('records') and sentence B contains the target word 2 ('archive'). In Condition 2, sentence A contains the target word 2 and sentence B contains the target word 1. Note that this example is given in English to ease understanding. See Appendix 1 for the complete set of French sentences created.

word as the time during which it was unmasked. For words unmasked only once, total reading time was equal to the first-pass reading time (i.e. the first – *and only* – unmasked period). For words unmasked several times, total reading time was the sum of all the unmasked periods.

2.5. Statistical analysis

Statistical analyses were carried out using R (R Core Team, 2018) with the following additional R-packages: ggplot2, tidyr, dplyr, gridextra, lme4, stringr. Analyses 1 and 2 were performed with linear mixed-effects models that allow the modeling of experimental designs with unbalanced repeated measures (Bolker et al., 2009; Cheng, Edwards, Maldonado-Molina, Komro, & Muller, 2010). For each analysis, several models were first constructed with total reading time and accuracy of each target word as dependent variables. Reading time and word frequency value were transformed in natural logarithm (ln) units. The continuous variables were centered around their mean. In a second step, the Akaike Information Criterion (AIC) and likelihood-ratio tests were used to assess an optimal random-effects structure (Zuur, Ieno, & Elphick, 2010). Once an optimal model structure had been chosen, significance of the fixed effects was estimated using t-values. Usually, the number of degrees of freedom for the t-values of the fixed effects are not exactly known with mixed-effects models (Baayen, Davidson, & Bates, 2008; Pinheiro & Bates, 2000). However, given the large number of observations in the present study, the t-distribution converges to a normal distribution. Therefore, following standard recommendations, t-values (i.e. estimate/standard error) that were larger than 2 were considered significant, which corresponds to a significance level of 5% in a two-tailed test (Baayen et al., 2008; Gelman & Hill, 2007). Finally, assumptions underlying the models were visually checked with diagnostic plots of residuals (Cohen, Cohen, West, & Aiken, 2003; Pinheiro & Bates, 2000). In the Results section fixed-effects estimates are reported along with their t-values and 95% confidence intervals (Bates, Mächler, Bolker, & Walker, 2015).

3. Results

3.1. Analysis 1: effect of word frequency value on reading performance

Here we tested the effect of frequency value of the target words (in occurrences/million) on both reading accuracy and total reading time. On average, target words were read accurately 93% of the time, with individual variations ranging from 69 to 100% depending on participants. We found that the effect of word frequency on reading accuracy was not significant (estimate = 0.005, 95% CI = [−0.003; 0.01]), probably due to ceiling effects. Fig. 3 shows the target word total reading time of as a function of target word frequency, for all trials and participants. This relationship was further analysed for correct trials only with a linear mixed-effects model containing the following factors as fixed effects: target word frequency, word length (in number of characters), age, low-vision rehabilitation history (yes or no) and "still reading" (yes or no). The random effects were the following: subjects, per subject frequency slopes, target words and condition (nested within target words). The mixed-effects analysis showed a significant effect of word frequency on reading time, as represented by the black solid line in Fig. 3. Results of the model are shown in Table 2.

The main factor of interest, word frequency, had a significant effect with a regression coefficient estimate of −0.10 (95% CI = [−0.138; −0.06]). As both reading time and frequency are expressed in natural log units, this means that multiplying frequency (in original units) by 10 multiplies reading time (in original units) by 0.79 (10 ˆ −0.10), i.e. a

