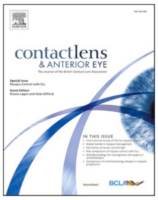
Contact Lens and Anterior Eye 46 (2023) 101853

Contents lists available at ScienceDirect

Contact Lens and Anterior Eye

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



Presbyopia correction with multifocal contact lenses: Evaluation of silent reading performance using eye movements analysis

Sotiris Plainis [a,b,*,1], Emmanouil Ktistakis [a,1], Miltiadis K. Tsilimbaris [a]

[a] *Laboratory of Optics and Vision (LOV), School of Medicine, University of Crete, Greece*
[b] *Optometry & Vision Science Research Group, Aston University School of Life and Health Sciences, Birmingham, UK*

ARTICLE INFO

Keywords:
Contact lenses
Presbyopia
Multifocal
Reading performance
Silent reading speed
Visual acuity
Reading speed

ABSTRACT

Purpose: Many activities of daily living rely on reading, thus is not surprising that complaints from presbyopes originate in reading difficulties rather in visual acuity. Here, the effectiveness of presbyopia correction with multifocal contact lenses (CLs) is evaluated using an eye-fixation based method of silent reading performance.

Methods: Visual performance of thirty presbyopic volunteers (age: 50 ± 5 yrs) was assessed monocularly and binocularly following 15 days of wear of monthly disposable CLs (AIR OPTIX™ plus HydraGlyde™, Alcon Laboratories) with: (a) single vision (SV) lenses – uncorrected for near (b) aspheric multifocal (MF) CLs. LogMAR acuity was measured with ETDRS charts. Reading performance was evaluated using standard IReST paragraphs displayed on a screen (0.4 logMAR print size at 40 cm distance). Eye movements were monitored with an infrared eyetracker (Eye-Link II, SR Research Ltd). Data analysis included computation of reading speed, fixation duration, fixations per word and percentage of regressions.

Results: Average reading speed was 250 ± 68 and 235 ± 70 wpm, binocularly and monocularly, with SV CLs, improving statistically significantly to 280 ± 67 ($p = 0.002$) and 260 ± 59 wpm ($p = 0.01$), respectively, with MF CLs. Moreover, fixation duration, fixations per word and ex-Gaussian parameter of fixation duration, μ, showed a statistically significant improvement when reading with MF CLs, with fixation duration exhibiting the stronger correlation ($r = 0.79$, $p < 0.001$) with improvement in reading speed. The correlation between improvement in VA and reading speed was moderate ($r = 0.46$, $p = 0.016$), as was the correlation between VA and any eye fixation parameter.

Conclusion: Average silent reading speed in a presbyopic population was found improved with MF compared to SV CL correction and was faster with binocular compared to monocular viewing: this was mainly due to the faster average fixation duration and the lower number of fixations. Evaluating reading performance using eye fixation analysis could offer a reliable outcome of functional vision in presbyopia correction.

1. Introduction and purpose

Presbyopia is rapidly increasing, estimated to affect 1.04 billion people globally in 2005 [1] and 1.8 billion (25% of the world's population) in 2015 [2]. As a result, numerous contact lens designs have been developed in an effort to provide sharp vision for every visual task, satisfying the demanding visual needs of the modern presbyope [3–6]. Contact lens manufacturers have produced a remarkable range of patented "aspheric multifocal" contact lens designs, which offer simultaneous-image correction [3–5,7]. Although such designs are effective, by improving vision for a range of distances, simultaneous viewing of in-focus and out-of-focus images may degrade vision for a specific distance, compared to single vision correction [8–11]. As a result, a significant percentage of the presbyopic population discontinues contact lens wear due to complaints of poor vision [12]. The patient-to-patient variation in visual performance clearly highlights a need for further research and the development of customised designs [13].

Vision is generally assessed among clinicians using visual acuity recordings, usually for far and near distance [4,11,14,15]. Visual acuity is affected in conditions when letter resolution and contrast are reduced, resulting from defocus blur, but are quite insensitive to the differing

---

* Corresponding author at: Laboratory of Optics and Vision (LOV), School of Medicine, University of Crete, Greece.
E-mail address: plainis@uoc.gr (S. Plainis).

[1] Sotiris Plainis and Emmanouil Ktistakis are equal contributors to this manuscript.

https://doi.org/10.1016/j.clae.2023.101853
Received 12 January 2023; Received in revised form 27 April 2023; Accepted 1 May 2023

multifocal designs used in presbyopia correction, especially when correlation for real life task performance is under investigation [16–18]. For example, eyecare practitioners may encounter that despite the excellent high-contrast acuity measured in the clinical practice, patients may still report poor vision while performing daily activities, which might result from ghosting and multiple images which do not usually affect high contrast vision [15,19,20]. It is, therefore, not surprising that many complaints from presbyopes originate when reading a book or a paragraph in an electronic mobile device [5,21–23], while it is well known that reading speed slows down when letters are blurred [24–28] or do not have enough contrast or luminance [29,30] or when binocular fusion is hampered [31–33].

Therefore, since the ability to read is a primary objective of functional vision and of fundamental importance in modern culture, it is not surprising that reading difficulty has been found to form a strong predictor of vision-related quality of life [22,34]. Reading ability is currently evaluated using various sentence-level reading acuity tests [35–37] or standardised passages with continuous text of fixed size, such as the International Reading Speed Texts (IReST), which also provide a more accurate estimation of reading speed [38–40].

Although reading content and complexity is thoroughly standardized in these texts, a significant inter-individual variation in reading speed exists [38,39], as a result of the high influence of cognitive, non-visual processes, such as linguistic and learning skills and personality characteristics (see for a review Starr and Rayner, 2001 [41]). Moreover, a prerequisite for the above-mentioned cards is to read the sentences “aloud” and “as fast as possible” [22,37,40,42], conditions which are not encountered frequently in daily reading tasks and mainly involve word recognition rather than sentence comprehension [43,44]. On the other hand, silent passage reading forms the preferred reading mode in real-life reading conditions [45,46], i.e. when working on an essay, responding to emails or reading a book, and involves paragraphs, composed of multiple sentences.

When reading, visual processing and sensorimotor coordination must happen to make a sequence of fixations and saccades [41]. Simultaneous recordings of eye movements during reading could be used as surrogate indicators of reading performance or to understand the impact of eye movements on reading [41,47,48]. In this study eye-movement based silent passage reading performance is evaluated in a presbyopic population using single vision (SV) and multifocal (MF) contact lens (CL) correction.

2. Methods

2.1. Participants

Thirty contact lens users participated in the study (age 50 ± 5 yrs, ranging from 45 to 60). All participants had healthy vision with no ocular or systemic pathology and any history of refractive or other ocular surgery and any neurological and psychiatric disorders which might have affected reading performance. Other exclusion criteria included spectacle-corrected visual acuity worse than 0.1 logMAR (0.8 decimal acuity equivalent), spherical equivalent > 3.00D and < -7.00 D, astigmatism > 1.25D, anisometropia > 2.0 D, clinically significant abnormal phorias, any history of refractive or other ocular surgery. Written consent was obtained from all participants after they received a detailed written description of the nature of the study. The study was conducted in adherence to the tenets of the Declaration of Helsinki and followed a protocol approved by the Research Ethics Committee of the University Hospital of Heraklion.

