Eye Movements and Reading Speed in Macular Disease: The Shrinking Perceptual Span Hypothesis Requires and Is Supported by a Mediation Analysis

Aurélie Calabrèse,[1] Jean-Baptiste Bernard,[2] Géraldine Faure,[3] Louis Hoffart,[4] and Eric Castet[2]

[1]Minnesota Laboratory for Low-Vision Research, University of Minnesota, Minneapolis, United States
[2]Aix Marseille University, CNRS, LPC UMR 7290, Marseille, France
[3]Low Vision Clinic, University Hospital of La Timone, Marseille, France
[4]Department of Ophthalmology, University Hospital of La Timone, Marseille, France

Correspondence: Eric Castet, Université Aix Marseille - CNRS, UMR 7290, Laboratoire de Psychologie Cognitive 3, place Victor Hugo - case D, 13331 Marseille cedex 3, France; eric.castet@univ-amu.fr.

Submitted: October 9, 2013
Accepted: April 24, 2014

Citation: Calabrèse A, Bernard J-B, Faure G, Hoffart L, Castet E. Eye movements and reading speed in macular disease: the shrinking perceptual span hypothesis requires and is supported by a mediation analysis. *Invest Ophthalmol Vis Sci*. 2014;55:3638–3645. DOI: 10.1167/iovs.13-13408

Purpose. Reading speed of patients with central field loss (CFL) correlates with the size of saccades (measured in letters per forward saccade [L/FS]). We assessed whether this effect is mediated by the total number of fixations, by the average fixation duration, or by a mixture of both.

Methods. We measured eye movements (with a video eye tracker) of 35 AMD and 4 Stargardt patients (better eye decimal acuity from 0.08–0.3) while they monocularly read single-line French sentences continuously displayed on a screen. All patients had a dense scotoma covering the fovea, as assessed with MP1 microperimetry, and therefore used eccentric viewing. Results were analyzed with regression-based mediation analysis, a modeling framework that informs on the underlying factors by which an independent variable affects a dependent variable.

Results. Reading speed and average fixation duration are negatively correlated, a result that was not observed in prior studies with CFL patients. This effect of fixation duration on reading speed is still significant when partialling out the effect of the total number of fixations (slope: -0.75, $P < 0.001$). Despite this large effect of fixation duration, mediation analysis shows that the effect of L/FS on reading speed is fully mediated by the total number of fixations (effect size: 0.96; CI [0.82, 1.12]) and not by fixation duration (effect size: 0.02; CI [-0.11, 0.14]).

Conclusions. Results are consistent with the shrinking perceptual span hypothesis: reading speed decreases with the average number of letters traversed on each forward saccade, an effect fully mediated by the total number of fixations.

Keywords: mediation model, visual span, central field loss, reading speed, fixation duration

Age-related macular degeneration (AMD) often causes dramatic central field loss (CFL) among elderly people who are therefore constrained to use eccentric (peripheral) viewing.[1] One major goal of these patients is to improve their ability to read text,[2] and many psychophysical investigations have been performed to characterize low-level issues associated with eccentric reading.[3] To read a text continuously displayed on a page, eye movements are required: a succession of fixations is made across the text so that visual information can be extracted at different locations and eventually integrated across fixations. Some eye-movement studies with CFL patients (AMD or Stargardt disease), by investigating the relationship between eye movement characteristics and reading speed, have reported a correlation between the number of letters per forward saccade (L/FS) (proportional but not equal to saccade size) and reading speed.[4–8] The authors of these studies have interpreted their results as evidence that the perceptual span is a major determinant of reading speed.[9–14] We refer to this hypothesis as the "shrinking perceptual span hypothesis."

The major problem with the model of reading speed underlying this hypothesis, as detailed below, is that it ignores the determinant role of fixation duration. We therefore propose an explicit model that articulates the causal relationships that link together relevant oculo-motor parameters, including fixation duration, and reading speed. In addition, our model relies on the mediation framework that has been fruitfully and extensively used in various scientific fields.[15–18] Mediation models are sometimes called causal models either in textbooks[19] or in scientific publications.[20] Whatever the name, the basic strategy of this kind of model is "to represent a theory in terms of the network of variables that are involved, explicitly stating the causal directions, sign (+ versus –), and nature of the relationship, if any, between all pairs of variables that are considered."[19]

The starting point of the causal network of relationships considered here is that reading speed is based on the total time required to read a text (for a given number of characters). In causal terms, there are only two oculo-motor parameters that can effectively alter this total time (see Equation 2 in the Methods section): the total number of fixations and their average duration.[13,21] In the language of mediation models, these two variables are therefore potential mediators of the

