

Reading with central vision loss: binocular summation and inhibition

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Abstract

Purpose: There are conflicting reports as to whether there is a binocular advantage or disadvantage when reading with central vision loss. This study examined binocular reading summation in patients with macular degeneration.

Methods: Seventy-one patients with bilateral central vision loss due to macular degeneration [mean age: 63 (S.D. = 21) years] participated. Reading performances during binocular and monocular viewing with the better eye (i.e., the eye with the best monocular visual acuity) were evaluated using different versions of the Italian MNREAD reading chart (www.precision-vision.com). Fixation stability and preferred retinal loci (PRLs) were recorded monocularly for each eye. The overall sample was split into inhibition, equality, and summation groups based on the binocular ratio (i.e., binocular/monocular) of the maximum reading speed.

Results: 41% of patients experienced binocular inhibition, 42% summation, and 17% equality. Binocular reading speed of the inhibition group was approximately 30 words per minute slower than those of the equality and summation groups, although the inhibition group had the best visual acuity. These patients generally had monocular PRLs in non-corresponding locations temporal or nasal to the scotoma, had the largest interocular acuity difference and lacked residual stereopsis. The three groups did not differ in fixational control, contrast sensitivity or critical print size.

Conclusions: Equal proportions of patients with central vision loss show binocular reading summation and inhibition. Patients with binocular reading inhibition have poorer reading performance and different clinical characteristics than those with binocular reading summation and equality.

Introduction

Reading with healthy vision is a seemingly automatic process, but its execution involves a complex interplay of precise oculomotor control, good visual acuity, low crowding effects and a wide visual span, that in large part are driven by foveal function. When central vision is damaged by macular diseases, all of these factors are perturbed, resulting in a reading performance so poor and frustrating that many

patients give it up entirely.^{1–4} The inability to read represents the chief complaint of these patients and it negatively impacts their quality of life. Because reading is a basic function needed for conducting activities of daily living, its improvement is the most sought after by patients entering low vision rehabilitation.^{5,6} Efforts have been made to design rehabilitation techniques that aim to improve oculomotor control by stabilising fixation, to alleviate crowding effects by using fonts with larger spacing between the

letters, and to enlarge visual span by relocating the preferred retinal locus (PRL) above or below the scotoma.⁷⁻¹¹ It has been shown that these approaches can lead to improvements in patients' reading performance.

Macular diseases such as age-related macular degeneration (AMD) also affect binocular function. Patients have poor or non-detectable stereo acuity and a significant proportion of them (for reasons that are not completely understood) experience binocular inhibition of visual acuity and contrast sensitivity; that is, binocular performance is poorer than the monocular performance with the better eye.¹²⁻¹⁴ Whether patients with central vision loss show binocular inhibition for reading performance is not entirely elucidated.

For people with a healthy visual system, binocular performance is typically better than monocular performance, a phenomenon known as binocular summation. During reading, this effect is driven by an increased efficiency of parafoveal pre-processing of the upcoming text during binocular viewing; specifically, fixation times are shorter during binocular versus monocular reading, although the saccade parameters are the same for both viewing conditions.¹⁵ In patients with central vision loss, evidence of binocular summation or inhibition is scarce and contradictory.

First, Kabanarou and Rubin¹⁶ tested monocular and binocular reading performance in 22 patients with late stage AMD and found an overall non-significant advantage of 6 words per minute (wpm) for binocular versus monocular reading. The authors concluded that binocular and monocular reading are comparable in AMD. However, a closer examination of the study revealed that 16 patients showed binocular reading summation and 6 had inhibition. It is possible that these effects cancelled each other out in the analysis of the overall sample, resulting in a nonsignificant advantage of binocular reading. The study also lacked clinical characteristics such as information about the PRL location relative to the scotoma or fixation stability that have been shown to influence reading performance.¹⁷⁻²⁰ Second, Tarita-Nistor *et al.*²¹ showed that in a sample of 20 patients with AMD, 30% of cases had binocular acuity inhibition; for these, binocular reading performance was very poor (an average of 45 wpm) and their monocular PRLs were generally located temporal or nasal to the scotoma and not on corresponding retinal locations. On the contrary, for those showing binocular acuity summation, reading speed was functional (i.e., an average of 107 wpm)²² and their monocular PRLs were generally above or below the scotoma and on corresponding retinal locations. Because the study did not have the monocular reading speed data, binocular reading summation was not evaluated. Finally, Tzaridis *et al.*²³ assessed binocular and monocular reading performance in 68 patients with macular telangiectasia type 2 (MacTel) and found that the

majority of patients showed binocular inhibition of reading speed. MacTel causes oval-shaped damage centred at the fovea in the later stages of the disease, but the onset of the scotoma is paracentral, almost always in the temporal or temporal-inferior area of the retina.²⁴ In the Tzaridis *et al.* investigation, all but three cases had paracentral scotomas (with a likely functional fovea) that projected into different areas of the visual field. The study found that binocular reading speed was associated negatively with the scotoma size of both eyes, with a bigger effect size for the scotoma in the left eye, but the magnitude of binocular inhibition was associated with scotoma measurements in the left eye only and not in the right eye. The authors suggested that for the left-to-right readers, there may be a rivalry effect caused by the paracentral scotoma projected to the right in the visual field (e.g., a temporal scotoma in the left retina) and this would be a possible mechanism for binocular reading inhibition. Although MacTel affects central vision, the scotomas are generally smaller and non-homonymous (i.e., in non-corresponding locations in the visual field), with better visual outcomes compared to those produced by AMD. For example, the average binocular and monocular reading speeds of patients with MacTel were 142 wpm and 159 wpm, respectively, and each of these values is considered to represent high functional reading (minimum reading speed required for high fluency reading is 160 wpm).²²

The purpose of this study was to investigate whether binocular reading has an advantage over monocular reading with the better eye in patients with macular degeneration. Given the severity of impairment in reading skills, it is important to understand the factors affecting reading performance since some of these factors could be partially remediated through rehabilitation.