2.2. Study lenses

Monthly disposable silicone-hydrogel contact lenses (AIR OPTIX™ plus HydraGlyde™, Alcon Laboratories, US) were used in the study in two different optical designs: (a) single vision (SV) spherical lenses (AIR OPTIX™ plus HydraGlyde™) with correction for far (and vision uncorrected for near) and (b) simultaneous image aspheric multifocal (MF) lenses (AIR OPTIX™ plus HydraGlyde™ Multifocal).

At the first visit participants passed a full eye examination in the clinic to confirm that they met the inclusion criteria. Distance prescription was determined by the spherical equivalent of the manifest refraction, adjusted for vertex distance, and an over-refraction, if needed, to ensure best binocular visual acuity performance for distance. The prescribed SV and MF lenses were of similar power for both eyes. The addition for the MF lenses was selected following manufacturer’s fitting guidelines, aiming for the minimum lens addition. Participants were informed to wear each pair of lenses for 2 weeks, for at least 6 days and 48 h per week. They were also advised to wear reading glasses for near work when needed during the wearing period of SV lenses.

Visual performance was assessed monocularly (right eye only) and binocularly, in a counterbalanced mode regarding the viewing condition, following 15 days of correction with each pair of lenses, first with SV and then with MF lenses. No safety events, as adverse or serious adverse events (AE/SAE) or adverse or serious device deficiencies (ADE/SADE) were reported during the whole duration of the study.

2.3. Visual acuity (VA)

Standardized visual (logMAR) acuity at 40 cm (“near” VA) and 4 m (“far” VA) was measured using the European-wide standardized logMAR charts (Precision Vision, USA) [49]. The charts for far recordings were held on a back-illuminated slim stand (Sussex Vision Ltd., UK) at 4 m distance (luminance was approximately 160 cd/m^2). Near recordings took place in a well-lit room (chart background luminance was 70 cd/m^2; illuminance at cornea was 75 lx). All subjects were asked to identify each letter starting from the upper left corner, and to proceed by row until they reached a row in which they could not correctly identify more than one letter. VA was derived in logMAR units from the calculation of correctly identified letters up to the last readable line.

2.4. Reading efficiency

Prior to passage reading performance measurements, word-level reading efficiency was assessed binocularly through a standardized test comprising two lists, one with relatively high-frequency words and a second one with phonotactically matched pseudowords [50]. Participants were asked to read each list aloud and as fast as they could without compromising accuracy. The number of words or pseudowords read correctly within 45 s was measured and then converted in words per minute.

2.5. Reading performance

Silent reading performance was evaluated with the Greek IReST standardised reading cards/passages [39], which form tests displaying multiple equivalent passages of about 140 words each with similar average word frequency and word length. A standard print size of 0.4 logMAR (1 M at 40 cm distance) was used. The passages were displayed on a screen with an average luminance of 50 cd/m^2. Four different passages were used in total, one for each condition in a counterbalanced order across participants to prevent any learning effects. Participants were instructed to read the text silently at a comfortable pace to understand the meaning of the passages. However, they did not have to answer any questions afterwards. Short breaks were allowed between measurements. Eye movements from both eyes were recorded simultaneously during passage reading, at a sampling rate of 500 Hz, using video oculography (Eye-Link II, SR Research Ltd). All measurements were performed with subjects seated on a chair, with their head stabilized by means of a chin rest to minimize head movements.

2.6. Data analysis

Eye movement files were initially analyzed with EyeLink Data Viewer (EyeLink II, SR Research Ltd, Canada) and with custom written scripts in Matlab. Reading performance was assessed with silent reading speed and with a set of eye-fixation based parameters during passage reading: number of fixations, fixation duration, and percentage of backward (regressive) saccades. Viewing was binocular but only data for the right eye were analyzed. Blink rate (number of blinks per minute) was also recorded but not analysed. Means and medians were calculated for all parameters for each participant, while frequency distributions of the parameters were checked for their normality. Reading speed (in words per minutes, wpm) was calculated from the number of passage words read from the passage divided by total reading time.

Fixations with duration between 75 and 1000 ms were included. Fixations with duration shorter than 75 ms were merged with neighbouring fixations if the latter were within an area of 1°. Fixation durations are not normally distributed; their frequency distribution always exhibits a pronounced right tail, i.e. an increased frequency of long fixations [51–55]. Analysis of the number of fixations during reading was based on mean number of fixations per word. Fixation duration and number of fixations per word refer only to the forward fixations. In addition, frequency distributions of fixations durations were analysed with an ex-Gaussian fitting, a convolution of a normal and exponential distribution. Ex-Gaussian analysis uses three parameters which correspond to the location/mean (μ) and the standard deviation (σ) of the Gaussian (normal) distribution, and the mean and the standard deviation (τ) of the exponential component [51]. The overall mean of the ex-Gaussian is $\mu + \tau$, and the overall standard deviation is $(\sigma 2 + \tau 2)1/2$.

Associations between measurements were assessed through Pearson correlation coefficients and evaluated at $p < 0.05$. Effects of “lens correction“ (MF vs. SV) and “viewing condition” (binocular vs. monocular) on dependent variables were assessed through two-way repeated measures analyses of variance (ANOVA), while differences within each variable were assessed though paired-sample t tests. Ninety-five per cent confidence intervals were also calculated. All analyses were performed using SPSS v27.

3. Results

3.1. Effects of CL correction and binocularity on visual performance measures

Two way repeated measures ANOVA, with “lens correction” and “viewing condition” as factors, showed that there is no interaction effect between these two factors in any of the parameters tested ($p > 0.30$). Almost all parameters were improved with MF compared to SV “lens correction” (see Table 1): near VA [F(1, 29) = 26.42, $p < 0.001$], reading speed [F(1, 29) = 12.08, p = 0.002], fixation duration [F(1, 29) = 10.97, p = 0.003], fixations per word [F(1, 29) = 4.33, p = 0.047], and ex-Gaussian parameter μ [F(1, 29) = 4.23, p = 0.049]. No statistically significant effects were found for percentage of regressions (p = 0.18) and Ex-Gaussian parameter τ (p = 0.18).

In addition, binocular viewing resulted in significantly better results for near VA [F(1, 29) = 67.16, $p < 0.001$], reading speed [F(1, 29) = 13.07, p = 0.001], fixation duration [F(1, 29) = 18.59, $p < 0.001$], and ex-Gaussian parameter μ [F(1, 29) = 9.68, p = 0.004]. Neither fixations per word (p = 0.22), percentage of regressions (p = 0.36), or Ex-Gaussian parameter τ (p = 0.24) were improved when viewed under binocular viewing conditions.

3.2. Visual acuity (“far” and “near”)

Average VA at far was found to be statistically significant different between SV (-0.06 ± 0.08 logMAR) and MF (0.00 ± 0.09 logMAR) lens correction ($p < 0.001$). Near VA with MFs improved by 0.20 ± 0.20 logMAR [95% CI: −0.285, −0.122] in both binocular and monocular viewing conditions ($p < 0.001$) (see Fig. 1). In addition, a statistically significant advantage of 0.12 ± 0.10 logMAR [95% CI from 0.09 to 0.15] with binocular over monocular viewing was observed ($p < 0.001$). No statistically significant interaction was found between lens correction (MF vs. SV) and viewing condition (F(1,29) = 0.18, p = 0.67).

Table 1
Average differences and p values for all visual performance measures for the two methods of lens correction (MF vs SV) and p values for the two viewing conditions (BIN vs MON) and their interaction (lens correction vs. condition).