www.iovs.org | ISSN: 1552-5783

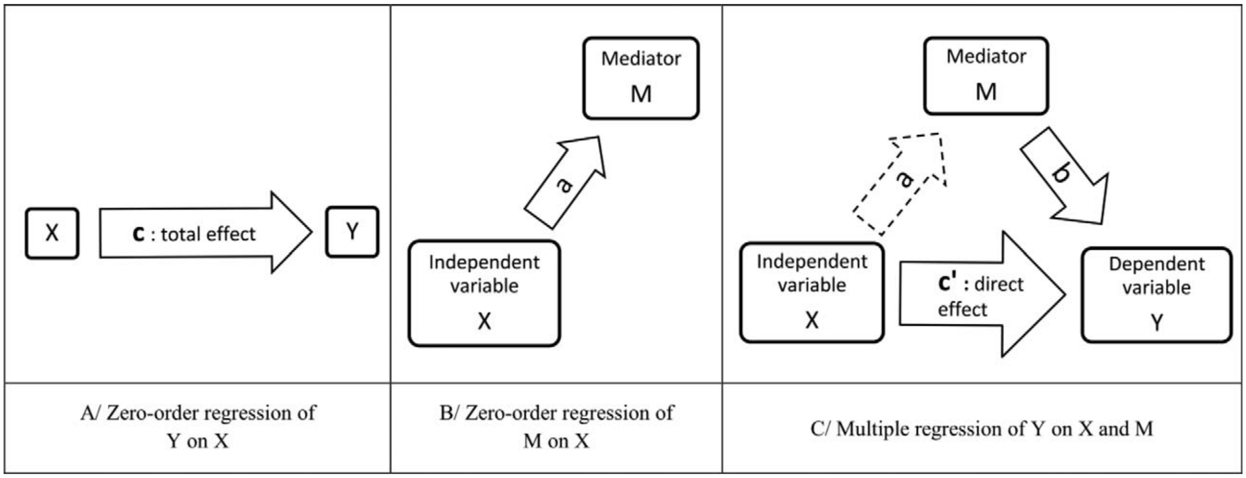

FIGURE 1. Illustration of a single-mediator model based on three regressions. (**A**) Total effect: zero-order regression of dependent variable *Y* on independent variable *X* (coefficient's name: c). (**B**) Zero-order regression of Mediator *M* on independent variable (coefficient's name: a). (**C**) Multiple regression of dependent variable on the two other regressors. The direct effect (c′) is the effect of the independent variable on the dependent variable when the effect of the mediator is partialled out. The *arrow* of the "a" effect is represented with *dashed lines* to remind that it is assessed in (**B**). The mediation model decomposes the total effect (c) of *X* on *Y* into two parts: the indirect effect of *X* on *Y*, quantified by a*b, and the direct effect of *X* on *Y* quantified by c′ ($c = a*b + c'$).

effects of other variables on reading speed. Factors that alter reading speed are necessarily exerting their effect through the total number of fixations, the average fixation duration, or both. Although this point might seem trivial, it was not acknowledged in previous formulations of the shrinking perceptual span hypothesis.

Once these two variables are included in a model of reading speed, it becomes possible to describe the whole network of causal links involved in the shrinking perceptual span hypothesis. First, the perceptual span would depend on low-level factors whose degradation is associated with CFL.[3] Notably, the perceptual span would decrease with eccentricity so that people with central scotomas would read with a smaller span.[22] Second, reading with a smaller span should induce smaller L/FS values (for a nonhorizontal saccade, which is often observed with CFL patients, L/FS is the horizontal saccade's component[4]). A last step, which is usually implicit in qualitative descriptions of the shrinking perceptual span hypothesis, although it is essential, is that having a smaller average L/FS value should increase the total number of fixations, which in turn would decrease reading speed: this means that the total number of fixations should be the unique mediator of the effect of L/FS on reading speed. A clear consequence of this point, which has been previously ignored, is that average fixation duration should not be a mediator of the effect of L/FS on reading speed, although average fixation duration is potentially a strong determinant of reading speed.[13,21]

Our mediation model of reading speed quantitatively takes into account the joint roles of average fixation duration and total number of fixations in reading speed. In addition, our model explicitly shows that the shrinking perceptual span hypothesis is a mediation hypothesis that involves the following causal links: L/FS, a factor assumed to reflect span size, exerts its effect on reading speed through number of fixations and not through average fixation duration. Therefore, a significant effect of L/FS on reading speed, which has been reported in previous studies,[4–8] is not sufficient to support this hypothesis. Such an effect alone does not inform us on the factor, number of fixations, or fixation duration, through which L/FS affects reading speed. Only a mediation of this effect through number of fixations would be consistent with the shrinking perceptual span hypothesis.

Some terminology is required to describe quantitative predictions of mediation models. A single-mediator model postulates that the effect of an independent variable *X* on a dependent variable *Y* (the "total" effect as assessed with a simple regression-coefficient c in Fig. 1A) is actually caused (partly or fully) by the intervention of a third factor *M* (a mediator). Two causal links are involved: the effect of *X* on *M* (coefficient a in Fig. 1B), and the effect of *M* on *Y* (coefficient b in Fig. 1C) estimated in a multiple regression after partialling out the "direct" effect of *X* on *Y* (coefficient c′ in Fig. 1C). The effect of *X* on *Y* mediated by *M* is called an "indirect" effect (it is estimated by the product a*b).

These clarifications allow us to define three kinds of possible predictions that have different levels of consistency with the shrinking perceptual span hypothesis. These predictions are discussed with reference to the double-mediator model presented in Figure 2. First, according to the strict

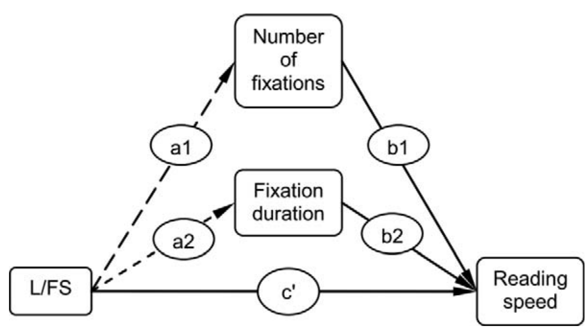

FIGURE 2. Double mediator model of the effect of L/FS on reading speed. L/FS can exert its effects on reading speed either through the number of fixations (this "indirect" effect is estimated by a1*b1) or through fixation duration (this "indirect" effect is estimated by a2*b2). The regression coefficients b1, b2, and c′ (direct effect) are estimated in a multiple regression of reading speed on "#fixations," fixation duration and L/FS. Regression coefficients a1 and a2 are estimated in two independent zero-order regressions as reminded by the *dashed arrows*. The total effect of L/FS on reading speed (c coefficient) is not shown in this figure.

shrinking perceptual span hypothesis presented above, there should be an indirect effect of L/FS on reading speed through the number of fixations (i.e., a significant a1*b1 product) and this indirect effect should be equal to the total effect (c = a1*b1): in the mediation terminology, this means that the effect of L/FS on reading speed would be "fully" mediated by the number of fixations. Second, a result that would not be consistent with this hypothesis would be a "full" mediation of the effect of L/FS on reading speed through fixation duration (i.e., a significant a2*b2 product and c = a2*b2). Although such a mediation hypothesis has never been explicitly proposed, it is a possibility that cannot be ignored simply because fixation duration is also a potential mediator through which L/FS could exert its effects on reading speed. Third, an intermediate result would be a mediation of the effect of L/FS on reading speed through both number of fixations and fixation duration. This would occur if both indirect effects (a1*a2 and b1*b2) were significant. Such a result would not be completely inconsistent with the shrinking perceptual span hypothesis but would be an incentive to complement it so as to explain the indirect effect of L/FS through fixation duration.