Methods

Participants

Seventy-one patients with bilateral central vision loss [36 females, 35 males; mean age: 63 (S.D. = 21) years] either due to AMD (N = 42) or Stargardt's disease (N = 29) participated in this prospective observational case series. Patients were referred from the National Centre of Services and Research for the Prevention of Blindness and Rehabilitation of Low Vision Patients (International Agency for Prevention of Blindness, Rome, Italy) from June 2019 to December 2019. The diagnosis of bilateral central vision loss was made by an ophthalmologist. Participants had a visual acuity of 1.3 logMAR or better. All spoke Italian fluently and none had a cognitive impairment. Patients had no other comorbid eye diseases, significant media opacities, neurological diseases, and speech or language impairment. They had not undergone ocular surgery within 90 days of testing and none had a history of amblyopia. The study

protocol was approved by the Ethical Committee of the Agostino Gemelli Foundation IRCCS (Rome, Italy) and conducted according to the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants. Demographic and clinical characteristics of the patients are shown in *Table 1*.

Apparatus and procedure

Data from each participant were recorded during a single 2.5 to 3-hour visit. The following measures were collected: 1) visual acuity, 2) reading performance, 3) contrast sensitivity, 4) stereo acuity, and 5) fixation stability and PRL location relative to the scotoma. Patients were told that the aim of the study was to evaluate their reading performance binocularly and with the better eye. All participants were informed about their performance on the MNREAD test (www.precision-vision.com) at the end of the examination. After the experimental session had been completed, patients were prescribed low vision aids as part of their standard care.

Visual acuity

Visual acuity was measured using the Early Treatment of Diabetic Treatment Study charts at 4 m (www.precision-vision.com) using a letter-by-letter scoring system.²⁵ Visual acuity was measured monocularly for each eye and binocularly. For each viewing condition (i.e., right eye viewing, left eye viewing, and binocular) a different version of the test was used. Patients used their habitual correction and were allowed enough time to read the letters. The better- and the worse-seeing eyes were identified as the eyes with the better and the worse visual acuity, respectively.

Reading performance

Both binocular and monocular reading performance (with the better eye) were evaluated using the Italian version of

the MNREAD acuity charts (www.precision-vision.com). Reading performance with the worse eye was not assessed. Two different versions of the black-on-white MNREAD acuity charts were used: for half of the patients, the MNREAD Version 1 was presented first, and for the other half Version 2 was presented first. The order of monocular with the better eye and binocular reading conditions was randomised for each patient. The MNREAD chart was placed on a stand and the patients adjusted the stand to their corrected viewing distance, while wearing their habitual spectacles. The reading distance remained the same for both the monocular and binocular testing. Subjects were instructed not to modify their reading distance and the examiner watched to ensure that this was the case. Participants were asked to read a sentence aloud, starting from the 1.3 logMAR sentence after hearing “start” from the examiner. Each sentence was timed with a stopwatch and all errors were recorded. The patients were instructed to stop after each sentence and not to look ahead at the next block until instructed. They were encouraged to read the smaller sentences until they were unable to do so.

Three parameters were calculated, namely: reading acuity, defined as the smallest print that could be read when adjusted for errors per the MNREAD manual’s instructions, critical print size defined as the smallest print size that could be read at the maximum reading speed, and maximum reading speed defined as the fastest reading speed achieved over the larger print sizes. In accordance with the manufacturer’s instructions, a correction factor was used where appropriate to account for the non-standardised reading distance.

Contrast sensitivity

Contrast Sensitivity was measured using the Pelli-Robson chart (www.precision-vision.com) at 1 m, with a + 1 spherical lens added to the distance refractive correction. Patients were asked to read the letters on the chart first binocularly and then monocularly with the better eye. Contrast level was considered good if patients identified at least two of the three letters in a triplet correctly. The test ended when the participant missed two of the three letters in a triplet. Pelli-Robson scoring sheets were used to determine the contrast sensitivity and recorded as log contrast sensitivity.

Stereo acuity test

The Stereo Fly Test (www.precision-vision.com) was used to measure stereo acuity and was administered according to the manufacturer’s instructions. The experimenter held the test straight in front of the patient to maintain the proper axis of polarisation at 40 cm. It was performed

Table 1. Demographic and clinical characteristics of the patients with central vision loss

	N	Sex	Age (years)	Visual acuity (logMAR)		
				Binocular	Right eye	Left eye
Overall sample	71	36F/ 35M	63 (21)	0.7 (0.3)	0.8 (0.3)	0.7 (0.3)
AMD	42	19F/ 23M	77 (7)	0.6 (0.2)	0.8 (0.3)	0.7 (0.3)
Stargardt’s	29	17F/ 12M	41 (16)	0.7 (0.3)	0.8 (0.3)	0.7 (0.2)

Age and visual acuity values are shown as means (S.D.).

under good lighting conditions and care was taken to avoid light reflections on the shiny surfaces. Patients were asked to wear their optical correction for the test distance under the polarised viewers. Starting with the fly, patients were asked to indicate whether they saw the objects presented to them as “popping out”. For the fly, patients were asked to “pinch” the tip of a wing between the thumb and forefinger, and a score of 3,552 arcsec was assigned if they were able to see it stereoscopically. The smallest possible score on the chart is 40 arcsec.

