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Reduced amblyopic eye fixation stability cannot be simulated using retinal-defocus-induced reductions in visual acuity

Rajkumar Nallour Raveendran[1,*], William Bobier, Benjamin Thompson

School of Optometry and Vision Science, University of Waterloo, Ontario, Canada

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ABSTRACT

Amblyopia is associated with impaired visual acuity (VA) and reduced fixation stability (FS). To assess whether impaired VA may cause reduced FS, the effects of retinal-defocus-induced visual acuity reductions on FS were measured in observers with amblyopia and controls. Fixational eye movements were measured in 8 patients with amblyopia and 12 controls. Monocular near VA of a subset of controls (n = 5) was then varied from 20/20 to 20/100 using convex lenses. The amblyopia group completed three monocular conditions; 1) amblyopic eye fixating, 2) fellow eye fixating and 3) fellow eye fixating with VA reduced to match the amblyopic eye. Fixational eye movements were quantified using bivariate contour ellipse area (BCEA) and microsaccadic amplitude. Amblyopic eye BCEA was significantly larger with increased microsaccadic amplitude compared to the fellow eye and control eyes. BCEA and VA were positively correlated for amblyopic eyes. VA impairments induced by retinal defocus did not reduce FS in controls or the fellow eye of observers with amblyopia, even when fellow eye VA was matched to that of the amblyopic eye. This suggests that reduced FS in amblyopic eyes cannot be simulated by acute VA reductions. Therefore, reduced amblyopic eye FS may not be a direct consequence of the VA loss alone. As in previous studies, a correlation between BCEA and VA for amblyopic eyes was observed. This relationship could be due to a third, mediating variable or an effect of fixational eye movements on VA.

1. Introduction

Amblyopia is commonly defined as an interocular visual acuity difference of at least two lines (0.2 logMAR) in the presence of an amblyogenic factor such as anisometropia or strabismus (Ciuffreda, Levi, & Selenow, 1991; Guo et al., 2016; Holmes & Clarke, 2006). Along with reduced visual acuity, the amblyopic eye also exhibits abnormal fixational eye movements (FEM) which cause fixation to be less stable than the fellow fixing eye and control eyes (Chung, Kumar, Li, & Levi, 2015; González, Wong, Niechwiej-Szwedo, Tarita-Nistor, & Steinbach, 2012; Raveendran, Babu, Hess, & Bobier, 2014; Shaikh, Otero-Millan, Kumar, & Ghasia, 2016; Subramanian, Jost, & Birch, 2013). FEM abnormalities include increased microsaccadic amplitude (Chung et al., 2015; Ciuffreda, Kenyon, & Stark, 1979; Shi et al., 2012), increased ocular drift amplitude (Chung et al., 2015; Ciuffreda, Kenyon, & Stark, 1980) and increased ocular drift velocity (Song et al., 2010). As a result, fixation in amblyopic eyes is more variable (less stable). This variance can be quantified by resolving horizontal and vertical variances into a bivariate contour ellipse area (BCEA) (Chung et al., 2015; González et al., 2012; Raveendran et al., 2014; Subramanian et al., 2013).

Several studies have reported a positive correlation between amblyopic eye visual acuity and amblyopic eye fixation stability (Chung et al., 2015; Shaikh et al., 2016; Srebro, 1983; Subramanian et al., 2013). Subramanian et al. (2013) measured fixation stability in 89 children using a Nidek MP1 microperimeter and reported a significant correlation between amblyopic eye visual acuity and fixation stability. When subtypes of amblyopia were analysed separately, the correlation was stronger for strabismic than anisometropic amblyopia. Later, Shaikh et al. 2016 classified observers with amblyopia into three categories; mild, moderate and severe, based on amblyopic eye visual acuity. Fixation stability was found to deteriorate with increasing severity of amblyopia (Shaikh et al., 2016).

The cause and effect relationship between impaired fixation stability and reduced visual acuity in amblyopia has not been determined. It is conceivable that reduced visual acuity could impair fixation stability, perhaps by reducing the spatial resolution of fixation targets. Alternatively, impaired fixation stability could reduce visual acuity by moving images away from the fovea and adding jitter. Chung et al. (2015) investigated this possibility by examining amblyopic eye BCEA along with factors that contribute to fixation stability; microsaccade

* Corresponding author at: School of Optometry and Vision Science, University of Waterloo, 200 Columbia Avenue West, Waterloo, Ontario, Canada.
E-mail address: rnallour@uwaterloo.ca (R.N. Raveendran).
[1] Present address: Envision Research Institute, Wichita, Kansas, USA.