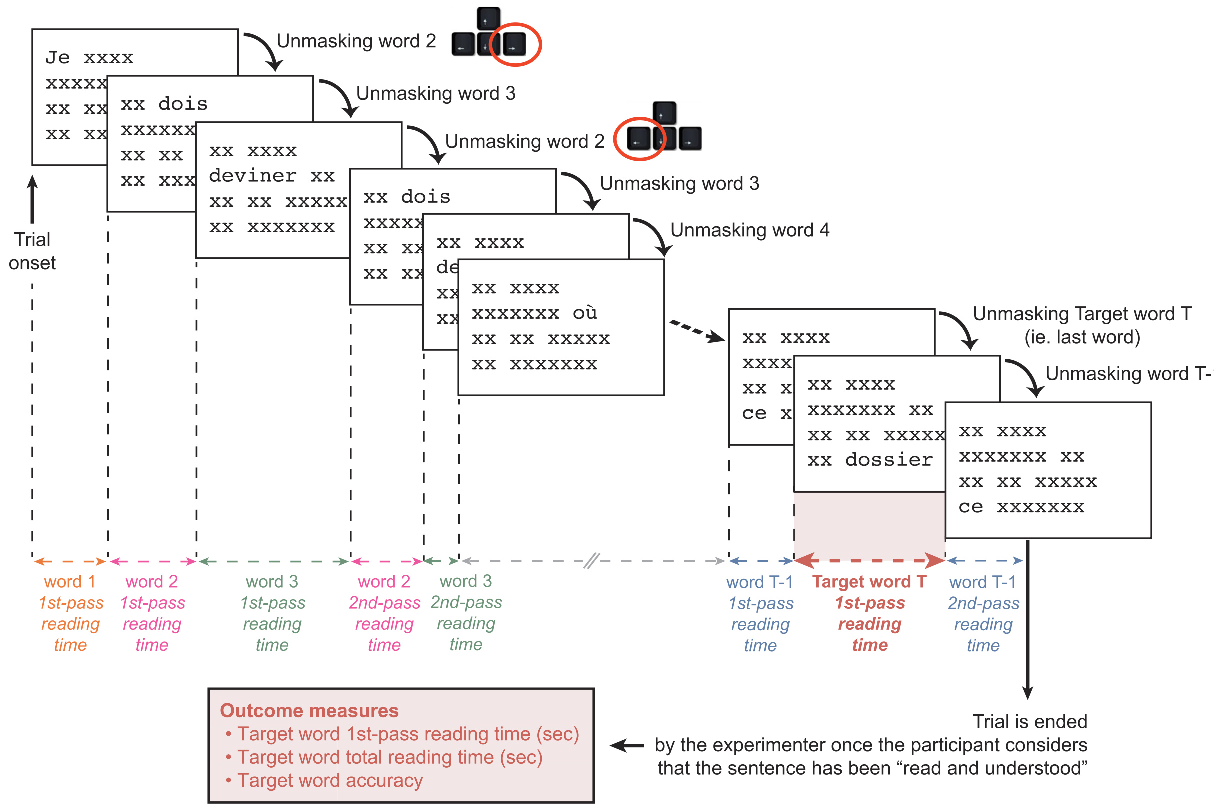

Fig. 2. Self-paced Reading paradigm Words are revealed one at a time by the participant, using keyboard presses. At any given time during a trial, a press on the right arrow key will unmask the upcoming word (while masking the currently visible word) and a press on the left arrow key will unmask the previous word (while masking the currently visible word). For words unmasked only once (e.g. word 1), the total reading time equals the 1st-pass reading time. For words unmasked more than once (e.g. word 2), the total reading time is the sum of each individual reading time pass. Target word T is located at the end of the sentence but is not necessarily unmasked at the end of the trial, as in this example where the participant unmasked the word T-1 to confirm it had been read accurately before responding to end the trial.

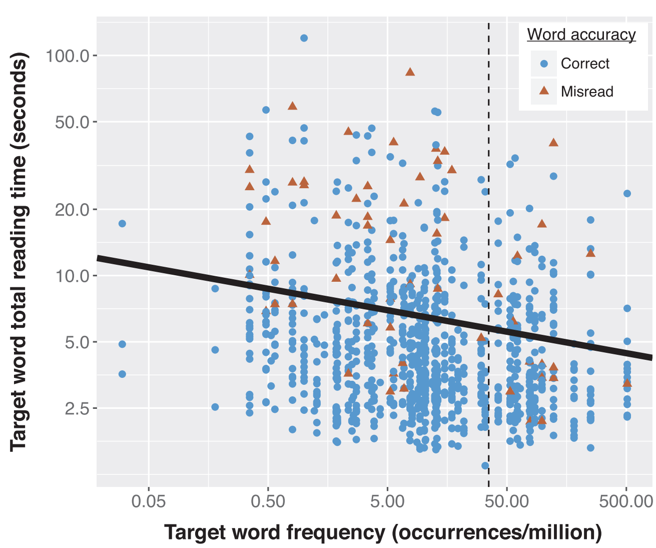

Fig. 3. Scatterplot of target word total reading time as a function of word frequency value (Analysis 1). Data are plotted for target words read both correctly (blue circles) and incorrectly (red triangles). The black solid line represents the slope of the frequency effect for words read correctly only, as estimated by the mixed-effects model. The dashed vertical line represents the mean word frequency value in initial units (about 35 occurrences/million). Note the log scales used for both axes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