Fixation stability and PRL location

For each eye, monocular fixation stability and PRL location were obtained using the MP-1 Microperimeter (www.nidektechnologies.it). The MP-1 Microperimeter has a built-in automatic eye-tracking system that registers horizontal and vertical eye position relative to an anatomical landmark (e.g., a retinal blood vessel) while compensating for stimulus projection location at a sampling rate of 25 Hz. The black and white image of the fundus is captured using an infrared camera, and eye positions are recorded while the patient fixates a target projected onto a graphics screen. The fixation stimulus was a 2 degree white cross. In a dark room, patients were seated with their head positioned in the headrest of the MP-1 Microperimeter and were asked to keep their gaze in the middle of the fixation cross. Testing was conducted one eye at a time while the other eye was patched. Fixation stability was recorded twice for each eye and data were acquired for a fixed interval of 15 seconds during each examination. After the first examination, patients were asked to rest with eyes closed until ready for a second fixation test. At the end of the examination, a fundus photograph was obtained. No mydriatic drops were used during this procedure. Subsequently, the fixational eye positions were registered on the colour fundus photographs offline.

Data analysis

Fixation stability was quantified with the 68% bivariate contour ellipse area (BCEA) and measured in deg^2 . The BCEA formula is calculated as follows:²⁶

$$\text{BCEA} = \pi \chi^2 \sigma_x \sigma_y \sqrt{1 - \rho^2}$$

where χ^2 is the chi-squared value (2df) corresponding to a probability of 0.68 (± 1 S.D.), σ_x and σ_y are the standard deviations of the horizontal and vertical eye positions, respectively, and ρ is the Pearson product moment correlation coefficient. The PRL location was evaluated as the distance from the former fovea to the center of the fixation cluster. The former fovea was assumed to be 15 degrees

temporal and 1.3 degrees below the middle of the optic disc, and the measurements were obtained using the radial grid of the microperimeter.²⁷

The binocular ratio (BR) of the maximum reading speed was defined as the binocular performance/monocular performance with the better eye (i.e., ratio of the binocular maximum reading speed to the monocular maximum reading speed). Using the BR as a criterion, the overall sample was split into three groups: 1) inhibition group with $\text{BR} < 0.95$, 2) equality group with $\text{BR} = 1 \pm 0.05$, and 3) summation group with $\text{BR} > 1.05$.^{14,21,28}

Data were first analysed for the overall sample with paired sample t-tests and Pearson product moment correlations. The outcome measures were visual acuity, contrast sensitivity and reading performance (i.e., maximum reading speed, critical print size and reading acuity) during both binocular and monocular viewing with the better eye. Then, the outcome measures were compared among the three groups. In addition to the outcome measures listed above, fixation stability and PRL distance from the former fovea for each eye were examined for the three groups. For the most part, data were analysed with 2 (viewing condition: monocular, binocular) \times 3 (group: inhibition, equality, summation) mixed factorial ANOVAs. Alpha level was set at 0.05 for all tests, and the familywise error rate controlled with the Bonferroni approach.

Results

Overall sample analysis

The differences in the outcome measures recorded during binocular and monocular viewing were examined with paired-samples t-tests. Binocular visual acuity did not differ from monocular visual acuity ($p = 0.30$). Contrast sensitivity was 1.12 (S.D. = 0.4) logCS during binocular viewing and 1.09 (S.D. = 0.4) logCS during monocular viewing. Although the difference was very small and probably of no clinical relevance, it was statistically significant, $t_{70} = 2.50$, $p = 0.02$. Reading performance (i.e., maximum reading speed, critical print size, and reading acuity) did not differ in the two viewing conditions (smallest $p = 0.4$). Mean maximum reading speed was 82 (S.D. = 41) wpm binocularly and 81 (S.D. = 37) wpm monocularly. Binocular outcome measures were highly correlated with monocular measures. These results are shown in *Figure 1*.

BR of the maximum reading speed: inhibition, equality, summation

The sample was divided into inhibition, equality, and summation groups based on the BR at the maximum reading speed. There were 29 cases (41%) with $\text{BR} < 0.95$ (inhibition group), 12 cases (17%) with $\text{BR} = 1 \pm 0.05$ (equality