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amplitude, microsaccade error and slow drift amplitude. Reduced fixation stability was associated with worse visual acuity in both strabismic and anisometropic amblyopia. Regression and mediation analyses indicated that the error magnitude of microsaccades (the difference between the saccade landing location and the preferred retinal location), BCEA and the amplitude of slow drifts were particularly important factors for predicting visual acuity in amblyopic eyes and may be limiting factors on acuity. The type of amblyopia (strabismic or anisometropic) was not identified as an important factor within the regression model.

Ukwade and Bedell (1993) studied the effect of optical blur on fixation stability in participants with normal vision and found no effect of blur on fixation. This suggests that simulated visual acuity reductions do not affect fixation stability in individuals with normal vision, although visual acuity was not measured directly in this study. Rather, a fixed range of lens powers was employed for all participants.

Building on these previous studies, the objective of this experiment was to test whether reducing visual acuity to specific levels using optical defocus alters fixation stability in observers with amblyopia and control participants with normal vision. The rationale was that if reduced visual acuity impairs fixation stability, then degrading visual acuity in control participants would reduce fixation stability. Similarly, if reduced VA contributes to the fixation stability impairment in amblyopia, reducing fellow fixing eye visual acuity to match amblyopic eye visual acuity should reduce the difference in fixation stability between the two eyes.

2. Methods

2.1. Participants

20 participants (12 control and 8 observers with amblyopia) took part in this study. All 12 control participants (age: 32 ± 5 years) had best corrected visual acuity better than or equal to 0 logMAR in both eyes, stereoacuity of 40″ and no strabismus or anisometropia. A subset of 5 controls completed the simulated visual acuity reduction component of the study. Of the 8 participants with amblyopia (age: 36 ± 9 yrs), 6 had anisometropic and 2 (S5 and S8) had mixed strabismic/anisometropic amblyopia (Table 1). Participants with amblyopia were recruited from a cohort of participants who were evaluated for enrollment in an amblyopia-treatment clinical trial (Gao et al., 2018; Guo et al., 2016). The detailed clinical assessment completed by each participant has been described (Guo et al., 2016). All participants with amblyopia had an interocular visual acuity difference of at least 2 logMAR lines and a fellow fixing eye visual acuity ≤0.02 logMAR. No participants had nystagmus. Anisometropia was defined as an interocular refractive error difference of ≥1.50 DS. All participants wore full refractive correction during testing and FEM measures.

All participants provided written, informed consent to take part in the study. This study was reviewed and approved by the University of Waterloo research ethics committee. All the procedures involved in this research adhered to the tenets of the Declaration of Helsinki.

2.2. Instruments

Stimuli were presented via a haploscope constructed from two cold mirrors (Edmund Optics, NJ, USA), placed orthogonally 15 cm from a chinrest. On either side of the mirrors, two 7″, 800 × 600 resolution LCD monitors (Lilliput®, California, USA) were placed at 25 cm for a total viewing distance of 40 cm. The monitors were controlled by a computer using an external multi-display adapter (DualHead2Go® from Matrox Graphics Inc., Quebec, Canada).

FEMs were measured using a video-based infra-red eyetracker (EyeLink-II: SR Research, Osgoode, Canada http://www.sr-research.com/EL_II.html) with a sampling rate of 500 Hz. The eye tracker had an accuracy of 0.5° and a spatial resolution of 0.01° (as indicated by the manufacturer). A custom nine-point calibration procedure as outlined in the instruction manual was completed and validated for each eye separately at the start of every trial. An average difference ≤0.5° between the calibration and the validation was considered acceptable as described in the device manual. Pilot measurements of saccades to fixed targets indicated that eye tracker accuracy was not degraded by the presence of the highest power convex lens used in this study.