21% decrease. Similarly, we can also express the effect's amplitude in the following way: multiplying frequency (in original units) by 1000 (from 0.5 to 500, i.e. the range where most of our values lie) multiplies reading time (in original units) by 0.5 ($1000^{-0.10}$), i.e. a 50% decrease. It is notable that low-frequency words are on average longer than high-frequency words, so that the frequency effect could have been induced by the confound between word length and word frequency (Kliegl, Olson, & Davidson, 1982; Rayner & Duffy, 1986) – the correlation was −0.17 in the present study. This possibility was however eliminated here by partialling out the effect of word length in the model. Finally, we did not find any interaction between word frequency and word length (estimate = −0.002, 95% CI = [−0.02; 0.02]. This result is not consistent with previous studies of natural reading in normally sighted skilled readers based on gaze duration (Hyönä & Olson, 1995; Kliegl et al., 2006). Because age is a predictor of reading speed, even for people with normal visual acuity and self-reported healthy vision (Calabrèse, Cheng, et al., 2016; Lott et al., 2001; Warrington, McGowan, Paterson, & White, 2018), we controlled for its effect by including this factor in our model. Although age was found to be non significant, it must be controlled for because it correlates with other factors, such as motor or attention deficits, that influence reading speed (Sass, Legge, & Lee, 2006). The last factor with a statistically significant effect on reading time was the binary "still reading" (estimate = −0.558, 95% CI = [−0.984; −0.132]). According to the model, participants who still read, even a few minutes each day, are expected to have their word reading time multiplied by 0.57 (exp [−0.558]), i.e. a decrease of 43%. Note that similar results were found when using first-pass reading time as the dependent variable, instead of total reading time (Fig. 2).

Table 2
Results of the mixed-effects model from Analysis 1: fixed effects estimates. The dependent variable is target word total reading time. The reference level of categorical binary factors is italicized. Factors showing a significant effect on reading time are in bold font.

	Estimate	Standard error	t-value	95% Confidence Interval
Intercept	2.09	0.025	8.3	[1.6; 2.56]
Word frequency (ln)	**−0.10**	**0.02**	**−4.98**	**[-0.138; −0.06]**
Word length (n. of characters)	−0.00004	0.023	−0.042	[-0.046; 0.044]
Age (years)	0.003	0.006	0.551	[-0.008; 0.015]
Low-vision rehabilitation	−0.063	0.197	−0.317	[-0.454; 0.321]
No				
Still reading	**−0.558**	**0.225**	**−2.482**	**[-0.984; −0.132]**
No				

3.2. Analysis 2: effect of word frequency category on reading performance

Within each pair of synonyms, we tested the effect of frequency category (low vs. high) of the target words on both reading accuracy and total reading time. First we found that frequency category did not have a significant effect on target word accuracy within pairs (estimate = −0.009, 95% CI = [−0.04; 0.02]): low-frequency synonyms were not read less accurately than their higher frequency counterpart. To analyse the effect of frequency category on target word total reading time, we removed all pairs containing one or two inaccurately read words.

The linear mixed-effects model was the same as in Analysis 1 except for two points. First, frequency category (low vs. high) was used as a fixed effect (instead of the continuous frequency value factor). Second, the random structure was different to accommodate for the within-pair analysis so that the optimal model contained: the subject factor, the pair factor and the by-pair category frequency factor as random effects. The results of the model are shown in Table 3.