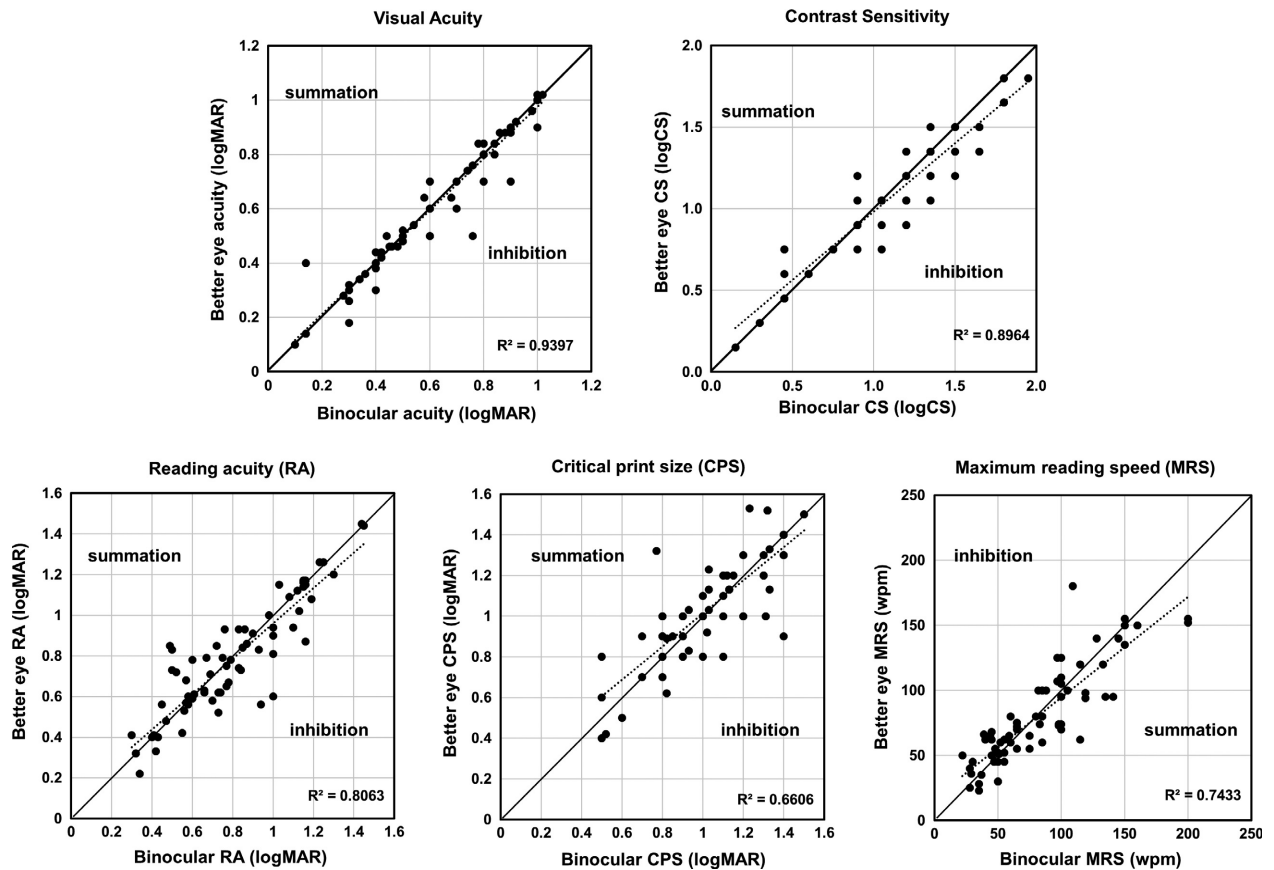


Figure 1. Binocular and monocular outcome measures (visual acuity, contrast sensitivity, reading acuity, critical print size, and maximum reading speed) for the overall sample.

group), and 30 cases (42%) with BR > 1.05 (summation group). The average BRs were 0.79 (S.D. = 0.12), 1.0 (S.D. = 0.04), and 1.29 (S.D. = 0.21) for the inhibition, equality, and summation groups, respectively. The mean age was 70 (S.D. = 14) years for the inhibition group, 53 (S.D. = 31) years for the equality group, and 60 (S.D. = 21) years for the summation group. The difference in mean age between the three groups was analysed with one-way ANOVA which yielded a significant result, $F_{2, 68} = 3.5, p = 0.04, \text{partial } \eta^2 = 0.09$. However, post-hoc analysis showed that only when using a more relaxed test such as the Tukey HSD, then a marginally significant difference between the inhibition and equality groups could be identified ($p = 0.049$). Moreover, the disease duration was similar for the three groups: 9.8 (S.D. = 7.7) years, 7.5 (S.D. = 6.3) years, and 10.4 (S.D. = 8.5) years for the inhibition, equality, and summation groups, respectively.

The analysis exploring the effect of viewing condition on the outcome measures for the three groups was performed using 2 (viewing condition: binocular, better eye) x 3 (group: inhibition, equality, summation) mixed factorial ANOVAs,

presented below. The means and standard deviations of the outcome measures for the three groups during binocular and monocular viewing with the better eye are shown in *Table 2*.

Maximum reading speed

The mixed factorial ANOVA revealed only a significant viewing condition x group interaction, $F_{2,68} = 59.2, p < 0.001, \text{partial } \eta^2 = 0.64$. During binocular viewing, the reading speed in the inhibition group was significantly slower by an average of 29 wpm compared with the summation group ($p = 0.01$), and slower by an average of 31 wpm than the equality group, although this difference was not significant ($p = 0.059$). During monocular reading with the better eye, the three groups did not differ significantly. Moreover, for the inhibition group, reading speed was significantly slower binocularly than monocularly ($p < 0.001$), while the opposite was true for the summation group ($p < 0.001$). Binocular reading was an average of 16 wpm slower in the inhibition group and 20 wpm faster in the summation

Table 2. Mean (S.D.) of the maximum reading speed, critical print size, reading acuity, visual acuity, and contrast sensitivity for the binocular and monocular viewing with the better eye for the three groups