	Lens Correction (MF vs SV)			BIN vs MON	Interaction
	Mean (SD)	95% CI	P value	P value	P value
Visual Acuity[1]	−0.20 (0.04)	−0.29 to −0.12	<0.001*	<0.001*	0.67
Reading Speed[2]	23.7 (6.8)	9.7 to 37.7	0.002*	0.001*	0.68
Fixations/ word[3]	−0.04 (0.02)	−0.08 to 0.00	0.047*	0.22	0.89
Fixation duration[4]	−17 (5)	−27 to −6	0.003*	<0.001*	0.31
Regressions (%)[5]	0.1 (0.6)	−1.2 to 1.3	0.93	0.36	0.95
ex-Gaussian μ[4]	−10 (5)	−21 to 0	0.049*	0.004*	0.31
ex-Gaussian τ[4]	−7 (3)	−12 to −1	0.18	0.24	0.82

* statistically significant change ($P < 0.05$).
Abbreviations; MF: multifocal, SV: single-vision, BIN: Binocular, MON: Monocular,
[1] in logMAR; [2] in words per minute; [3] average number of forward fixations per word [4] In ms, [5] Percentage of regressions in total number of saccades.

3.3. Reading speed and eye fixation parameters

Average reading speed with SV lenses was 250 ± 68 and 235 ± 70 wpm, binocularly and monocularly, respectively, improving to 280 ± 67 and 260 ± 59 wpm, with multifocal CLs (see Fig. 2). The average improvement in reading speed with MF lens correction was found to be statistically significant [F(1, 29) = 12.08, 95% CI from 11 to 38 wpm, p = 0.002), both in binocular (30 ± 46 wpm, p = 0.002) and monocular (25 ± 48 wpm, p = 0.01) viewing conditions.

Binocular summation in reading speed was statistically significant [F (1, 29) = 13.07, p = 0.001], with average reading speed with SV lenses improving from 235 ± 75 wpm monocularly to 250 ± 67 wpm binocularly (an average improvement of 15 ± 48 wpm, p = 0.04), while average binocular advantage with MF lenses was 21 ± 46 wpm (p = 0.002). No significant interaction was found between lens correction and viewing condition (p = 0.68).

Regarding the eye fixation parameters, fixation duration showed a statistically significant improvement with MF lenses by 13 ± 33 ms (p = 0.048) and 20 ± 31 ms (p = 0.01) in binocular and monocular viewing conditions, respectively (see Fig. 3). Binocular advantage in fixation duration was found statistically significant, with an average difference of 17 ± 34 ms (95% CI from 9 to 25 ms). Improvement in binocular viewing condition was statistically significant, both with SV (21 ± 42 ms, p = 0.004) and MF (14 ± 28 ms, p = 0.045) contact lenses. However, no statistically significant interaction between lens correction and viewing condition was found (p = 0.31).

A marginally statistically effect of lens correction on the number of fixations per word was found [F(1,29) = 4.33, p = 0.047) with the number of fixations showing an average improvement of 0.04 ± 0.12 fpw [95% CI from 0.00 to 0.08 fpw] with MF compared to SV lens correction. The improvement with MF correction in each viewing condition was not found statistically significant different, i.e. 0.04 ± 0.11 fpw in binocular (p = 0.053) and 0.04 ± 0.13 fpw in monocular (p = 0.12) (see Fig. 4). In general, no statistically significant difference was

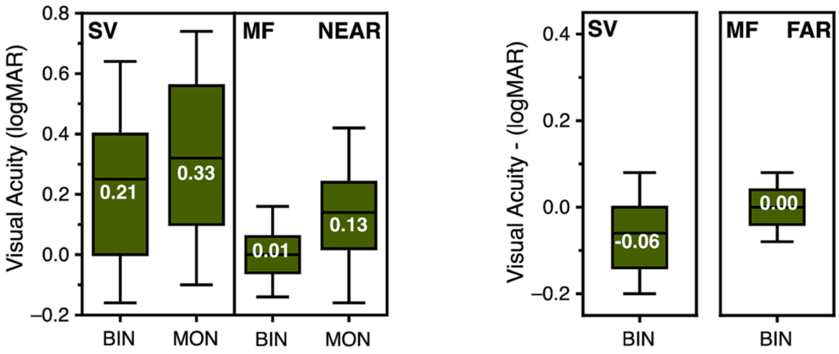


Fig. 1. Box plots of near (left) and far (right) VA with participants (N = 30) corrected with single vision (SV) vs. multifocal (MF) contact lenses. Data for both monocular (MON) and binocular (BIN) viewing conditions are depicted for near visual acuity.

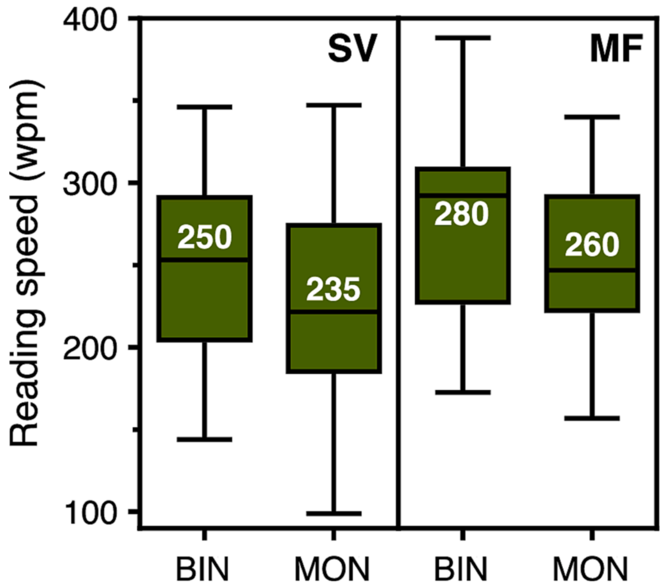


Fig. 2. Box plots of reading speed values in the conditions tested: single vision (SV) vs. multifocal (MF) contact lenses for both monocular and binocular viewing conditions (N = 30).

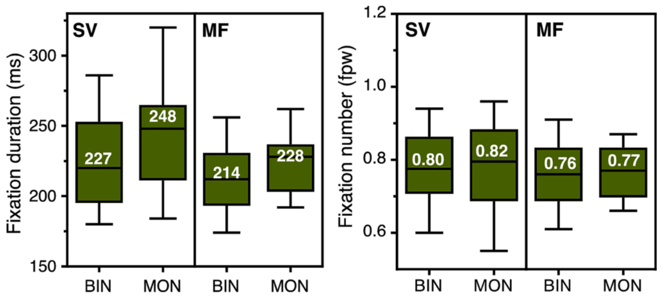


Fig. 3. Box plots of eye fixation parameters (fixation duration, left – number of forward fixations, right) with participants (N = 30) corrected (a) with single vision (SV) and (b) multifocal (MF) contact lenses for both binocular and monocular viewing conditions.