Within-pair frequency category was found to be a significant predictor of target word total reading time (estimate = −0.13; 95% CI = [−0.23; −0.04]). This means that high-frequency words have a reading time that is multiplied by 0.87 (exp[−0.133]) compared to their low-frequency synonyms (i.e. a 13% decrease). This effect is represented in Fig. 4 by thick solid lines. The dashed lines in this figure show the mean values for each participant, emphasizing that the amplitude of the frequency effect at the population level (solid lines) is quite small compared to the between-subjects differences. Despite being statistically significant, the 13% decrease in reading time induced by higher frequencies does not seem impressive in terms of clinical relevance. This relatively modest decrease is most likely due to the limited frequency ratio assigned to synonyms of each pair. Indeed, the within-pair frequency ratio was set between 5 and 10 in the present work (Fig. 1 – step1), with an average of 7.07. Using results from Analysis 1 to predict the amplitude of the frequency category effect without by-pair grouping, we find that total reading time for high-frequency words would be multiplied by 0.82 (7.07 ^ −0.10 – see Table 2) compared to their low-frequency synonyms. This 18% decrease, predicted from Analysis 1, is thus very close to the 13% reduction found in Analysis 2. We hypothesize that increasing the ratio of frequencies within pair of synonyms should boost the frequency category effect up to a clinically relevant improvement. Finally, we found that the "still reading" factor had a significant effect on total reading time (Fig. 4 & Table 3), similar to the one reported in Analysis 1.

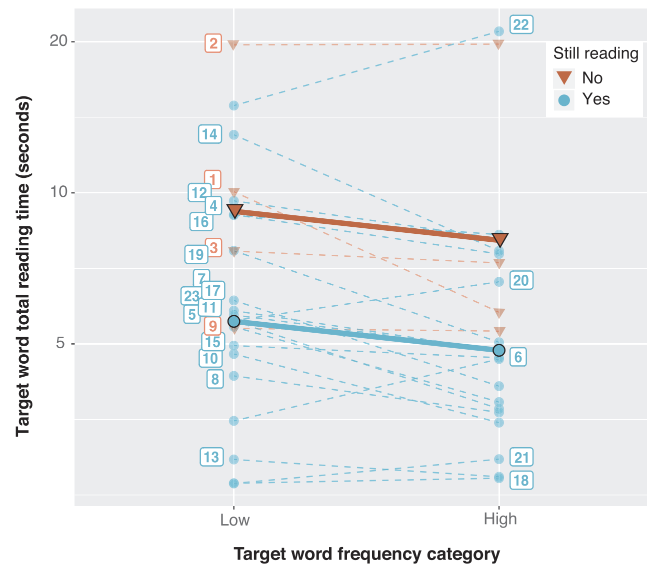

Fig. 4. Effect of frequency category on target word reading time for both the "still reading" (blue circles) and the "not still reading" (red inverted triangles) groups (Analysis 2). Solid lines connect the estimates for each group as given by the mixed-effects model. Dashed lines connect the mean reading time values for each participant, labeled from 1 to 23. Individual trends (downward vs. upward) are represented by the labels' position (left vs. right). Note the log scale for the y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The general objective of this work was to investigate whether and

Table 3
Results of the mixed-effects model from Analysis 2: fixed effects estimates. The dependent variable is the target words total reading time. The reference level of categorical binary factors is italicized. Factors with a significant effect on reading time are in bold font.

	Estimate	Standard error	t-value	95% Confidence interval
intercept	2.21	0.27	8.2	[1.7; 2.7]
Frequency category	**−0.133**	**0.046**	**−2.882**	**[−0.227; −0.043]**
Low frequency				
Word length (n. of characters)	0.051	0.034	1.498	[−0.016; 0.118]
Age (years)	0.003	0.007	0.501	[−0.009; 0.016]
Low vision rehabilitation	−0.188	0.214	−0.88	[−0.588; 0.211]
No				
Still reading	**−0.505**	**0.24**	**−2.104**	**[−0.953; −0.057]**
No				

how the degraded visual input of individuals with central field loss alters the processes linking low-level visual analysis of words to lexical access. More precisely, our first purpose was to assess the effect of word frequency on word reading time when individuals with bilateral maculopathy are engaged in natural reading. The dependent variable in our study was the reading time of target words (included within sentences) whose visual and linguistic properties are accurately controlled. This has never been studied before in visually impaired patients during natural reading (i.e. eye-mediated reading).