	Inhibition <i>N</i> = 29		Equality <i>N</i> = 12		Summation <i>N</i> = 30	
	Binocular	Better eye	Binocular	Better eye	Binocular	Better eye
Maximum reading speed (wpm)	65 (28)	81 (33)	96 (39)	96 (39)	94 (46)	74 (38)
Critical print size (logMAR)	1.05 (0.3)	1.02 (0.2)	1.0 (0.3)	1.0 (0.3)	1.0 (0.2)	1.05 (0.2)
Reading acuity (logMAR)	0.86 (0.3)	0.78 (0.3)	0.74 (0.3)	0.74 (0.3)	0.77 (0.3)	0.81 (0.3)
Visual acuity (logMAR)	0.58 (0.3)	0.56 (0.3)	0.71 (0.3)	0.73 (0.3)	0.70 (0.3)	0.68 (0.2)
Contrast sensitivity (logCS)	1.0 (0.3)	1.0 (0.3)	1.0 (0.3)	1.0 (0.3)	1.0 (0.3)	1.1 (0.2)

group than monocular reading. These results are shown in Figure 2 and in Table 2.

Critical print size

A similar analysis was carried out for the critical print size. The within-subject effect, between-subject effect, and their interaction were not significant (smallest $p = 0.07$). These results are shown in Table 2.

Reading acuity

The mixed factorial ANOVA revealed only a significant viewing condition \times group interaction, $F_{2,68} = 7.6$, $p = 0.001$, partial $\eta^2 = 0.18$. For the inhibition group, reading acuity was significantly poorer binocularly than monocularly ($p = 0.001$). There was no difference in reading acuity in the two viewing conditions for the equality group. For the summation group, binocular reading acuity was an average of 0.04 logMAR better than monocular reading acuity, but this difference failed to reach significance ($p = 0.052$). No other follow-up comparisons were significant. These results are shown in Table 2 and plotted in Figure 3 together with the visual acuity findings.

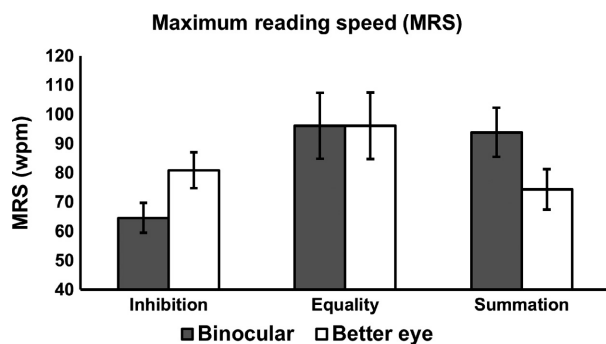


Figure 2. Maximum reading speed during binocular and monocular viewing with the better eye for the three groups. Error bars are ± 1 S.E.

Visual acuity

The mixed factorial ANOVA revealed no significant effect. Visual acuity of the inhibition group (both monocularly with the better eye and binocularly) was about 0.15 logMAR (1.5 acuity lines) better than those of the equality and summation groups. These results are shown in Table 2. We further examined whether the three groups differed in terms of interocular acuity difference, defined as the monocular acuity of the worse eye minus the acuity of the better eye. One-way ANOVA showed a significant effect, $F_{2,68} = 8.02$, $p = 0.001$, partial $\eta^2 = 0.19$. Interocular acuity difference was significantly higher in the inhibition group than in the equality ($p = 0.009$) and summation groups ($p = 0.002$). Mean interocular acuity difference was 0.39 (S.D. = 0.3) logMAR, 0.14 (S.D. = 0.2) logMAR, and 0.17 (S.D. = 0.2) logMAR for the inhibition, equality, and summation groups, respectively.

Table 2 shows a large difference of more than 2 lines between visual acuity and reading acuity in the inhibition

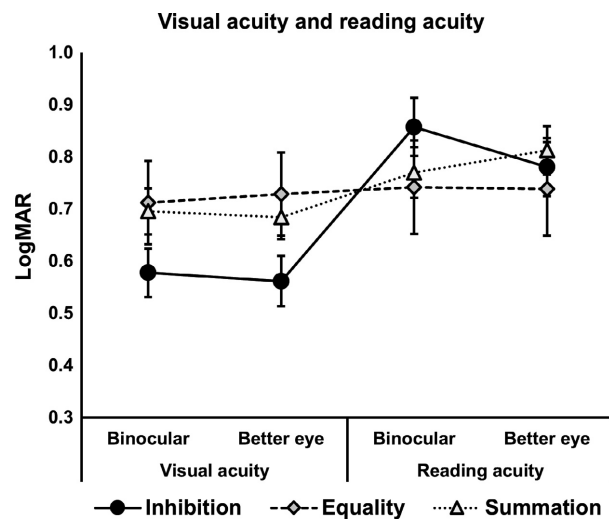


Figure 3. Visual acuity and reading acuity during binocular and monocular viewing with the better eye for the three groups. Error bars are ± 1 S.E.

group but not in the other two groups. To examine further the interaction between visual acuity and reading acuity for the three groups, we performed a 2 (viewing condition: binocular, monocular) \times 2 (acuity: reading, distance) \times 3 (group: inhibition, equality, summation) mixed factorial ANOVA. This analysis revealed only two significant results. First, the acuity main effect was significant, $F_{1,68} = 11.4$, $p = 0.001$, partial $\eta^2 = 0.14$. Overall, reading acuity was significantly higher than visual acuity. Second, the viewing condition \times acuity \times group interaction effect was significant, $F_{2,68} = 6.2$, $p = 0.003$, partial $\eta^2 = 0.15$. For the inhibition group, visual acuity was significantly better than reading acuity during monocular and binocular viewing ($p < 0.001$), while for the summation group, visual acuity was significantly better than reading acuity ($p = 0.02$) for the monocular but not for binocular viewing. For the equality group, there were no significant differences between visual and reading acuity in any of the viewing conditions. For the inhibition group, reading acuity was significantly worse during binocular than monocular viewing ($p = 0.001$). No other pairwise comparisons were significant. These results are shown in *Figure 3*.