2.3. Procedure

The fixation stimulus (Fig. 1) consisted of an 8.1° outer box and a 1° central fixation cross presented on a mean luminance background (105 cd/m^2). The contrast of the central fixation cross was 100%, based on Weber's contrast ratio. Only monocular FEMs were measured and the non-viewing eye was occluded completely using a black occluder. This study was part of a larger research program (Nallour Raveendran, 2017) that included dichoptic FEM measures, which is why a haploscope was used for stimulus presentation. The haploscope was placed inside a black box as shown in Fig. 1 to avoid extra peripheral cues and

Table 1
Clinical details of observers with amblyopia.

	Participant		Refractive error	VA (dist) logMAR	VA (near) logMAR	Sensory & motor status		
	Age	Gender				W4DT	Stereoacuity (arc sec)	Angle of strabismus
S1	38	F	AME: +3.50DS/−1.00DC × 135 FFE: plano	AME: 0.5 FFE: −0.3	AME: 0.66 FFE: −0.1	D: Fusion N: Fusion	60	No strabismus
S2	48	F	AME: +4.00DS FFE: plano	AME: 0.46 FFE: −0.10	AME: 0.46 FFE: −0.04	D: Fusion N: Fusion	400	No strabismus
S3	26	M	AME: +3.50DS FFE: plano	AME: 0.3 FFE: 0.0	AME: 0.4 FFE: 0.0	D: Fusion N: Fusion	> 800	No strabismus
S4	33	F	FFE: plano AME: +5.50DS/−1.50DC × 70	FFE: −0.2 AME: 0.5	FFE: 0.0 AME: 0.4	D: Fusion N: Fusion	100	No strabismus
S5	30	M	AME: +5.00DS FFE: +3.00DS	AME: 0.7 FFE: 0.0	AME: 0.8 FFE: 0.02	D: Fusion N: Fusion	> 800	8–10Δ intermittent exotropia
S6	42	M	AME: +1.50/−3.25 × 170 FFE: plano	AME: 0.4 FFE: 0.02	AME: 0.9 FFE: 0.0	D: Suppression N: Diplopia	> 800	No strabismus
S7	47	M	FFE: plano AME: +1.75DS	FFE: 0.0 AME: 0.3	FFE: 0.0 AME: 0.4	D: Fusion N: Fusion	200	No strabismus
S8	25	F	AME: +3.50DS FFE: plano	AME: 0.56 FFE: 0.0	AME: 0.48 FFE: 0.0	D: Suppression N: Suppression	> 800	14–16Δ esotropia

D – Distance; N – Near; VA – visual acuity; W4DT – Worth four dot test; AME – Amblyopic eye; FFE – Fellow fixing eye; DS – Diopters in sphere; DC – Diopters in cylinder. Stereoacuity was measured using Randot® stereoacuity test.