We used the method of self-paced reading as it allowed us to measure the reading time of individual words either for first-pass reading or for second- and nth-pass reading. Thus, when a word is unmasked for long periods (e.g. 10 s), we can safely assume that many fixations have been made and constitute a cluster as previously described (Calabrèse, Bernard, et al., 2016). Results obtained with this method can be fruitfully compared to those from eye movement studies of natural reading (Clifton et al., 2016; Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008; Rayner, 1998). In this huge literature, one important dependent variable is "gaze duration", classically defined as the total fixation time on word n before gaze position moves on to word n + 1 for the first time: this might correspond to one or several fixations (when several fixations are made, they are called "refixations" on the same word). Another measure is "total fixation duration" (sum of all fixations on a word n, including those induced by regressive saccades from words to the right of word n). Gaze duration is typically interpreted as reflecting earlier processes than those measured by total fixation duration. In our study, we assume that our two dependent variables, first-pass reading time and total reading time, are relevant proxies of gaze duration and total fixation duration (the only approximation being that durations of saccades are ignored). It is worth noting that in normal reading, short connector words and articles are often skipped entirely by gaze position, whereas the self-paced reading paradigm forces subjects to fixate on each word of the sentence, possibly modifying their reading behavior. However, this point is not relevant in the present study because none of the target words were short connector words or articles.

Our results show a clear-cut effect of word frequency on word reading time (whether first-pass reading time or total reading time) even after partialling out the effect of word length (Kliegl et al., 1982; Rayner & Duffy, 1986). This result is consistent with recent findings reporting that reading speed was significantly reduced by the presence of clusters of fixations and that these clusters seemed located near the words with the lowest frequency (Calabrèse, Bernard, et al., 2016). This result is also in line with the effect of word frequency for subjects with normal vision: higher frequency words yield faster reading speed. However, the effect of word frequency found in our CFL participants is much greater than what has been reported before for normally sighted subjects. In an influential natural reading study with skilled readers, it was reported that gaze duration decreases from 240 to 207 ms when word frequency is multiplied by 1000 – from 1 to 4 log 10 units (Kliegl et al., 2006). Despite some differences in methodology between this work and the present study, the 14% decrease in gaze duration reported in Kliegl et al., 2006 can be compared to the much larger 50% decrease that we report in Analysis 1 for the same range of word frequencies. Such difference suggests that low-vision individuals rely more on lexical inference than normally sighted subjects.

Our work might be related to a previous study investigating the effect of word frequency on lexical decision accuracy with normally sighted observers (Lee, Legge, & Ortiz, 2003). The task was to decide whether stimuli of different durations and seen either with foveal or peripheral vision were words or pseudo-words. The authors reported that significant frequency effects occurred for the shortest durations in central vision, 25–50 ms, whereas significant frequency effects did not occur in peripheral vision until 100 ms. Although it is difficult to predict how these effects relate to a natural reading task, this study was important because it raised the major question of lexical access in peripheral vision. This important issue was also addressed in "Mr Chips", an implemented ideal-observer model of low-vision reading (Legge, Hooven, Klitz, Mansfield, & Tjan, 2002; Legge, Klitz, et al., 1997). Because this model integrates visual and lexical information to predict the pattern of eye fixations required to read a given text, lexical access constraint is expected to induce frequency effects on fixation duration.

Our results do not show any evidence for an effect of word length on word reading time although this effect is commonly reported in eye movement research on natural reading: word reading time increases with word length, mainly as a result of the increasing number of "refixations" (Hyönä & Olson, 1995; Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl et al., 2006, 1982; Vitu, McConkie, Kerr, & O'Regan, 2001; Vitu, O'Regan, & Mittau, 1990). Typically, normally sighted readers would make one single fixation on 5-character words and two fixations on 10-character words. This apparent discrepancy about the word length effect between CFL and normally sighted readers is probably due to diverse factors. First, the range of word lengths used in our study is probably too small (relative to the high variability in the dependent variable) to uncover an effect of word length whose amplitude and robustness are known to be smaller than the frequency effect for instance. Word length goes from 5 to 10 characters in the present study, whereas the range of lengths can be as high as 2–20 in some studies (Kliegl et al., 2006). Second, it is possible that the effect of word length is absent, or difficult to measure, in our study because people with CFL systematically make many fixations on nearly all the words of a sentence (Calabrèse, Bernard, et al., 2016; Calabrèse et al., 2014; Scherlen, Bernard, Calabrese, & Castet, 2008). This high base level would make any subtle difference such as the word length effect more difficult to extract.