Our mediation model of reading speed was applied to data collected with patients (35 AMD and 4 Stargardt) who all had a dense macular scotoma covering their fovea.

Methods

Patients

Patients were recruited for the present study over a 1.5-year period from referrals to the Low Vision Clinic at the La Timone Hospital (Marseille, France). The criteria for including patients in the experiments were the following. The patients had a confirmed diagnosis of established AMD or Stargardt disease from an ophthalmologist. They all had binocular central scotomas and no other significant disease. Those with a history of neurologic disease or cognitive impairment were not included. Microperimetry was performed with a commercially available instrument (MP-1; Nidek Technologies, Padova, Italy) on the eye with best acuity. Analyzing the microperimetry results allowed us to select only eyes with a dense scotoma that covered the fovea (maximal display luminance: 127 cd/m^2). This ensured that these eyes relied on eccentric viewing (details of the methods have been described previously[23,24]). All patients spoke French as their first language. The research was conducted in accordance with the tenets of the Declaration of Helsinki. Informed consent was obtained from all participants before testing.

Eventually, based on these criteria, data of 39 patients were collected. Only 38 patients were included in the analyses because initial visual inspection of the relationships between variables for the 39 patients suggested that one of them was an outlier. This patient had a relatively low reading speed (2.2) with a very large L/FS (1.8), a pattern that was not observed with any of the other patients. A nonarbitrary method, analysis of leverage values with an index plot, confirmed that there was a large gap between this patient's point and the remainder.[19] The pattern of results and their statistical significance were similar when this patient was included.

Stimuli

Fourteen French meaningful sentences were sequentially displayed on a 21-inch cathode ray tube monitor (1024 × 768 pixels) driven by a display controller (Cambridge Research System Visage, Cambridge, UK). Viewing distance was 40 cm. Characters were white (92 cd/m^2) on a black background. Each sentence was displayed in Times New Roman font over one line in the middle of the screen. This font was chosen to replicate as closely as possible the conditions of major previous studies.[4,5] The sentences were created using the following constraints. They all had a simple syntactic structure (e.g., "Elle est allée courir": "She went for a run"). Words could not have more than eight characters and proper names were excluded. Only the present or perfect tenses were used. Words were chosen to span a large range of frequencies (in occurrences per million): from 19209 ("à") to 0.14 ("antivol") (median: 1278). Word frequency was derived from the French lexical database "Lexique,"[25] based on the corpus of texts "Frantext" (487 books published after 1950 constituting a total of 31 million words). All sentences had 18 to 21 characters (mean: 19.6) including spaces. Print size, defined as the vertical angular size of the lowercase letter x (x-height), was three times the Early Treatment Diabetic Retinopathy Study acuity threshold measured for each patient.[26,27]

Reading

Reading was monocular (eye with the best acuity), and an appropriate correction for near vision (Metrovision lenses; Metrovision, Perenchies, France), corresponding to the viewing distance, was added over distance prescription. The other eye was covered. Patients were asked to read aloud each of the 14 sentences without making errors. If at least one word was read incorrectly, the sentence was judged incorrect and excluded from the analysis: verbal feedback was given to the patient as to the error. The experimenter triggered the presentation of each sentence by pressing a button and then pressed the same button to indicate that the patient had finished reading the sentence. Eye recording was also dependent on these button presses. Response latency was recorded for each sentence. Reading speed was calculated in "standard-length words" per minute where each six characters counts as one standard-length word.[28]

Eye Recording

Subjects' gaze location was recorded 500 times per second with an EyeLink II eye tracker (EL II head-mounted binocular Eyetracker; SR Research, Ltd., Mississauga, ON, Canada) using the head compensation mode. In this mode, the head is free to move (±30°); however, to reduce the risk of displacing the head-mounted eyetracker, patients were encouraged to maintain their head as motionless as possible. Before each session, a 3-point gaze calibration was performed followed by a 3-point validation (top-left, top-right, bottom middle). Calibration and/or validation were repeated until the validation error was smaller than 1.0° on average and smaller than 1.5° for the worst point.

Ocular data were extracted offline with the Data Viewer software (SR Research, Ltd.) into a file whose rows correspond to successive fixations. Each row contains a set of relevant data, such as fixation duration and location, previous and next saccade amplitude (the latter was used to assess the horizontal component of saccades). For EyeLink recordings, the eye-event detection is based on an internal heuristic saccade detector built in the EyeLink tracker program. A saccade is determined by three criteria: velocity, acceleration, and displacement thresholds (in the present study, these were respectively set to 30°/s, 8000°/s^2, and 0.1°). A blink is defined as a period of saccade-detector activity with the pupil data missing for three or more samples in a sequence. A fixation event is defined as any period that is not a blink or saccade.

Then, for each sentence, reading speed (in words per minute), number of fixations, mean fixation duration (in ms), and mean horizontal component of forward saccades (in letters) were calculated. As recommended in Scherlen et al.,[29] the latter factor was not calculated as the number of letters (per sentence) divided by the total number of forward saccades: it was an average of saccadic horizontal components (in letters) across all individual forward saccades (the conversion from degrees of visual angle to letters is based on our measurements showing that the ratio between x-height and average interletter spacing is one for the Times New Roman font (see Legge and Bigelow[30]). This factor is referred to here as L/FS to preserve terminology continuity with its initial study.[4] Each of these factors was natural log-transformed for consistency with Equation 2 below. The median value of these factors across sentences was used to obtain a robust estimate for each patient. Each regressor was then grand-mean centered across patients to allow an easy interpretation of the intercept values. A summary of these variables is presented in Table 1.