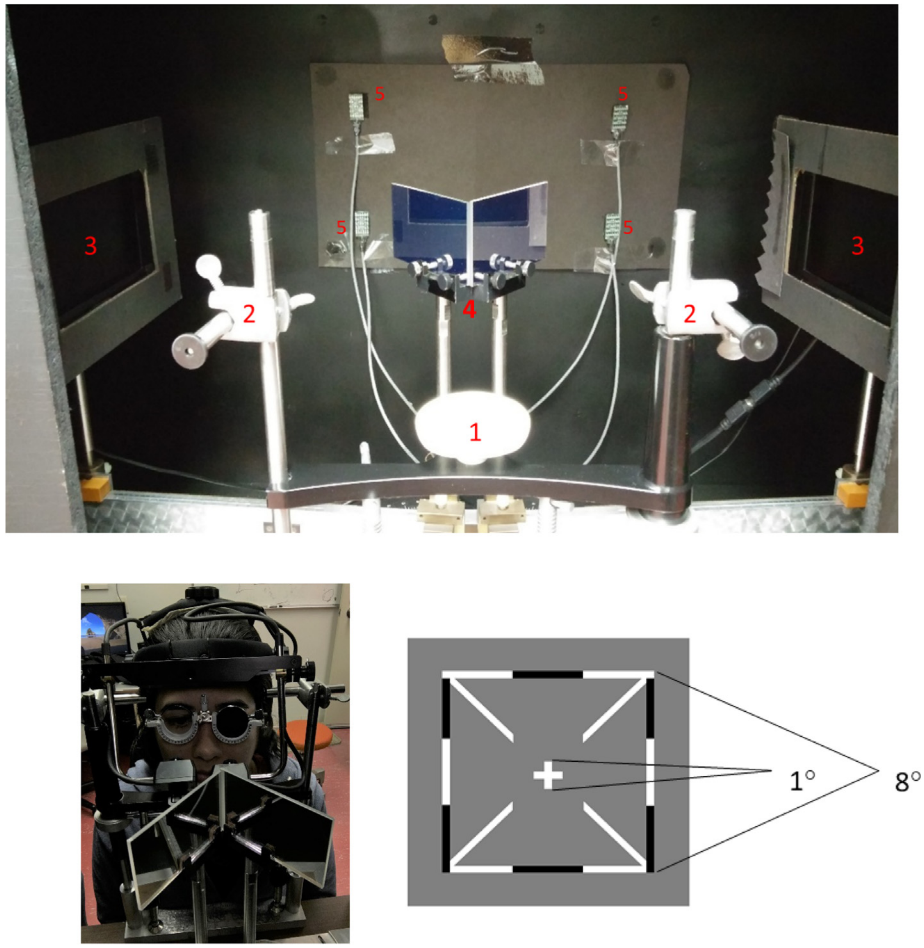

Fig. 1. a) Haploscope. The haploscope was constructed from: 1) a chinrest, 2) two clamps that support the head to minimize any lateral movement, 3) two 7″ LCD monitors that were placed 25 cm from the center of rotation of the instrument, 4) two cold mirrors that were placed orthogonally at the distance of 15 cm from the eyes and 5) four IR markers which were placed behind the mirrors, 40 cm from the chinrest, b) Figure showing a participant wearing a trial frame and viewing the visual stimulus through the haploscope mirrors. c) Visual stimulus. Participants were asked to maintain steady fixation at the central cross.

the eye movement measurements were conducted in an otherwise dark room.

For control participants who completed the optical defocus measures (n = 5), one eye was randomly chosen and near visual acuity was measured using a logMAR letter chart (Precision vision®) at 40 cm. Monocular best corrected near visual acuity was then reduced to 0.2, 0.4, 0.6 and 0.7 logMAR using corrected curve convex (plus) lenses. Corrected curve convex lenses were used because they relax accommodation and maintain a constant image size. Lenses were placed in a trial frame on top of any habitual correction. First, a +2.50 D corrected curve convex lens was placed in the trial frame to relax accommodation for the working distance of 40 cm. Additional plus lenses were added until the participant could not read the line below the required visual acuity level. For control participants, the following dioptric power ranges were used to achieve each logMAR visual acuity level: 0.2, +3.00 to +3.50 DS; 0.4, +3.50 to +4.25 DS; 0.6, +4.00 to +5.00 DS; 0.7, +4.50 to +5.50 DS. FEMs were measured at each simulated visual acuity level. Each trial lasted 15 s with 10 trials per visual acuity level. Trial order was randomized.

In participants with amblyopia, three different monocular viewing conditions were tested; 1) amblyopic eye fixating, 2) fellow fixing eye fixating and 3) fellow fixing eye fixating with visual acuity matched to that of the amblyopic eye using corrected curve convex lenses (following the same procedure used for controls). For observers with amblyopia, the dioptric power range of +4.00 D to +6.50 D was used to simulate VA ranges from 0.4 to 0.9 logMAR.

2.4. Data analysis

Fixation stability was quantified using global bivariate contour ellipse area [BCEA] (González et al., 2012; Steinman, Cushman, & Martins, 1982; Timberlake et al., 2005) defined using the following equation:

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

where χ^2 is the chi-square value (2 degrees of freedom) corresponding to a probability value of 0.682 (i.e. ± 1 SD); σ_x, σ_y correspond to standard deviations of horizontal and vertical eye positions, respectively; ρ corresponds to the Pearson correlation coefficient between horizontal and vertical eye positions. BCEA provides the area of the ellipse that encompasses 68% of eye positions within a trial. Therefore, larger BCEA values indicate less stable fixation.