The secondary purpose of our work was to consider the potential of text simplification as a valuable tool allowing to improve reading performance of visually impaired patients. One of the many possibilities offered by text simplification is to replace complex words by their simpler synonyms (Saggion, 2017), a transformation which requires agreement on a definition of word complexity. In this work, we decided to use word frequency as a surrogate of word complexity. Our second statistical analysis was thus performed on pairs of target word synonyms and showed an effect of relative frequency category (low vs. high) on word reading time: participants read target words of higher relative frequency faster than their lower frequency synonyms.

Importantly, the amplitude of this frequency category effect could be approximated from the mixed-effects model run in Analysis 1, which did not take into account the by-pair grouping. This result is encouraging because it shows that a moderate frequency effect can be observed between synonyms having a relatively moderate difference in frequency (the frequency ratio ranged from 5 to 10 in the present study, with an average of 7) over a very large range of frequencies. In other words, our results do not apply only to the low frequency words of the French language. They apply to a large range of frequencies (say between 0.5 and 50 occurrences per million – Fig. 3) and thus concern a very large number of words. As long as the numerous words lying within this range have synonyms of slightly higher frequency (ratio > about 7), a benefit in reading time is predicted by our statistical analysis. Of course, if synonyms with a higher ratio than 10 exist, they should be chosen preferentially by text simplification algorithms as the predicted reading time decrease would be larger.

Recent advances in the domain of natural language processing, at the frontier between linguistics computer science and artificial intelligence, should allow a large-scale implementation of text simplification methods. Among the current possibilities offered by text simplification, lexical simplification based on word frequency, among other factors, is easy to implement in automated algorithms and could be applied to various contexts (in electronic books, web sites, etc.). Hopefully, reducing the complexity of lexical units in text, without changing meaning, should improve overall reading performance of low-vision readers. We feel that the most important aspect of this improvement would not be the increased performance (e.g. in reading speed) *per se* but the possibility of keeping a certain level of motivation for reading activities. What our results clearly show is that people who keep on reading are those who read faster. This correlation between the motivation to read and word reading speed may create either a vicious circle or a virtuous one. It seems therefore important to help low-vision persons fight against this pattern. Our hope is that text simplification might encourage low-vision readers to read more and more often, which would, in turn, maintain a certain level of practice preventing them from stopping reading activities altogether.

5. Conclusion

This study showed a robust and large amplitude effect (+50%) of word frequency on word reading time when participants with macular diseases read text. The strength of this effect suggests that lexical access in CFL readers heavily relies on inferential processes compared to normally sighted observers. Our study also highlighted the potential benefits of lexical simplification when replacing a word by a synonym of higher frequency. More generally, the long-term challenge of this work is to investigate what aspects of visual, lexical and sentence processing can be simplified in order to significantly improve reading performance of low-vision patients.

One asset of our study is that the amplitude of the frequency effect is quantified by a regression coefficient while controlling for other relevant factors. This should allow future research to quantitatively compare whether the frequency effect is more capable of improving reading speed than other factors. Similarly, regression analyses should also help decide if the effects of frequency or other factors are the same for different categories of reading deficits (e.g. dyslexia, aphasia). If differential effects were found, this would suggest that methods of text simplification should be adapted to the specific needs of different reading disorders.

Acknowledgments

This work was supported by the Fondation de France and by the Belgian FNRS. The authors thank Dr Frédéric Chouraqui and Dr Alban Comet for their help in recruiting the participants.

Funding

This work was supported by the Fondation de France and by the Belgian FNRS.

Declarations of interest

None.