Contrast sensitivity

The 2 (viewing condition: binocular, better eye) \times 3 (group: inhibition, equality, summation) mixed factorial ANOVA revealed no significant within-subject, between-subject, or interaction effects. These results are shown in *Table 2*.

Fixation stability and PRL eccentricity

Fixation stability was analysed with a 2 (eye: better, worse) \times 3 (group: inhibition, equality, summation) mixed factorial ANOVA. This analysis revealed only a significant within-subject main effect, $F_{1,68} = 19.9$, $p < 0.001$, partial $\eta^2 = 0.23$. Fixation stability with the better eye was significantly better than that with the worse eye. A similar analysis was performed for the PRL distance from the former fovea. There was only a significant within-subject main effect, $F_{1,68} = 10.0$, $p = 0.002$, partial $\eta^2 = 0.13$. The PRL distance from the former fovea was significantly larger for the worse eye than for the better eye in the inhibition group ($p = 0.001$), but not in the other two groups. The PRL eccentricity in the better eye did not differ between the three groups. These results are shown in *Figure 4*.

PRL correspondence and location relative to the scotoma

In order to examine the PRL correspondence, we used 4 quadrants generated by Cartesian axes with an origin at the former fovea and rotated 45 deg away from the vertical on the fundus photographs. The PRLs were considered to be

in corresponding positions if: 1) they were in the same quadrant in both eyes as projected in the visual field (i.e., PRL was in the temporal quadrant on the retina in one eye and the nasal quadrant on the retina of the fellow eye), and 2) were at a similar distance from the former fovea when inspected visually. Most patients in the equality (92%) and summation groups (83%) had the PRLs in corresponding locations in the two eyes, but the opposite was true for the inhibition group, with 68% of cases with PRLs in non-corresponding locations.

We also examined the PRL location in the better eye with respect to the scotoma on the retina and classified this location as superior, inferior, nasal, and temporal. The PRL in the better eye was inferior or superior to the scotoma in the majority of cases in the equality (75%) and summation (67%) groups, but only in 31% of cases in the inhibition group, in which more patients had the PRL temporal or nasal to the scotoma (38%). These results are shown in *Figure 5*.

For the inhibition group, we further examined whether the PRL in the worse eye would fall onto a scotoma when viewing binocularly, assuming that the PRL in the better eye does not change from monocular to binocular viewing and that the PRL in the worse eye lies in a corresponding location to that of the better eye. We found that for 15 cases (52%) the PRL in the worse eye would fall onto a scotoma that was in retinal correspondence with the PRL from the better eye (see schematics in *Figure 6*).

Residual stereoacuity

Residual stereoacuity was found in only 38% of cases in the inhibition group, but in 50% of the equality group and 73% of the summation group. For those individuals with residual stereopsis, mean stereoacuity was 1455 arcsec (S.D. = 1675), 775 arcsec (S.D. = 1374), and 1182 arcsec (S.D. = 1350) for the inhibition, equality, and summation groups, respectively. Patients with PRLs in non-corresponding locations (for all groups) were more likely not to have measurable residual stereoacuity (72%, 100%, and 80% of the inhibition, equality, and summation groups, respectively).

Eye preference

We examined retrospectively whether the better eye was also the preferred eye. During the clinical evaluation, patients are typically asked about eye preference and this information is collected by the attending ophthalmologist. Data were available for only 42 patients: 21 in the inhibition group, 5 in the equality group and 16 in the summation group. Overall, for 38 patients (90%) the preferred eye was the one with the better visual acuity. However, this was

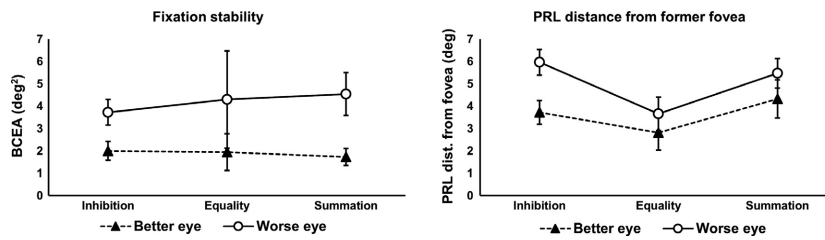


Figure 4. Fixation stability (left panel) and PRL distance from the former fovea (right panel) in the better eye and in the worse eye for the three groups. Standard errors are ± 1 S.E.

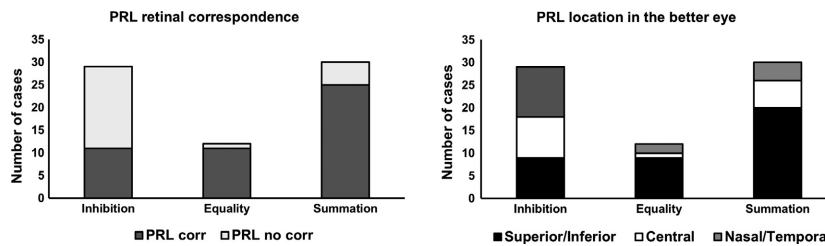


Figure 5. Retinal correspondence of the PRL in the two eyes (left panel) and PRL location relative to the scotoma in the better eye (right panel) for the three groups.