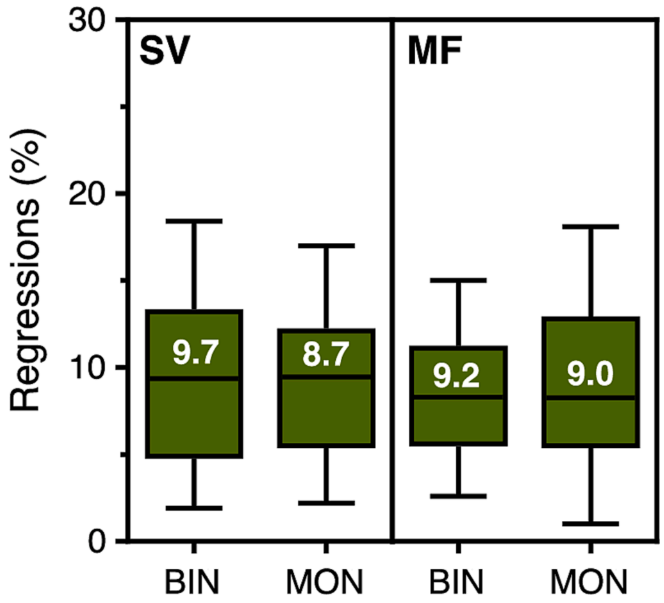


Fig. 4. Box plots of percentage of regressions with participants (N = 30) corrected (a) with single vision (SV) and (b) multifocal (MF) contact lenses for both binocular and monocular viewing conditions.

observed between monocular and binocular viewing conditions ($p = 0.22$).

Average percentage of regressions was just below 10% in all conditions, as shown in Fig. 4. No statistically significant main effect of lens correction on percentage of regressions was found [F(1,29) = 1.91, $p = 0.178$]. Similarly, there was no effect of binocularity on percentage of regressions [F(1,29) = 0.22, $p = 0.647$].

Fig. 5 depicts the box plots of the ex-Gaussian parameters, μ and τ, of fixations durations analysis. A statistically significant improvement (average difference −10 ± 30 ms, 95% CI from −21 to 0) with MF compared to SV CL correction was found for the ex-Gaussian parameter μ, [F(1,29) = 4.23, $p = 0.049$]. Similarly, ex-Gaussian parameter, τ, was found improved by an average of 7 ± 21 ms with MF CL correction [F(1,29) = 6.11, $p = 0.020$].

Moreover, a statistically significant binocular advantage in μ was observed for both SV (from 188 ± 41 to 173 ± 25 ms, $p = 0.038$) and MF (from 176 ± 19 to 168 ± 23 ms, $p = 0.023$) lens correction [F(1,29) = 9.68, $p = 0.004$]. No difference between binocular and monocular viewing was found for ex-Gaussian parameter τ ($p = 0.24$).

Fig. 6 plots the correlations of the improvement in reading speed (ie. the difference in reading speed with MF compared to SV contact lens correction) with fixation parameters. The improvement was strongly correlated with fixation duration ($r = 0.79$, $p < 0.001$), the difference in the number of fixations per word ($r = 0.69$, $p = 0.01$) and ex-Gaussian parameter μ ($r = 0.64$, $p = 0.02$). No statistically significant correlation was found for the percentage of regressions ($r = 0.13$, $p = 0.50$) and the ex-Gaussian parameter τ ($r = 0.33$, $p = 0.10$).

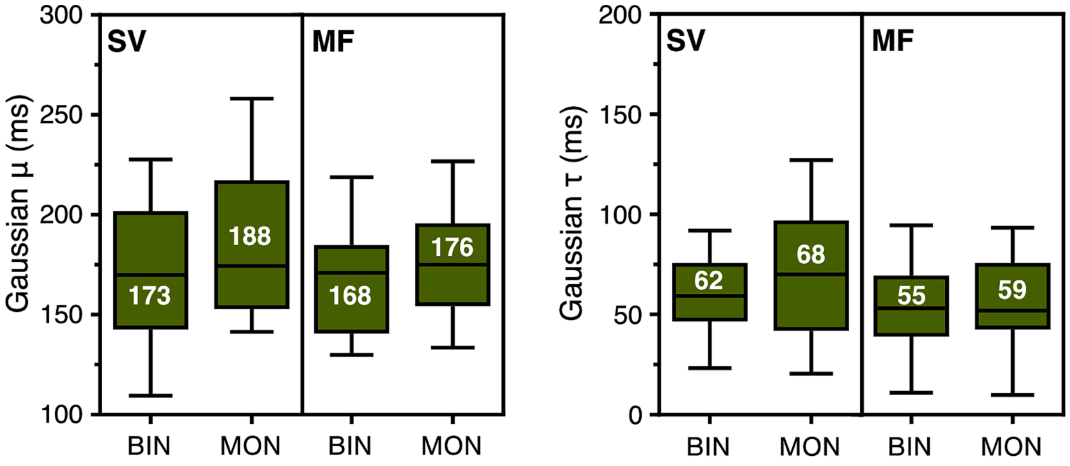


Fig. 5. Box plots of ex Gaussian parameters, μ and τ, with participants (N = 30) corrected (a) with single vision (SV) and (b) multifocal (MF) contact lenses for both binocular and monocular viewing conditions.

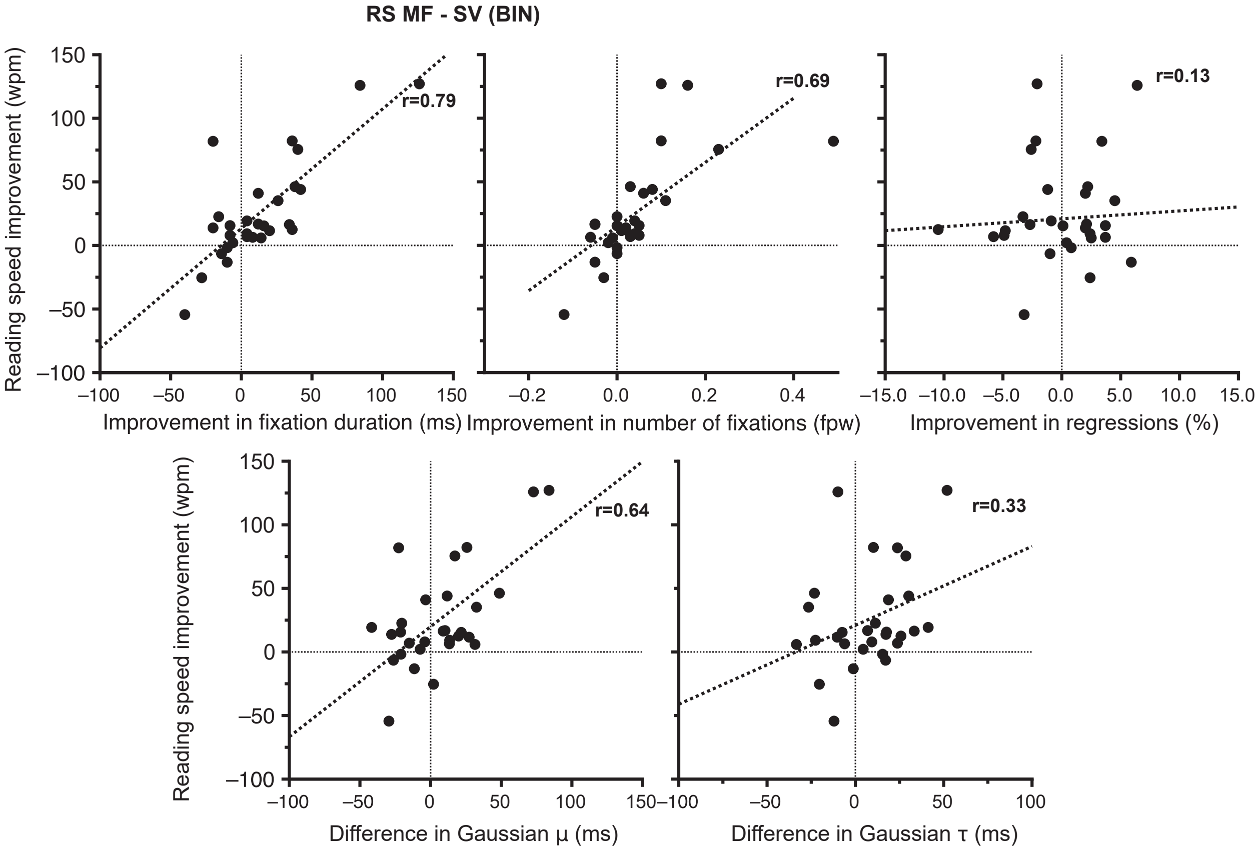


Fig. 6. Correlation of the improvement in reading speed between MF and SV CL correction with fixation parameters (upper), i.e. fixation duration (left), number of fixations (middle) and regressions (right), and the ex-Gaussian fixation analysis parameters (lower), μ (left) and τ (right).