Statistical Analysis

We used the R free software for statistical computing[31] along with the following additional R packages: ggplot2, MBESS, lmSupport, lavaan.

To help us decide what transformations to apply on the variables, we first derived the formula allowing measurement of reading speed on the basis of number of fixations and mean fixation duration:

$$\text{Total Reading time} = \text{Number of Fixations} \times (\text{Mean Fixation Duration} + \text{Mean Saccade Duration})$$

We rewrote for simplicity as

$$RT = NF \times (FD + SD) \qquad (1)$$

Reading speed can be calculated for a given number of words (k) as k/RT, so that Equation 1 becomes the following:

$$\text{Reading Speed} = k \times 1/\Big(NF \times (FD + SD)\Big)$$

To obtain a linear combination of terms (rather than multiplicative terms), logs are taken on both sides:

$$\log(RS) = \log(k) + \log(1/NF) + \log\Big(1/(FD + SD)\Big)$$

$$\log(RS) = k1 - \log(NF) - \log\Big((FD + SD)\Big) \qquad (2)$$

Results

For the 38 patients kept in the analysis, 4 had Stargardt disease, 11 had dry AMD, and 23 had wet AMD in the better seeing eye. Ages of Stargardt patients were 28, 29, 35, and 47 years and, for AMD patients, age ranged from 60 to 94 years (first quartile: 80, median: 83, third quartile: 87). Decimal visual acuity varied from 0.08 to 0.3 (first quartile: 0.1, median: 0.12, third quartile: 0.19). Equivalent logMAR values ranged from 1.1 to 0.5 (mean = 0.87, SD = 0.16). Proportions of regressive saccades ranged from 0.24 to 0.65 (mean = 0.45, SD = 0.1). Summary statistics about the factors used in the analyses, namely reading speed, number of fixations, fixation duration, and L/FS in their original units (i.e., not log transformed) are presented in Table 1.

A scatterplot matrix was inspected to check the linear relationships between the dependent variable (reading speed) and the three oculomotor factors, as well as among the factors (Fig. 3); dashed lines represent loess smoothers.[19] The first row of this matrix shows the effect of each factor on reading speed. Each of the three zero-order regression coefficients is large and significantly different from zero: the three estimated coefficients are respectively −1.07 ($P < 0.001$, $r^2 = 0.95$), −1.68 ($P < 0.004$, $r^2 = 0.21$), and 0.96 ($P < 0.001$, $r^2 = 0.26$) for #fixations, fixation duration, and L/FS.

These results first confirm the correlation between L/FS and reading speed. This confirmation is important because previous studies did not use a direct measure of L/FS (instead L/FS was assessed as the ratio between the number of letters for a given sentence and the number of forward saccades), which raised several issues, as reviewed in Scherlen et al.[29]

Although the correlation between number of fixations and reading speed is a robust result, having been reported in all previous studies with AMD patients, the correlation between average fixation duration and reading speed is a new result. We therefore decided, before performing mediation analysis, to check whether this effect was still present when partialling out the effect of "#fixations." A multiple regression of reading speed on "#fixations" and fixation duration was performed. Results are presented in Table 2: both effects are significant showing that "#fixations" and fixation duration both have a unique effect on reading speed (i.e., each effect is significant even when partialling out the effect of the other factor).

Revealing the unique effect of fixation duration on reading speed is important per se but also because it increases the likelihood that the effect of L/FS on reading speed might be mediated by fixation duration. In a single-mediator model, the indirect effect of L/FS through fixation duration is estimated with the product of this unique effect (coefficient b) by the effect of L/FS on fixation duration (coefficient a): if the latter effect were found large enough, the product a*b might be quite large and result in a significant indirect effect of L/FS through fixation duration. The mediation analyses presented below, however, show that this is not the case.

Mediation Analysis

We started mediation analysis with a simple mediation model to test whether the indirect effect of L/FS on reading speed through number of fixations is equal to the total effect of L/FS on reading speed (c = a*b), or equivalently whether the direct effect c' is null.

The zero-order regression of reading speed on L/FS (total effect) was presented earlier (first row, fourth column in Fig. 3; regression coefficient "c" = 0.96). Then, as illustrated in Figure 1B, the coefficient, referred to as "a," of the zero-order regression of the mediator "#fixations" on L/FS was estimated. Results show a significant effect with a large coefficient (Table 3).

Finally, the results of the multiple regression of reading speed on #fixations and L/FS are presented in Table 4 (see illustration in Fig. 1C). The direct effect, c', of L/FS on reading speed is null (and not significant), whereas its total effect, c, was large (0.96) and significant. This qualitatively suggests that a*b = c. A formal test relies on a point estimate of the indirect effect (a*b), which is simply obtained by multiplication of coefficients a (Table 3) and b (Table 4), namely −0.90 * −1.064 = 0.96. This point estimate is equal to the estimate of the total effect c (a*b = c).

Following recent recommendations,[32] point estimates of indirect effects must be supplemented with confidence intervals (CIs) and with assessments of the effect size (see Table 5). Effect sizes and CIs were derived from bootstrap 95% confidence limits

Table 1. Summary Information About the Variables Used in the Analyses

Variable	Abbreviation	Mean (SD)	Min–Max	Transformation Used in the Analyses	Grand Mean Centered
Reading speed, wpm (dependent variable)	RS	26.8 (15)	4.3–60.7	Natural log	No
No. of fixations	NF or #fixations	37.8 (32.7)	13–177	Natural log	Yes
Fixation duration, ms	FD	279.1 (51.3)	171–429.7	Natural log	Yes
Horizontal component of forward saccades, in letters	L/FS	1.98 (0.68)	0.91–3.52	Natural log	Yes

Numeric values are in original units (i.e., without log transformation).

with 10,000 bootstrap replications. The last row of Table 5 shows that the size of this indirect effect ([a*b]/c) is close to 1 (this ratio is known as the mediation ratio in epidemiological research[33]); the indirect effect of L/FS through #fixations is thus approximately equal to the total effect of L/FS. The relatively narrow CI indicates good accuracy.