Appendix 1

C'est en rentrant dans la cour que j'ai vu mon **garçon (fiston)**
J'aimerais bien aller à la maison avec mon **fiston (garçon)**
Il est dommage qu'il n'ait pas pu montrer ses **capacités (aptitudes)**
Il aurait vraiment pu essayer de développer ses **aptitudes (capacités)**
La petite fille demande si elle peut faire des **biscuits (galettes)**
Il a proposé de venir chez elle et d'apporter des **galettes (biscuits)**
Après tout ce qu'il lui a dit, elle ne peut que le **détester (mépriser)**
Plus le temps passait, plus il était amené à la **mépriser (détester)**
Pour bien dessiner, tout est question de bonnes **habitudes (pratiques)**
Pour faire ce métier, il faut avoir de bonnes **pratiques (habitudes)**
Cette décision n'a rien à voir avec une **punition (sanction)**
Je pense qu'il aurait préféré une autre **sanction (punition)**
Cet homme grand a quelque chose en lui de très **étrange (suspect)**
Il est entré dans la maison et il avait l'air **suspect (étrange)**
Après toutes ces années, voici sa plus belle **découverte (trouvaille)**
Tout le monde a été impressionné par cette **trouvaille (découverte)**
Je sais qu'il a toujours de l'air chaud qui sort de sa **narine (naseau)**
Il utilise une solution spéciale pour nettoyer chaque **naseau (narine)**
C'est sur les grands boulevards qu'a eu lieu cette **marche (défilé)**
Ils se sont préparés longtemps pour organiser ce **défilé (marche)**
Il reste de la terre car ce trou était facile à **remplir (combler)**
Ses enfants l'ont vécu comme un vide difficile à **combler (remplir)**
Toute son équipe savait qu'il a donné sa vie à sa **recherche (invention)**
Ils veulent faire connaître au monde entier leur **invention (recherche)**
Je lui ai montré une peinture avec un magnifique **buisson (arbuste)**
Si tu vas derrière la pharmacie, tu verras un étrange **arbuste (buisson)**
En politique, comme en amour, on a parfois besoin de **repos (trêve)**
Etant donnée ton attitude, tu ne mérites pas de **trêve (repos)**
Ils ont essayé par tous les moyens de le **corrompre (débaucher)**
Ce n'est pas faute d'avoir tenté de les **débaucher (corrompre)**
L'homme est bon par nature, la société ne fait que le **dégrader (dépraver)**
Avec son passé, cela n'a pas été très difficile de le **dépraver (dégrader)**
Cette association compte plus de curieux que de **disciples (adhérents)**
Il faudrait encore leur demander d'appeler les **adhérents (disciples)**
Elle m'a prévenu qu'elle voulait qu'on respecte son **souhait (vouloir)**
Cependant, il n'est pas question qu'on suive son **vouloir (souhait)**
Pour réussir ce plat, il faut choisir une belle **salade (laitue)**
Si tu y penses, rapporte de la lessive et une **laitue (salade)**
Il aurait fallu être très malin pour le **prévoir (prédire)**
Il faut que tu arrêtes d'essayer de tout **prédire (prévoir)**
Le passé composé est un temps très facile à **utiliser (employer)**
Tu disposes de nombreux outils, il faut les **employer (utiliser)**
Je compte sur toi pour m'aider à trouver la **somme (total)**
Il a remarqué que cela ne correspond pas au **total (somme)**
Pendant le rendez-vous, elle l'a trouvé complètement **dingue (cinglé)**
L'autre jour il leur est arrivé quelque chose de **cinglé (dingue)**

Les fêtes approchent et tu ne dois pas oublier de le **rendre (livrer)**
Ils l'ont prévenu qu'il n'avait que deux jours pour se **livrer (rendre)**
Pour réparer cet ordinateur, il faut faire une nouvelle **demande (requête)**
Il a pris un rendez-vous et son patron pourra recevoir sa **requête (demande)**
Il était gêné de demander une culotte de femme au **commerçant (colporteur)**
Je n'ai pas assez d'argent pour aller chez ce **colporteur (commerçant)**
Je dois deviner où tu as rangé ce **dossier (archive)**
Je n'ai pas réussi à retrouver cette **archive (dossier)**
J'ai rencontré un homme avec un humour **piquant (mordant)**
Ses commentaires manquent souvent de **mordant (piquant)**
Penser est pour lui un accident au lieu d'un état **permanent (continuel)**
Il faut rester calme et serein même si c'est un défi **continuel (permanent)**
Cette nouvelle m'a laissé dans un état de grand **abattement (sidération)**
Il a traversé une phase de colère puis de profonde **sidération (abattement)**
C'est pour cela que toute la famille part faire une **marche (balade)**
Il avait besoin de changer d'air et est allé faire une **balade (marche)**
Après avoir travaillé sur cette loi, il a décidé de la **retarder (ajourner)**
Ce n'est pas possible de perdre encore du temps et de l'**ajourner (retarder)**

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