3.4. Correlations of reading speed parameters with visual acuity and reading efficiency

The correlation of reading speed with logMAR acuity was found moderate in SV (r equaled −0.55, p = 0.010 and −0.42, p = 0.044, in binocular and monocular viewing condition, respectively) and very weak in MF lens correction (r < 0.20). Moreover, a statistically significant moderate correlation was found between the improvement in binocular reading speed with the enhancement in corresponding VA (r = 0.46, p = 0.016) (see Fig. 7). Moderate correlations were also found between the improvement in VA and fixation duration (r = 0.36, p = 0.07), number of fixations (r = 0.42, p = 0.035) and fixation parameter μ (r = 0.40, p = 0.057). No correlation was found for regressions (r = 0.00, p = 1.00) and fixation parameter τ (r = 0.05, p = 0.80).

Finally, silent passage reading speed was moderately predicted by word reading efficiency, both in the SV (r = 0.43, p = 0.038) and MF (r = 0.40, p = 0.046) lens correction. A modest-size correlation was found between word reading efficiency and the number of fixations (r equaled −0.33, p = 0.09 for SV and 0.48, p = 0.02 for MF correction, respectively), while a weak correlation was found for the percentage of regressions (r equaled 0.24, p = 0.22 for SV and 0.27, p = 0.17 for MF correction, respectively) and the ex-Gaussian parameter τ (r equaled

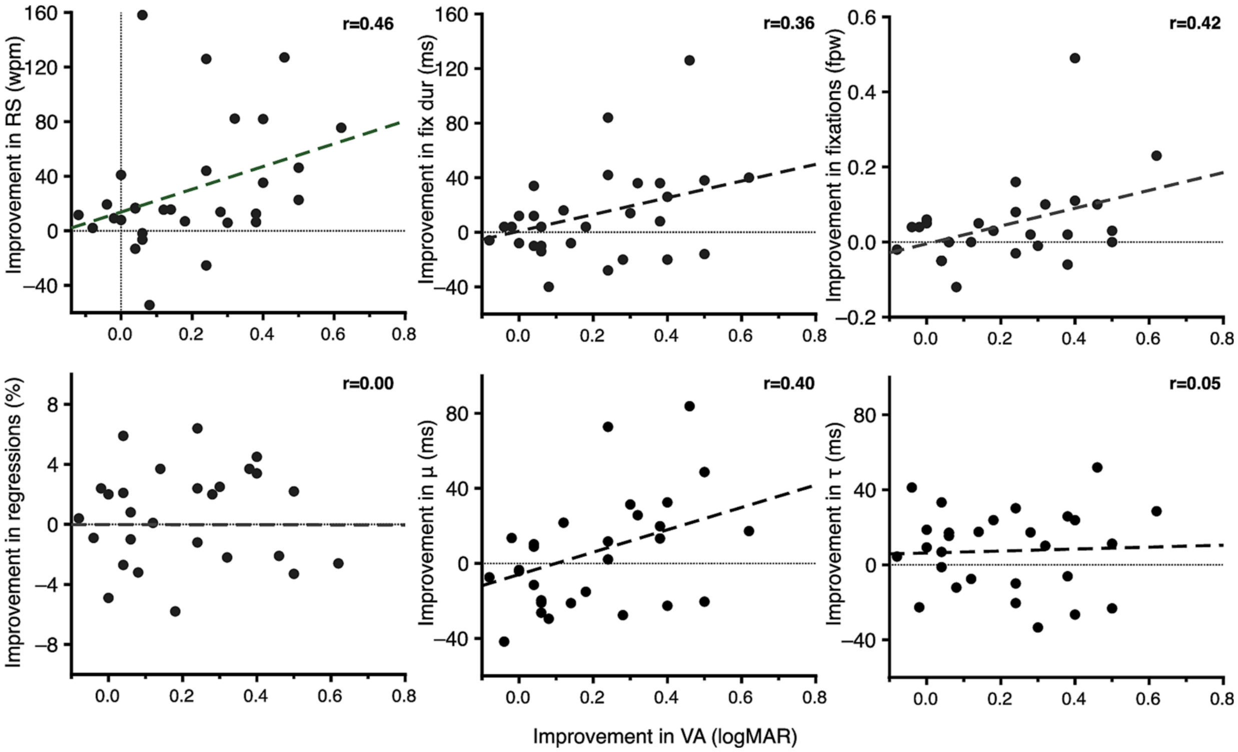


Fig. 7. Correlation of the improvement in reading speed between MF and SV CL correction with reading speed (upper, left), the fixation parameters [fixation duration (upper, middle), number of fixations (upper, right) and regressions (lower, left)], and the ex-Gaussian fixation analysis parameters μ and τ (lower, middle and right).

0.25, $p = 0.20$ for SV and 0.22, $p = 0.25$ for MF correction, respectively). Very weak correlation was found for fixation duration and ex-Gaussian parameter μ ($r < 0.12$).

4. Discussion

In this study functional vision for a group of presbyopes, between 45 and 60 years of age, was assessed following correction with multifocal contact lenses and compared with single vision correction for distance. Since many activities of daily living rely on participants' ability to read, in addition to the traditional measures of logMAR acuity, reading performance was evaluated using a series of standardised passages included in the Greek IReST cards [39]. Moreover, the implementation of a high-resolution video eyetracker allowed for recordings of silent reading behaviour, which forms a prerequisite in real-life reading conditions [22,45,46], and simultaneous analysis for a range of eye fixation parameters used as surrogate indicators of reading performance [41].

The results show that both near visual acuity and silent reading speed improved significantly in MF compared to SV lens correction. The improvement was independent of viewing condition (binocular vs. monocular), suggesting that clinical evaluation of vision with MF contact lenses could be performed binocularly only, with no need for separate monocular measurements. It is of interest to note that specific eye fixation parameters when reading exhibited a statistically significant enhancement with MF compared to SV lens correction, i.e. fixation duration, fixations per word and ex-Gaussian parameter of fixation duration, μ. Moreover, their improvement was well correlated with the improvement in reading speed with MF correction, with fixation duration exhibiting the stronger correlation. This confirms previous findings, which have observed that both fixation duration, and the ex-Gaussian parameter, μ, are mostly influenced by the optical and syntactic parameters of the text and the visuomotor and reading process [51,56,57]. More specifically, it has been shown that fixation duration increases when words are partially shaded [58] or have low contrast [30,51], with ex-Gaussian parameter μ influenced by text contrast [51] and the landing position of the eyes within the word [57].