A single-mediator model of the effect of L/FS on reading speed through fixation duration was then performed (results not displayed), and showed that the indirect effect through fixation duration is null (estimate of a*b: 0.07; 95% CI [–0.19, 0.25]).

To strengthen the results of these single-mediator analyses, we finally performed a double-mediator analysis,[34,35] as schematically represented in Figure 2. Estimates of indirect effects and effect sizes along with their 95% confidence limits were derived from 10,000 bootstrap replications (Table 6). These results confirm the previous single-mediator analyses. The indirect effect of L/FS on reading speed through #fixations is still close to the total effect with a slightly better accuracy, and the indirect effect of L/FS through fixation duration is null. Reanalysis, including the outlier patient (see Methods), did not change the pattern and significance of results (estimate of a1*b1/c = 0.92, 95% CI [0.55, 1.28]; estimate of a2*b2/c = 0.07, 95% CI [–0.24, 0.56]).

Discussion

In this study, patients with CFL had to read single-line French sentences. As assessed with microperimetry, all patients had a dense macular scotoma covering the fovea so that eccentric viewing was necessarily involved in the reading process. We first showed that number of fixations and average fixation duration both have significant effects on reading speed as assessed with zero-order regressions. The effect of fixation duration is consistent with evidence in normally sighted observers that slower readers have longer fixation durations than faster readers.[36,37] It is also consistent with a previous gaze-contingent scotoma study showing that fixation duration and reading speed are negatively correlated.[38] However, when compared with studies of CFL patients, evidence for a correlation between average fixation duration and reading speed is a new result that was never observed in previous studies.[4–8] The reasons of these discrepancies are currently unclear, especially because the effect of fixation duration reported here has a large amplitude and is still present when partialling out the effect of the total number of fixations. One possible reason, as is often the case in clinical investigations, is that experimental paradigms are very different across studies. For instance, in some previous studies, oculo-motor parameters and reading speed were recorded in different experimental sessions and with different texts.

Interestingly, our finding that reading speed is negatively correlated with fixation duration is compatible with a recent study.[38] These authors show that reading speed (measured with a Rapid Serial Visual Presentation paradigm [RSVP]) is negatively correlated with temporal threshold for letter recognition as estimated in another experiment. Therefore, their results combined with ours suggest that average fixation

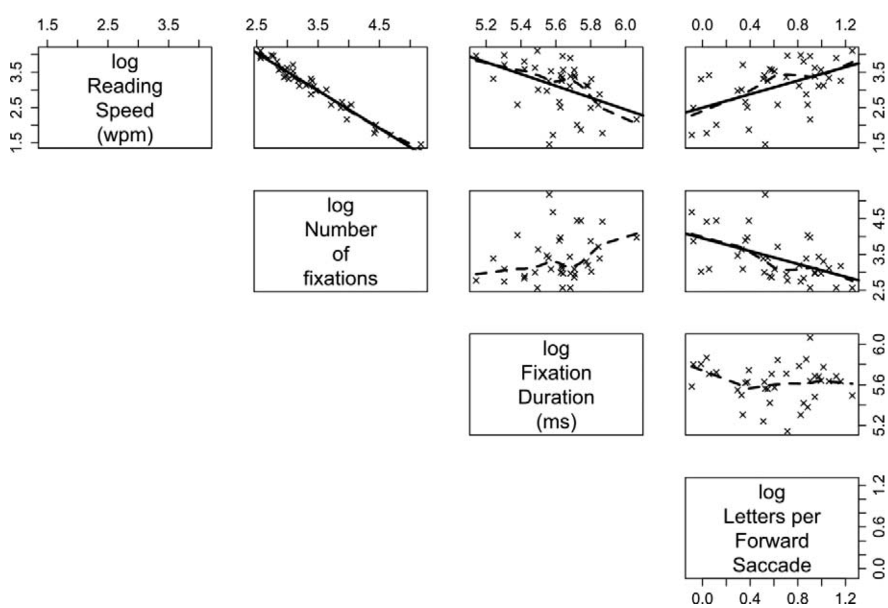

Figure 3. Scatterplot matrix of the variables under study: Reading speed (in words per minute), #fixations, fixation duration (in ms), and L/FS. *Dashed lines* are loess functions (i.e., smoothing functions that help visualize whether the relationships are linear). *Solid lines* are the zero-order regression fits (only shown when the effects are significant). Independent variables are not centered in this figure (although they are in the analyses) to show the range of log-transformed values for each variable.

TABLE 2. Results of the Multiple Regression of Reading Speed on "#Fixations" and Fixation Duration

	Estimate	SE	*t* Value	Pr(>|t|)
Intercept	3.09	0.01	249.00	<0.001
#fixations	−1.00	0.02	−48.94	<0.001
Fixation duration	−0.75	0.07	−10.73	<0.001

Residuals SE: 0.07 on 35 *df*. Multiple $R^2 = 0.988$; adjusted $R^2 = 0.988$ ($P < 2.2e^{-16}$).

duration during reading with eye movements is proportional to the temporal threshold estimated in the Cheong et al.[38] study.