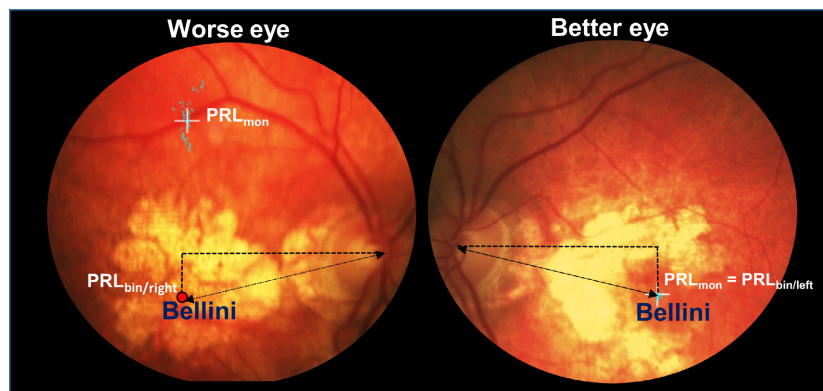


Figure 6. The figure shows an example of a patient from the inhibition group who has the monocular PRLs (PRL_{mon}) in non-corresponding locations. During binocular viewing the two eyes are yoked and — assuming that the monocular PRL in the better eye does not change location during binocular reading ($PRL_{mon} = PRL_{bin/left}$) — the corresponding $PRL_{bin/right}$ in the worse eye falls onto the probable scotoma. This is represented by the red circle in the left panel. The word “Bellini” is read with the PRL, but is shown here below the PRLs for clarity.

not the case for four patients: one in the inhibition group, one in the equality group, and two in the summation group.

Discussion

This study examined binocular reading summation in a large sample of patients with central vision loss. Given the contradictory reports from the literature, we explored whether there is a binocular advantage or disadvantage in reading with macular degeneration and examined factors that could affect reading summation. The main findings

were that for the overall sample, binocular and monocular reading performances were similar, but 41% of patients experienced binocular inhibition, 42% binocular summation, and 17% equality, and these groups of patients differed in major ways. The inhibition group had the lowest binocular reading speed, but the best visual acuity and the largest reserve from visual acuity to reading acuity (i.e., largest difference between visual and reading acuity). These patients generally had monocular PRLs in non-corresponding locations, the PRL in the better eye located temporal or nasal to the scotoma, the largest interocular acuity difference and lacked residual stereopsis. The three groups did

not differ in fixational control, contrast sensitivity or critical print size. This study highlights important factors associated with binocular reading inhibition that could be addressed through rehabilitation.

The present study reconciles the scarce, but contradictory reports from the literature related to binocular reading summation in patients with central vision loss.^{16,21,23} We found no real binocular advantage in any measures, including visual acuity, contrast sensitivity, reading acuity, critical print size and maximum reading speed for the overall sample of patients with central vision loss. The null result in reading speed is consistent with that reported by Kabanorou and Rubin,¹⁶ who showed a small, but nonsignificant advantage of 6 wpm during binocular versus monocular reading for their overall sample. Likewise, we report almost identical reading speeds during monocular and binocular viewing (i.e., 80 wpm and 81 wpm, respectively) for the whole group. Tzaridis *et al.*²³ found binocular reading inhibition in most patients with MacTel, but the clinical manifestation of the disease is different from AMD and Stargardt's disease, with generally smaller and non-homonymous scotomas and better visual outcomes. Tarita-Nistor *et al.*²¹ showed that one third of a small sample of patients with AMD had binocular acuity inhibition, and their reading speed was exceptionally poor. These patients (similar to those of the current study) generally had monocular PRLs in non-corresponding locations, and the PRL situated temporal or nasal to the scotoma in the better eye, but this was not typical for those showing binocular summation. Unfortunately, their study did not present data for monocular reading with the better eye; rather the binocular ratio of acuity was used as a criterion to divide the sample. In the current study we found equally large proportions of patients with binocular reading inhibition and summation; in the analysis of the overall sample these effects cancelled each other out. Furthermore, we found that the inhibition group differed in important ways from the summation and equality groups.

For the inhibition group there was a binocular disadvantage in reading speed of 16 wpm, whereas for the summation group there was a binocular advantage of 20 wpm. Importantly, for the inhibition group, binocular reading speed was about 30 wpm slower than those of the equality and summation groups; their binocular reading speed was 65 wpm which is considered slow reading, whereas the equality and summation groups had binocular reading speeds of 96 wpm and 94 wpm, respectively, and both these values are considered functional reading (i.e., a reading speed greater than 80 wpm).²²