On the other hand, the improvement in reading speed in MF lens correction was not associated with a change in the percentage of regressions and the ex-Gaussian parameter τ, which are known to be mainly depend on cognitive processing [41,51]. The cognitive nature of regressions and the ex-Gaussian parameter τ, is confirmed in this study by their correlation with word reading efficiency, which is absent in the case of fixation duration and the ex-Gaussian parameter μ. This is in agreement with previous studies, which link number of regressions with the level of text comprehension [56,59], while consistent evidence of dissociation between μ and τ ex-Gaussian parameters indicates that there are indeed two processes contributing to the location (μ) and skew (τ) of distributions of eye fixations in reading [55].

Similarly, the improvement in silent passage reading speed in binocular viewing, was accompanied by a faster average fixation duration and ex-Gaussian parameter μ, in both SV and MF lens correction. No difference was found for the number of forward fixations, the percentage of regressions and ex-Gaussian parameter τ, consistent with previous findings which denote a decrease in fixation duration under binocular compared to monocular viewing conditions [30,60,61], and in accordance with binocular summation studies revealing facilitatory interaction between the signals from the two eyes [62–64].

An important finding of the study is the weak/moderate correlation between VA and silent reading speed and eye fixation parameters in all conditions. More specifically, a weak correlation was found between improvement in VA with MF compared to SV correction and corresponding changes in fixation duration, number of fixations and ex-Gaussian parameter μ, while no correlation was found with percentage of regressions and ex-Gaussian parameter τ. The failure of standard measures of VA to predict the enhancement in patients' reading performance is not surprising and confirms findings from relevant literature [22,65,66]. Reading is known to be facilitated by parafoveal visual information [46,67,68], thus reading rate has been found to better correlate with extrafoveal visual performance and the crowding effect [65,66]. It is also well established that parafoveal information contributes to faster silent, compared to oral, reading speed through a reduction in both the duration and number of fixations, while reading slows down when parafoveal information is masked [69,70]. Regarding presbyopia correction, reading speed has been shown to align with task performance to a greater degree than visual acuity, providing a useful measure of functional vision [21]. Silent reading may also better reveal the reduced perceptual span, i.e. the region of effective vision, that elderly readers exhibit during reading [69].

Since silent reading speed is affected by various factors, including cognitive and linguistic processing [22,42,45], it may not be used as the sole indicator of functional visual performance. Eye movement-based analyses and supplementary assessments of reading capacity, as computed in this study, could better identify and distinguish the effect of several sources of variance when assessing reading performance, as may reveal additional aspects of the complex process of reading [39,41,48]. On the other hand, oral reading speed, currently evaluated using various sentence-level reading acuity tests, such as the MNRead and Radner charts [36,37,42,71], may be limited by various processes, such as psychological stress during examination, pronunciation (because the articulatory motor system has a lower speed threshold than the visual decoding system) [72], while is time consuming to compute, involving manual time measurement, sentence unveiling, and error recording since it is undertaken simultaneously by the examiner [73].

A limitation of the experimental design of the study is that although a consistent improvement with MF compared to SV lenses was found in specific testing reading metrics, there is no comparison with “best near vision correction”, from the perspective of a wearer or a clinician, as is the case in the simultaneous use of SV lenses with reading spectacles. A recent experimental crossover study, comparing near vision when using SV lenses (with near correction) with two monovision approaches [48], failed to show any statistically significant differences in oral reading speed and corresponding eye fixation parameters between these modes of correction. This is not surprising, since differences of small magnitude in reading performance cannot be precisely assessed, due the high variability of the method, which is even higher when silent reading performance is under investigation [44]. In the current study, the results at near are inevitably biased in favour of the MF over SV lenses, leading to marked effects on reading performance and more sensitive correlations between performance measures.

5. Conclusion

Presbyopia correction with MF lenses leads to significantly improved near visual acuity and silent reading speed compared to SV lenses, in both monocular and binocular viewing conditions, although correlation is moderate between the above measures. Near vision in general and ability to read, in particular, is of great importance and interest to presbyopes. Since reading forms a strong predictor of functional vision, having a disproportionate impact on a patient’s quality of life, there is a growing interest in advancing reading performance as a primary outcome measure in clinical trials. Silent reading performance, measured with standardized passages with continuous text, forms the preferred reading mode of competent readers from early age and is more relevant to the real-life reading process. Although further research is needed, this study shows that evaluating silent reading performance using eye fixation analysis, offers a reliable outcome of functional vision in presbyopia correction, compensating also for the high within and between subject variability observed with silent reading speed.

Funding

This study was supported by an investigator-initiated study grant from Alcon (IIT# 52977371).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Holden BA, Fricke TR, Ho SM, Wong R, Schlenther G, Cronje S, et al. Global vision impairment due to uncorrected presbyopia. Arch Ophthalmol 2008;126:1731–9. https://doi.org/126/12/1731 [pii]10.1001/archopht.126.12.1731.

[2] Fricke TR, Tahhan N, Resnikoff S, Papas E, Burnett A, Ho SM, et al. Global prevalence of presbyopia and vision impairment from uncorrected presbyopia: systematic review, meta-analysis, and modelling. Ophthalmology 2018;125(10):1492–9.

[3] Plainis S, Atchison DA, Charman WN. Power profiles of multifocal contact lenses and their interpretation. Optom Vis Sci 2013;90:1066–77. https://doi.org/10.1097/OPX.0000000000000030.

[4] Bakaraju RC, Ehrmann K, Ho A. Extended depth of focus contact lenses vs. two commercial multifocals: Part 1. Optical performance evaluation via computed through-focus retinal image quality metrics. J Optom 2018;11:10–20. https://doi.org/10.1016/j.optom.2017.04.003.

[5] Richdale K, Cox I, Kollbaum P, Bullimore MA, Bakaraju RC, Gifford P, et al. BCLA CLEAR – Contact lens optics. Contact Lens Anterior Eye 2021;44(2):220–39.

[6] Wolffsohn JS, Davies LN. Presbyopia: Effectiveness of correction strategies. Prog Retin Eye Res 2019;68:124–43. https://doi.org/10.1016/j.preteyeres.2018.09.004.

[7] Remón L, Pérez-Merino P, Macedo-de-Araújo RJ, Amorim-de-Sousa AI, González-Méijome JM. Bifocal and multifocal contact lenses for presbyopia and myopia control. J Ophthalmol 2020;2020:1–18. https://doi.org/10.1155/2020/8067657.

[8] Monsálvez-Romín D, González-Méijome JM, Esteve-Taboada JJ, García-Lázaro S, Cerviño A. Light distortion of soft multifocal contact lenses with different pupil size and shape. Contact Lens Anterior Eye 2020;43:130–6. https://doi.org/10.1016/j.clae.2019.11.014.

[9] Sanchez I, Ortiz-Toquero S, Blanco M, Martin R. A new method to analyse the effect of multifocal contact lenses on visual function. Cont Lens Anterior Eye 2018;41:169–74. https://doi.org/10.1016/j.clae.2017.11.005.

[10] Rajagopalan AS, Bennett ES, Lakshminarayanan V. Visual performance of subjects wearing presbyopic contact lenses. Optom Vis Sci 2006;83:611–5. https://doi.org/10.1097/01.opx.0000232185.00091.4500006324-200608000-00016 [pii].