Our results confirm the relationship between L/FS (number of letters per forward saccade) and reading speed reported previously with CFL patients.[4–8] This confirmation was needed because the measure used to assess L/FS in these studies actually did not directly measure L/FS. Instead, L/FS was assessed as the ratio between the number of letters for a given sentence and the number of forward saccades. We previously discussed why using this measure, which covaries with the number of fixations, might reflect effects due to the number of fixations rather than to L/FS per se.[37]

The authors of these eye-movement studies have interpreted the correlation between L/FS and reading speed as evidence that the perceptual span is a major determinant of reading speed (assuming that L/FS reflects the average perceptual span).[4–8] In parallel with these studies (where reading required eye movements), studies of eccentric reading with the RSVP paradigm (i.e., when eye movements are not required) have accumulated evidence concerning the predominant influence of the visual span on reading speed.[3,22,39–42] There have been many discussions and controversies about the correct characterizations of different types of span in the eye-movement literature, especially in relation to reading.[9,12,14] Although the terminology is sometimes confusing, it is acknowledged that two different spans must be distinguished: the visual span and the perceptual span (sometimes called the span of effective vision). For instance, O'Regan[10] calls visual span "what can be seen without making use of lexical knowledge and contextual constraints," and perceptual span "what can be perceived by additionally making use of them." Many studies have shown that the perceptual span differs in several ways from the visual span; for instance, it is dynamic (i.e., it can change from fixation to fixation), of wider extent, and asymmetric (larger to the right[43]). Another important difference is that the perceptual span is attentionally constrained.[44–48] This is suggested for instance by the reduction of the perceptual span when foveal processing difficulty increases (thus increasing foveal attentional engagement).

The shrinking perceptual span hypothesis assumes that L/FS reflects the average perceptual span. The underlying logic is that the size of each forward saccade is calculated by the oculo-motor system so that the next fixation's span is adjacent to the current fixation's span. In this view, the whole chain of causal links is thus the following: a reduced span induces smaller forward saccades, hence an increase in the total number of fixations (a step that is overlooked in the literature), and eventually a slower reading rate. Ignoring the "number of fixations" step leads one to think that a positive correlation between L/FS and reading speed is sufficient to support the perceptual span hypothesis.[4–8] However, as made explicit by our mediation model of reading speed, this effect of L/FS on reading speed might also be due to an indirect effect of L/FS through fixation duration, which would not be consistent with the shrinking perceptual span hypothesis. Such a mediation through fixation duration could be related to some evidence in the literature on free viewing of visual scenes that there are two interspersed modes of viewing: global and local scanning. Global scanning periods are associated with large-amplitude saccades and short-duration fixations, whereas local scanning periods are associated with smaller-amplitude saccades and longer fixations.[49] One could argue that this mixture of scanning strategies also occurs in reading, with different proportions of the two different modes leading to different reading speeds. Thus, low reading speeds would correspond to a predominance of the local scanning strategy, whereas higher reading speeds would be induced by a greater predominance of the global scanning strategy.

Our results clearly distinguish between the two predictions presented above (mediation through number of fixations or through fixation duration) and are consistent with the shrinking perceptual span hypothesis: there is a large indirect effect of L/FS on reading speed through the total number of fixations, and this effect is close to the total effect of L/FS on reading speed. In contrast, there is no indirect effect of L/FS on reading speed through fixation duration (although the effect of fixation duration on reading speed is large). In sum, the effect of L/FS on reading speed is fully mediated by the total number of fixations, as predicted by a mediation formalization of the shrinking perceptual span hypothesis.

Our study and several previous eye-movement investigations of this hypothesis present some limitations. It is known that people who are forced to read magnified text do so by moving the text being read and/or their head.[50] This introduces a pattern of slow eye movements interleaved with

TABLE 3. Zero-Order Regression of "#Fixations" on L/FS

	Estimate	SE	*t* Value	Pr(>|t|)	"Name" in Mediation Analysis
Intercept	0.00	0.09	0.00	1	
L/FS	−0.90	0.25	−3.63	0.0009	a

The regression coefficient of L/FS is referred to as "a." Residuals SE: 0.55 on 36 *df*. Multiple $R^2 = 0.27$; adjusted $R^2 = 0.25$.

TABLE 4. Multiple Regression of Reading Speed on "#Fixations" and L/FS

	Estimate	SE	*t* Value	Pr(>|t|)	"Name" in Mediation Analysis
Intercept	3.089	0.026	120.213	<0.001	
#fixations	−1.064	0.048	−22.254	<0.001	b
L/FS	0.004	0.083	0.048	0.96	direct effect: c′

The regression coefficients of "#fixations" and L/FS are referred to respectively as b and c′. Residuals SE: 0.16 on 35 *df*. Multiple $R^2 = 0.95$; adjusted $R^2 = 0.95$ ($P < 2.2e^{-16}$).

TABLE 5. Single-Mediator Model: Point Estimates and 95% CIs for the Indirect Effect of L/FS Through #Fixations and for (a*b)/c, a Common Measure of Effect Size

	Point Estimate	CI Lower Percentile	CI Upper Percentile
Indirect effect: a*b	0.96	0.45	1.49
Ratio of indirect to total effect: a*b/c	0.996	0.85	1.27

The 95% CIs are obtained by bootstrap with 10,000 resamples.

TABLE 6. Results for the Double-Mediator Model of the Effect of L/FS Through #Fixations and Fixation Duration (see Fig. 2 for the Coefficients' Labels)

		Point Estimate	CI Lower Percentile	CI Upper Percentile
Indirect effect through #fixations	Indirect effect: a1*b1	0.86	0.42	1.33
	Ratio of indirect to total effect: (a1*b1)/c	0.96	0.82	1.12
Indirect effect through fixation duration	Indirect effect: a2*b2	0.03	−0.08	0.12
	Ratio of indirect to total effect: (a2*b2)/c	0.02	−0.11	0.14

Point estimates and 95% confidence intervals for the two indirect effects and for the two corresponding measures of effect size (a*b/c) are presented. The 95% CIs are obtained by bootstrap with 10,000 resamples.

saccades, which bears some resemblance to the reflexive optokinetic nystagmus. In our study, this pattern was not observed mainly because the text was fixed on the monitor. It is thus possible that the characteristics of saccades might be different in our study compared with situations where text and head are free to move, an issue that should be investigated in future research. Another limitation might be due to the short sentences that were used in the present work. It is possible that long sentences or texts would increase the number and size of both backward and forward saccades.[51] For instance, a long-range backward saccade might have a confirmatory purpose, such as checking information present several words behind, which in turn would induce a subsequent large forward saccade, skipping over already identified words.