What determines the binocular reading inhibition in such a large proportion of patients? To answer this question, we examined other factors that affect reading performance. Although the inhibition group had a similar monocular

fixation pattern for the two eyes to the equality and summation groups, the PRL in the worse eye was at a larger eccentricity than that for the better eye, and this was not the case for the other two groups. In addition, PRLs were frequently in non-corresponding locations and situated temporal or nasal to the scotoma in the better eye; a location that can shorten the normal visual span required for fluent reading. This pattern of results is suggestive of a probable change in PRL location in the worse eye when the condition changes from monocular to binocular viewing to come into retinal correspondence with that from the better eye, but this may result in a location that falls inside the scotoma²⁹ (see *Figure 6*). Indeed, we found that this may have been the case for 52% of cases in the inhibition group (however, this is only true when assuming that the monocular PRL in the better eye drives binocular control, and it does not change location). This suggests that the text can disappear into the scotoma of the worse eye. It is possible that due to a perceptual filling-in phenomenon,³⁰ the worse eye sees an image without the text (i.e., a different image from the better eye) that may rival the image from the better eye, thus driving the inhibitory binocular processes for the specific reading task. In addition, patients in the inhibition group suffered from a lack of stereoacuity and had large asymmetry in visual acuity between the two eyes. Taken together, all these factors may be conducive of binocular reading inhibition, although the exact inhibitory mechanism remains unknown.

To illustrate these findings, consider the patient from the inhibition group shown in *Figure 6*. This individual had monocular PRLs in non-corresponding locations; in the better eye the PRL was paracentral (only 1 deg below the former fovea) but 9 deg superior to the former fovea in the worse eye. Assuming that the PRL in the better eye does not change with viewing condition, then the PRL in the worse eye would fall onto the scotoma to come into a corresponding retinal location with that of the better eye during binocular viewing. Also, this patient had no detectable stereoacuity and a large interocular acuity difference of 3 lines. All these factors may have contributed to their poor reading speed and binocular inhibition: reading speed was 30 wpm binocularly (i.e., spot reading) and 45 wpm monocularly (i.e., slow reading).²²

Interestingly, we found no difference in reading acuity and critical print size for the three groups, but surprisingly, binocular and monocular visual acuities were significantly better in the inhibition group than for the summation group. This produced a large reserve from visual acuity to reading acuity of about 3 lines in the inhibition group, which is very important because it highlights the potential for reading rehabilitation. In vision rehabilitation settings, the performance of the better eye is frequently used to predict binocular performances,^{8,16,31} but our data strongly suggest that the reserve from visual acuity to reading acuity

and interocular acuity differences are key elements that may influence maximum reading speed during binocular viewing. The results indicate that for patients with central vision loss, reading performance should be measured both monocularly and with both eyes open because different outcomes can be obtained depending on the viewing condition and the patient's clinical characteristics. Furthermore, patients with binocular reading inhibition may prefer to use monocular low vision aids with the better eye while occluding the worse eye. Indeed, our electronic health records revealed that 52% of patients in the inhibition group showed this preference, while those in the equality and summation groups preferred binocular visual aids. We suggest that low vision rehabilitation practitioners should always investigate both monocular and binocular reading in patients with central vision loss, and prescribe the best visual aid in accordance with the patient's preference and optimum performance. These findings have important implications for the development of future reading rehabilitation approaches that would incorporate binocular function rather than focusing only on the better eye^{8,32,33}.

The question that remains to be answered is whether binocular inhibition is a robust phenomenon in patients with central vision loss. It has been shown that binocular inhibition exists for contrast sensitivity,^{12,13} visual acuity,¹⁴ and now reading speed, but no test-retest study has been performed. The current study shows that patients with binocular reading inhibition differ in important ways from those with binocular reading equality and summation, and we suspect that immediate re-testing will yield similar results. However, macular diseases are progressive, and therefore the patients' clinical characteristics can change over time. For example, it is possible that a patient's binocular summation recorded at one point in time will deteriorate to binocular inhibition later on if the disease progresses more aggressively in one eye than the other to produce a large interocular acuity difference, a monocular PRL in the worse eye that is further away in the periphery, and a presumptive corresponding retinal location with the PRL of the better eye that would fall into the scotoma in the worse eye. This remains an empirical question that only a longitudinal study will be able to address.

A limitation of this study is that reading performance with the worse eye was not measured. This would have provided more insight into the interocular differences for the three groups, which were evident for the visual acuity measures. However, we could not measure reading performance for the worse eye because only two versions of the MNRead Italian charts currently exist; one was used for binocular reading and the other for monocular reading with the better eye, presented randomly. Recently, the MNRead test has been released as an iPad app; this app offers five versions of the test in the English language, but

the Italian version is still restricted to only two versions. Future studies should explore this issue. Moreover, stereoacuity was measured with the Stereo Fly Test which provides non-stereoscopic cues up to a point, and we also acknowledge this limitation. In addition, the role of the dominant eye (which may not always be the eye with the better acuity) in binocular reading summation should be investigated further in patients with central vision loss.

In conclusion, we found no binocular reading advantage for the overall sample of patients with central vision loss, but equal proportions of patients exhibit inhibition and summation, and these effects cancel each other out in the overall analysis. Patients with binocular reading inhibition differ in major ways from those with binocular reading summation or equality. Their poor reading speed and binocular reading inhibition were probably due to several factors including: 1) monocular PRLs in non-corresponding locations; 2) the location of the PRL in the better eye temporal or nasal to the scotoma; 3) large interocular acuity difference and 4) lack of residual stereopsis. The large reserve from visual acuity to reading acuity found in the inhibition group suggests that rehabilitation may be possible. These data provide strong evidence for the importance of binocular function evaluation when devising reading rehabilitation techniques for patients with visual impairment due to central vision loss.

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Conflict of interest

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

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