[11] Plainis S, Ntzilepis G, Atchison DA, Charman WN. Through-focus performance with multifocal contact lenses: effect of binocularity, pupil diameter and inherent ocular aberrations. Ophthalmic Physiol Opt 2013;33:42–50. https://doi.org/10.1111/opo.12004.

[12] Rueff EM, Varghese RJ, Brack TM, Downard DE, Bailey MD. A Survey of presbyopic contact lens wearers in a university setting. Optom Vis Sci 2016;93:848–54. https://doi.org/10.1097/OPX.0000000000000881.

[13] Faria-Ribeiro M, González-Méijome JM. Multifocal contact lenses: towards customisation? Ophthalmic Physiol Opt 2019;39:37–45. https://doi.org/10.1111/opo.12597.

[14] García-Lázaro S, Albarrán-Diego C, Ferrer-Blasco T, Radhakrishnan H, Montés-Micó R. Visual performance comparison between contact lens-based pinhole and simultaneous vision contact lenses. Clin Exp Optom 2013;96:46–52. https://doi.org/10.1111/j.1444-0938.2012.00791.x.

[15] Fedtke C, Bakaraju RC, Ehrmann K, Chung J, Thomas V, Holden BA. Visual performance of single vision and multifocal contact lenses in non-presbyopic myopic eyes. Contact Lens Anterior Eye 2016;39:38–46. https://doi.org/10.1016/j.clae.2015.07.005.

[16] Papas EB, Decenzo-Verbeten T, Fonn D, Holden BA, Kollbaum PS, Situ P, et al. Utility of short-term evaluation of presbyopic contact lens performance. Eye Contact Lens 2009;35(3):144–8.

[17] Diec J, Tilia D, Thomas V, Bakaraju RC. Predicting short-term subjective vision performance of contact lenses used in myopia control. Eye Contact Lens Sci Clin Pract 2018;44:308–15. https://doi.org/10.1097/ICL.0000000000000460.

[18] Madrid-Costa D, García-Lázaro S, Albarrán-Diego C, Ferrer-Blasco T, Montés-Micó R, Garcia-Lazaro S, et al. Visual performance of two simultaneous vision multifocal contact lenses. Ophthalmic Physiol Opt 2013;33:51–6. https://doi.org/10.1111/opo.12008.

[19] Sha J, Tilia D, Kho D, Amrizal H, Diec J, Yeotikar N, et al. Visual performance of daily-disposable multifocal soft contact lenses: A randomized, double-blind clinical trial. Optom Vis Sci Off Publ Am Acad Optom 2018;95(12):1096–104.

[20] Bakaraju RC, Tilia D, Sha J, Diec J, Chung J, Kho D, et al. Extended depth of focus contact lenses vs. two commercial multifocals: Part 2. Visual performance after 1 week of lens wear. J Optom 2018;11(1):21–32.

[21] Gupta N, Wolffsohn JSW, Naroo SA. Comparison of near visual acuity and reading metrics in presbyopia correction. J Cataract Refract Surg 2009;35:1401–9. https://doi.org/10.1016/j.jcrs.2009.03.026.

[22] Rubin GS. Measuring reading performance. Vision Res 2013;90:43–51. https://doi.org/10.1016/j.visres.2013.02.015.

[23] Datta A, Richdale K, Tomiyama ES, Hu C, Logan A-K, Skidmore K, et al. Near visual function measured with a novel tablet application in patients with astigmatism. Clin Exp Optom 2021;104(1):42–7.

[24] Casagrande M, Baumeister M, Buhren J, Klaproth OK, Titke C, Kohnen T. Influence of additional astigmatism on distance-corrected near visual acuity and reading