Future research also should extend our work by investigating new hypotheses on the possible causal determinants of the factors included in our model. For instance, additional experiments could be performed with different levels of luminance contrast that are known to alter reading speed. Then, the contrast factor could be included in a mediation model to test whether its effect on reading speed is mediated by the number of fixations or by average fixation duration. Our model also could be extended to look for the factors that are causal determinants of L/FS. For instance, variations in the L/FS factor could be directly affected by factors known to influence the visual span, and this could be tested by a measure of each patient's visual span with the RSVP trigram method.[22] On the other hand, some authors argue that it is the speed of comprehension that affects eye movements note vice-versa.[20] It seems therefore possible that this cognitive factor might be the cause of variations in the L/FS factor. This hypothesis could be investigated by measuring an index of speed of comprehension for each patient, and by including this factor in our model as a potential cause of variations in the L/FS factor. In summary, future research should investigate determinants of reading speed by integrating within a mediation model the complex causal relationships linking visual, oculo-motor, and cognitive parameters with each other.

Finally, we advocate the use of mediation analysis to help develop programs of visual rehabilitation or training for low-vision patients,[7,52–58] along lines similar to the strategies used in health behavior intervention research programs.[16,59] Mediation analysis should allow researchers to target the mechanisms by which different interventions or training programs improve the dependent variable of interest, here reading speed (when eye movements are required).

Acknowledgments

Supported by a French Ministry of Research and Technology grant (AC) and a Bourse de Doctorat pour Ingénieur (BDI) grant from the Centre National de la Recherche Scientifique (CNRS) (J-BB).

Disclosure: **A. Calabrèse**, None; **J.-B. Bernard**, None; **G. Faure**, None; **L. Hoffart**, None; **E. Castet**, None

References

1. Neelam K, Nolan J, Chakravarthy U, Beatty S. Psychophysical function in age-related maculopathy. *Surv Ophthalmol*. 2009; 54:167–210.
2. Elliott DB, Trukolo-Ilic M, Strong JG, Pace R, Plotkin A, Bevers P. Demographic characteristics of the vision-disabled elderly. *Invest Ophthalmol Vis Sci*. 1997;38:2566–2575.
3. Legge GB. *Psychophysics of Reading in Normal and Low Vision*. Mahwah, NJ: Lawrence Erlbaum Associates; 2007.
4. Bullimore MA, Bailey IL. Reading and eye movements in age-related maculopathy. *Optom Vis Sci*. 1995;72:125–138.
5. Crossland MD, Rubin GS. Eye movements and reading in macular disease: further support for the shrinking perceptual span hypothesis. *Vision Res*. 2006;46:590–597.
6. Raasch TW, Rubin GS. Reading with low vision. *J Am Optom Assoc*. 1993;64:15–18.
7. Rubin GS, Feely M. The role of eye movements during reading in patients with age-related macular degeneration (AMD). *Neuro-Ophthalmology*. 2009;33:120–126.
8. Rumney NJ, Leat SJ. Why do low vision patients still read slowly with a low vision aid? In: Kooijman AC, Looijestijn PL, Welling JA, van der Wildt GJ, eds. *Low Vision: Research and New Developments in Rehabilitation*. Amsterdam: IOS Press; 1994:269–274.
9. McConkie GW. Eye movements and perception during reading. In: Rayner K, ed. *Eye Movements in Reading: Perceptual and Language Processes*. New York: Academic Press; 1983:65–96.
10. O'Regan JK. Eye movements and reading. In: Kowler E, ed. *Eye Movements and Their Role in Visual and Cognitive Processes*. Amsterdam: Elsevier Science Publishers; 1990: 395–453.
11. O'Regan JK. The control of saccade size and fixation duration in reading: the limits of linguistic control. *Percept Psychophys*. 1980;28:112–117.
12. O'Regan K. Saccade size control in reading: evidence for the linguistic control hypothesis. *Percept Psychophys*. 1979;25: 501–509.
13. Rayner K. Eye movements in reading and information processing: 20 years of research. *Psychol Bull*. 1998;124: 372–422.
14. Rayner K. The perceptual span and eye movement control during reading. In: Rayner K, ed. *Eye Movements in Reading: Perceptual and Language Processes*. New York: Academic Press; 1983:97–120.
15. Baron RM, Kenny DA. The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. *J Pers Soc Psychol*. 1986;51:1173–1182.
16. Fairchild AJ, MacKinnon DPA. General model for testing mediation and moderation effects. *Prev Sci*. 2009;10:87–99.
17. Judd CM, Kenny DA, McClelland GH. Estimating and testing mediation and moderation in within-subject designs. *Psychol Methods*. 2001;6:115–134.