performance. Br J Ophthalmol 2014;98:24–9. https://doi.org/10.1136/bjophthalmol-2013-303066.
[25] Chung STL, Jarvis SH, Cheung SH. The effect of dioptric blur on reading performance. Vision Res 2007;47:1584–94. https://doi.org/10.1016/j.visres.2007.03.007.
[26] Wills J, Gillett R, Eastwell E, Abraham R, Coffey K, Webber A, et al. Effect of simulated astigmatic refractive error on reading performance in the young. Optom Vis Sci 2012;89:271–6. https://doi.org/10.1097/OPX.0b013e3182429c6b.
[27] Plainis S, Mitropoulou M, Anastasakis A, Tsilimbaris M, Colenbrander A. Effect of blur on reading performance: monocular vs. binocular viewing. 4th Annu Conf Eur Acad Optom Opt, Dublin, Ireland: 2012.
[28] Kwon MY, Legge GE. Spatial-frequency requirements for reading revisited. Vision Res 2012;62:139–47. https://doi.org/10.1016/j.visres.2012.03.025.
[29] Legge GE, Rubin GS, Luebker A. Psychophysics of reading–V. The role of contrast in normal vision. Vis Res 1987;27(7):1165–77.
[30] Johansson J, Pansell T, Ygge J, Seimyr GO. The effect of contrast on monocular versus binocular reading performance. J Vis 2014;14:8. https://doi.org/10.1167/14.5.8.
[31] Kirkby JA, Webster LAD, Blythe HI, Liversedge SP. Binocular coordination during reading and non-reading tasks. Psychol Bull 2008;134:742–63. https://doi.org/10.1037/a0012979.
[32] Yammouni R, Evans BJW. Is reading rate in digital eyestrain influenced by binocular and accommodative anomalies? J Optom 2021;14:229–39. https://doi.org/10.1016/j.optom.2020.08.006.
[33] CITT-ART Investigator Group. Effect of vergence/accommodative therapy on attention in children with convergence insufficiency: A randomized clinical trial. Optom Vis Sci 2021;98:222–33. https://doi.org/10.1097/OPX.0000000000001659.
[34] Mangione CM, Berry S, Spritzer K, Janz NK, Klein R, Owsley C, et al. identifying the content area for the 51-item national eye institute visual function questionnaire. Arch Ophthalmol 1998;116:227–33. https://doi.org/10.1001/archopht.116.2.227.
[35] Mansfield J, Ahn S, Legge G, Luebker a. A new reading-acuity chart for normal and low vision. … Vis Syst Tech Dig 1993;3:232–5.
[36] Radner W. Standardization of reading charts: A review of recent developments. Optom Vis Sci 2019;96:768–79. https://doi.org/10.1097/OPX.0000000000001436.
[37] Radner W, Obermayer W, Richter-Mueksch S, Willinger U, Velikay-Parel M, Eisenwort B. The validity and reliability of short German sentences for measuring reading speed. Graefe's Arch Clin Exp Ophthalmol 2002;240:461–7. https://doi.org/10.1007/s00417-002-0443-5.
[38] Hahn GA, Penka D, Gehrlich C, Messias A, Weismann M, Hyvarinen L, et al. New standardised texts for assessing reading performance in four European languages. Br J Ophthalmol 2006;90:480–4. https://doi.org/10.1136/bjo.2005.087379.
[39] Gleni A, Ktistakis E, Tsilimbaris MK, Simos P, Trauzettel-Klosinski S, Plainis S. Assessing variability in reading performance with the new Greek standardized reading speed texts (IReST). Optom Vis Sci 2019;96:761–7. https://doi.org/10.1097/OPX.0000000000001434.
[40] Trauzettel-Klosinski S, Dietz K. Standardized assessment of reading performance: the new international reading speed texts IReST. Investig Ophthalmol Vis Sci 2012;53:5452–61. https://doi.org/10.1167/iovs.11-8284.
[41] Starr MS, Rayner K. Eye movements during reading: some current controversies. Trends Cogn Sci 2001;5:156–63. https://doi.org/10.1016/S1364-6613(00)01619-3.
[42] Brussee T, van Nispen RMA, Klerkx EMFJ, Knol DL, van Rens GHMB. Comparison of reading performance tests concerning difficulty of sentences and paragraphs and their reliability. Ophthalmic Physiol Opt 2015;35:324–35. https://doi.org/10.1111/opo.12204.
[43] Carver RP. Predicting accuracy of comprehension from the relative difficulty of the material. Learn Individ Differ 1990;2:405–22. https://doi.org/10.1016/1041-6080(90)90002-X.
[44] Ramulu PY, Swenor BK, Jefferys JL, Friedman DS, Rubin GS. Difficulty with out-loud and silent reading in Glaucoma. Investig Ophthalmol Vis Sci 2013;54:666–72. https://doi.org/10.1167/iovs.12-10618.
[45] Ramulu PY, Swenor BK, Jefferys JL, Rubin GS. Description and validation of a test to evaluate sustained silent reading. Invest Ophthalmol Vis Sci 2013;54:673–80. https://doi.org/10.1167/iovs.12-10617.
[46] Rayner K. Eye movements in reading and information processing: 20 years of research. Psychol Bull 1998;124:372–422.
[47] Glimne S, Brautaset RL, Seimyr GÖ. The effect of glare on eye movements when reading. Work 2015;50:213–20. https://doi.org/10.3233/WOR-131799.
[48] Zeri F, Naroo SA, Zoccolotti P, De Luca M. Pattern of reading eye movements during monovision contact lens wear in presbyopes. Sci Rep 2018;8:1–9. https://doi.org/10.1038/s41598-018-33934-6.
[49] Plainis S, Tzatzala P, Orphanos Y, Tsilimbaris MK. A modified ETDRS visual acuity chart for European-wide use. Optom Vis Sci 2007;84:647–53. https://doi.org/10.1097/OPX.0b013e3180dc9a60.
[50] Simos PG, Sideridis GD, Kasselimis D, Mouzaki A. Reading fluency estimates of current intellectual function: demographic factors and effects of type of stimuli. J Int Neuropsychol Soc 2013;19:355–61. https://doi.org/10.1017/S1355617712001518.
[51] White SJ, Staub A. The distribution of fixation durations during reading: Effects of stimulus quality. J Exp Psychol Hum Percept Perform 2012;38:603–17. https://doi.org/10.1037/a0025338.
[52] Rayner K, Liversedge SP, White SJ, Vergilino-Perez D. Reading disappearing text: cognitive control of eye movements. Psychol Sci 2003;14(4):385–8.
[53] White SJ. Eye movement control during reading: Effects of word frequency and orthographic familiarity. J Exp Psychol Hum Percept Perform 2008;34:205–23. https://doi.org/10.1037/0096-1523.34.1.205.
[54] Staub A. The effect of lexical predictability on distributions of eye fixation durations. Psychon Bull Rev 2011;18:371–6. https://doi.org/10.3758/s13423-010-0046-9.
[55] Staub A, Benatar A. Individual differences in fixation duration distributions in reading. Psychon Bull Rev 2013;20:1304–11. https://doi.org/10.3758/s13423-013-0444-x.
[56] Staub A, White SJ, Drieghe D, Hollway EC, Rayner K, Drieghe SA, et al. Distributional effects of word frequency on eye fixation durations. J Exp Psychol Hum Percept Perform 2010;36(5):1280–93.
[57] Reingold EM, Reichle ED, Glaholt MG, Sheridan H. Direct lexical control of eye movements in reading: evidence from a survival analysis of fixation durations. Cogn Psychol 2012;65:177–206. https://doi.org/10.1016/j.cogpsych.2012.03.001.
[58] Leyland LA, Kirkby JA, Juhasz BJ, Pollatsek A, Liversedge SP. The influence of word shading and word length on eye movements during reading. Q J Exp Psychol 2013;66:471–86. https://doi.org/10.1080/17470218.2011.599401.
[59] Schotter ER, Tran R, Rayner K. Don't believe what you read (only once): comprehension is supported by regressions during reading. Psychol Sci 2014;25:1218–26. https://doi.org/10.1177/0956797614531148.
[60] Jainta S, Jaschinski W. Individual differences in binocular coordination are uncovered by directly comparing monocular and binocular reading conditions. Invest Ophthalmol Vis Sci 2012;53:5762–9. https://doi.org/10.1167/iovs.12-9707.
[61] Johansson J, Pansell T, Ygge J, Seimyr GÖO. Monocular and binocular reading performance in subjects with normal binocular vision. Clin Exp Optom 2014;97:341–8. https://doi.org/10.1111/cxo.12137.
[62] Tsika C, Tsilimbaris MK, Makridaki M, Kontadakis G, Plainis S, Moschandreas J. Assessment of macular pigment optical density (MPOD) in patients with unilateral wet age-related macular degeneration (AMD). Acta Ophthalmol 2011;90:e573–8. https://doi.org/10.1111/j.1755-3768.2011.02170.x.
[63] Home R. Binocular summation: A study of contrast sensitivity, visual acuity and recognition. Vision Res 1978;18:579–85. https://doi.org/10.1016/0042-6989(78)90206-7.
[64] Legge GE. Binocular contrast summation—I. Detection and discrimination. Vision Res 1984;24(4):373–83.
[65] Rubin GS, Feely M. The role of eye movements during reading in patients with age-related macular degeneration (AMD). Neuro-Ophthalmology 2009;33:120–6. https://doi.org/10.1080/01658100902998732.
[66] Frömer R, Dimigen O, Niefind F, Krause N, Kliegl R, Sommer W, et al. Are individual differences in reading speed related to extrafoveal visual acuity and crowding? PLoS One 2015;10(3):e0121986.
[67] Risse S. Effects of visual span on reading speed and parafoveal processing in eye movements during sentence reading. J Vis 2014;14:1–13. https://doi.org/10.1167/14.8.11.
[68] Pelli DG, Tillman KA, Freeman J, Su M, Berger TD, Majaj NJ. Crowding and eccentricity determine reading rate. J Vis 2007;7:1–36. https://doi.org/10.1167/7.2.20.
[69] Rayner K, Castelhano MS, Yang J. Eye movements and the perceptual span in older and younger readers. Psychol Aging 2009;24:755–60. https://doi.org/10.1037/a0014300.
[70] Rayner K. The perceptual span and peripheral cues in reading. Cogn Psychol 1975;7:65–81. https://doi.org/10.1016/0010-0285(75)90005-5.
[71] Calabrèse A, To L, He Y, Berkholtz E, Rafianm P, Legge GE. Comparing performance on the MNREAD iPad application with the MNREAD acuity chart. J Vis 2018;18:1–11. https://doi.org/10.1167/18.1.8.
[72] Laubrock J, Kliegl R. The eye-voice span during reading aloud. Front Psychol 2015;6:1432. https://doi.org/10.3389/fpsyg.2015.01432.
[73] Subramanian A, Pardhan S. The repeatability of MNREAD acuity charts and variability at different test distances. Optom Vis Sci 2006;83:572–6. https://doi.org/10.1097/01.opx.0000232225.00311.53.