18. MacKinnon DP. Integrating mediators and moderators in research design. *Res Soc Work Pract*. 2011;21:675–681.
19. Cohen J, Cohen P, West SG, Aiken LS. *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences*. Mahwah, NJ: Lawrence Erlbaum Associates; 2003.
20. Carver RP. *The Causes of High and Low Reading Achievement*. Mahwah, NJ: Lawrence Erlbaum Associates; 2000.
21. Nuthmann A, Henderson JM. Using CRISP to model global characteristics of fixation durations in scene viewing and reading with a common mechanism. *Vis Cogn*. 2012;20:457–494.
22. Legge GE, Mansfield JS, Chung ST. Psychophysics of reading. XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Res*. 2001;41:725–743.
23. Calabrese A, Bernard JB, Hoffart L, et al. Wet versus dry age-related macular degeneration in patients with central field loss: different effects on maximum reading speed. *Invest Ophthalmol Vis Sci*. 2011;52:2417–2424.
24. Calabrese A, Bernard JB, Hoffart L, et al. Small effect of interline spacing on maximal reading speed in low-vision patients with central field loss irrespective of scotoma size. *Invest Ophthalmol Vis Sci*. 2010;51:1247–1254.
25. New B, Pallier C, Brysbaert M, et al. Lexique 2: a new French lexical database. *Behav Res Methods Instrum Comput*. 2004; 36:516–524.
26. Lovie-Kitchin JE, Bowers AR, Woods RL. Oral and silent reading performance with macular degeneration. *Ophthalmic Physiol Opt*. 2000;20:360–370.
27. Whittaker SG, Lovie-Kitchin J. Visual requirements for reading. *Optom Vis Sci*. 1993;70:54–65.
28. Carver RP. *Reading Rate: A Review of Research and Theory*. San Diego: Academic Press; 1990.
29. Scherlen AC, Bernard JB, Calabrese A, Castet E. Page mode reading with simulated scotomas: oculo-motor patterns. *Vision Res*. 2008;48:1870–1878.
30. Legge GE, Bigelow CA. Does print size matter for reading? A review of findings from vision science and typography. *J Vis*. 2011;11(5):1–22.
31. R Development Core Team. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing; 2012. Available at: http://www.R-project.org.
32. Preacher KJ, Kelley K. Effect size measures for mediation models: quantitative strategies for communicating indirect effects. *Psychol Methods*. 2011;16:93–115.
33. Ditlevsen S, Christensen U, Lynch J, Damsgaard MT, Keiding N. The mediation proportion: a structural equation approach for estimating the proportion of exposure effect on outcome explained by an intermediate variable. *Epidemiology*. 2005;16: 114–120.
34. MacKinnon DP. Contrasts in multiple mediator models. In: Rose JS, Chassin L, Presson CC, Sherman SJ, eds. *Multivariate Applications in Substance Use Research: New Methods for New Questions*. Mahwah, NJ: Lawrence Erlbaum Associates Publishers; 2000:141–160.
35. Preacher KJ, Hayes AF. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behav Res Methods*. 2008;40:879–891.
36. Everatt J, Underwood G. Individual differences in reading subprocesses: relationships between reading ability, lexical access, and eye movement control. *Lang Speech*. 1994;37: 283–297.
37. Underwood G, Hubbard A, Wilkinson H. Eye fixations predict reading comprehension: the relationships between reading skill, reading speed, and visual inspection. *Lang Speech*. 1990; 33:69–81.
38. Cheong AM, Legge GE, Lawrence MG, Cheung SH, Ruff MA. Relationship between visual span and reading performance in age-related macular degeneration. *Vision Res*. 2008;48:577–588.
39. Kwon M, Legge GE, Dubbels BR. Developmental changes in the visual span for reading. *Vision Res*. 2007;47:2889–2900.
40. Legge GE, Hooven TA, Klitz TS, Stephen Mansfield JS, Tjan BS. Mr. Chips 2002: new insights from an ideal-observer model of reading. *Vision Res*. 2002;42:2219–2234.
41. Legge GE, Klitz TS, Tjan BS. Mr. Chips: an ideal-observer model of reading. *Psychol Rev*. 1997;104:524–553.
42. Yu D, Cheung SH, Legge GE, Chung ST. Effect of letter spacing on visual span and reading speed. *J Vis*. 2007;7(2):1–10.
43. Rayner K, Well AD, Pollatsek A. Asymmetry of the effective visual field in reading. *Percept Psychophys*. 1980;27:537–544.
44. Henderson JM, Ferreira F. Effects of foveal processing difficulty on the perceptual span in reading: implications for attention and eye movement control. *J Exp Psychol Learn Mem Cogn*. 1990;16:417–429.
45. Deubel H, Schneider WX. Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vision Res*. 1996;36:1827–1837.
46. Castet E, Jeanjean S, Montagnini A, Laugier D, Masson GS. Dynamics of attentional deployment during saccadic programming. *J Vis*. 2006;6(3):196–212.
47. Ghahghaei S, Linnell KJ, Fischer MH, Dubey A, Davis R. Effects of load on the time course of attentional engagement, disengagement, and orienting in reading. *Q J Exp Psychol (Hove)*. 2013;66:453–470.
48. Inhoff AW, Pollatsek A, Posner MI, Rayner K. Covert attention and eye movements during reading. *Q J Exp Psychol A*. 1989; 41:63–89.
49. Tatler BW, Vincent BT. Systematic tendencies in scene viewing. *J Eye Move Res*. 2008;2:1–18.
50. Bowers AR. Eye movements and reading with plus-lens magnifiers. *Optom Vis Sci*. 2000;77:25–33.
51. Vitu F. Visual extraction processes and regressive saccades in reading. In: Underwood G, ed. *Cognitive Processes in Eye Guidance*. Oxford: Oxford University Press; 2005:1–32.
52. Bernard J-B, Arunkumar A, Chung STL. Can reading-specific training stimuli improve the effect of perceptual learning on peripheral reading speed? *Vision Res*. 2012;66:17–25.
53. Chung STL. Improving reading speed for people with central vision loss through perceptual learning. *Invest Ophthalmol Vis Sci*. 2011;52:1164–1170.
54. He Y, Legge GE, Yu D. Sensory and cognitive influences on the training-related improvement of reading speed in peripheral vision. *J Vis*. 2013;13(7):1–14.
55. Nguyen NX, Stockum A, Hahn GA, Trauzettel-Klosinski S. Training to improve reading speed in patients with juvenile macular dystrophy: a randomized study comparing two training methods. *Acta Ophthalmol*. 2011;89:e82–e88.
56. Rubin GS. Vision rehabilitation for patients with age-related macular degeneration. *Eye*. 2001;15:430–435.
57. Seiple W, Szlyk JP, McMahon T, Pulido J, Fishman GA. Eye-movement training for reading in patients with age-related macular degeneration. *Invest Ophthalmol Vis Sci*. 2005;46: 2886–2896.
58. Yu D, Legge GE, Park H, Gage E, Chung ST. Development of a training protocol to improve reading performance in peripheral vision. *Vision Res*. 2010;50:36–45.
59. MacKinnon DP, Fairchild AJ, Fritz MS. Mediation analysis. *Annu Rev Psychol*. 2007;58:593–614.

Investigative Ophthalmology & Visual Science