Microsaccades were detected using an unsupervised cluster detection method (Otero-Millan, Castro, Macknik, & Martinez-Conde, 2014) conducted on the unfiltered eye movement data. This method uses cluster analysis to segregate microsaccades from noise in the eye movement signal. The algorithm first detects potential microsaccades by identifying velocity peaks that are separated by at least 30 ms (to avoid detecting overshoots as separate events) in both the vertical and horizontal components of the eye movement trace. After detection, the algorithm uses clustering (a statistical method to group elements with similar properties) to divide the detected events into noise and microsaccades. This method has been reported to reduce microsaccade detection errors by 62% (Otero-Millan et al., 2014). In addition, the algorithm does not require microsaccades to be binocularly conjugate, which is important when studying populations were fixation stability may differ between the two eyes.

To ensure that microsaccades had been correctly identified, a main sequence plot was generated to assess whether the expected linear relationship between microsaccade amplitude and peak velocity was present (Bahill, Clark, & Stark, 1975; Martinez-Conde, Macknik, Troncoso, & Hubel, 2009). Both amplitude distributions and mean amplitudes were generated for each condition.

BCEA and microsaccadic amplitude data were analysed using ANOVA and t-tests after logarithmic transformation (but the raw values were used for figures). Log transformed data were normally distributed (Shapiro-Wilk Normality test, all $p > 0.05$). Repeated measures tests were used to compare between the amblyopic eye and fellow fixing eye and independent measures tests were used for comparisons including controls. A p value < 0.05 was considered significant with no correction for multiple comparisons.

3. Results

3.1. Comparison between controls and observers with amblyopia

3.1.1. Fixation stability

BCEA analysis of data collected without any convex lens induced optical blur (Fig. 2) revealed that amblyopic eyes had larger BCEAs (reduced stability) ($1.02 \pm 0.17\ deg^2$) compared to fellow fixing eyes ($0.48 \pm 0.10\ deg^2$, $t_7 = 2.72$; $p = 0.03$) and control eyes ($0.52 \pm 0.2\ deg^2$, $t_{18} = 2.99$; $p = 0.007$). Fellow fixing eye BCEA did not differ significantly from controls ($t_{18} = 0.57$; $p = 0.57$).

3.1.2. Microsaccades

The main-sequence plot (Fig. 3A) showed the expected linear relationship between amplitude and peak velocity for all eyes indicating that microsaccades had been identified correctly (mean r of best linear fit ± SD: Controls: 0.8 ± 0.2; amblyopic eye: 0.9 ± 0.1; fellow fixing eye: 0.9 ± 0.05). The distribution of microsaccadic amplitude collapsed across all eyes in each condition (Fig. 3B) revealed a higher proportion of large amplitude microsaccades for the amblyopic eyes compared to the fellow fixing and control eyes. Consistent with this, mean microsaccadic amplitude (Fig. 3C) was significantly larger for the amblyopic eyes compared to the fellow fixing ($t_7 = 3.16$; $p = 0.02$) and control ($t_{18} = 2.71$; $p = 0.01$) eyes. Microsaccadic amplitude did not differ significantly between the fellow fixing and control eyes ($t_{18} = -0.35$; $p = 0.73$). There was no significant difference in microsaccadic frequency between two groups – AME vs. controls ($t_{18} = 0.74$; $p = 0.47$), AME vs. FFE ($t_7 = 0.11$; $p = 0.91$) & FFE vs. controls ($t_{18} = 0.69$; $p = 0.50$) (Fig. 3D).

Prior to analyzing the effect of simulated visual acuity deficits in the fellow fixing eye of observers with amblyopia and the observers with normal binocular vision, the relationship between amblyopic eye visual acuity and BCEA was evaluated. There was a significant positive relationship between amblyopic eye visual acuity and BCEA ($r = 0.7$; $p = 0.04$; Fig. 4) whereby less stable fixation was associated with poorer visual acuity.

3.2. Effect of simulated visual acuity deficits on FEM in control participants and observers with amblyopia

Simulated visual acuity deficits in control participants ($n = 5$) did not significantly affect FEM (Fig. 5A). Repeated measures ANOVA revealed no significant main effect of visual acuity (5 levels) on BCEA ($F_{4,16} = 0.7$, $p = 0.6$). Similarly, microsaccadic amplitude [$F_{4,16} = 1.7$, $p = 0.2$] (Fig. 5B) and microsaccadic frequency [$F_{4,16} = 0.64$, $p = 0.64$] (Fig. 5C) were unaffected by simulated acuity deficits in controls. There was a non-significant trend for increased BCEA and

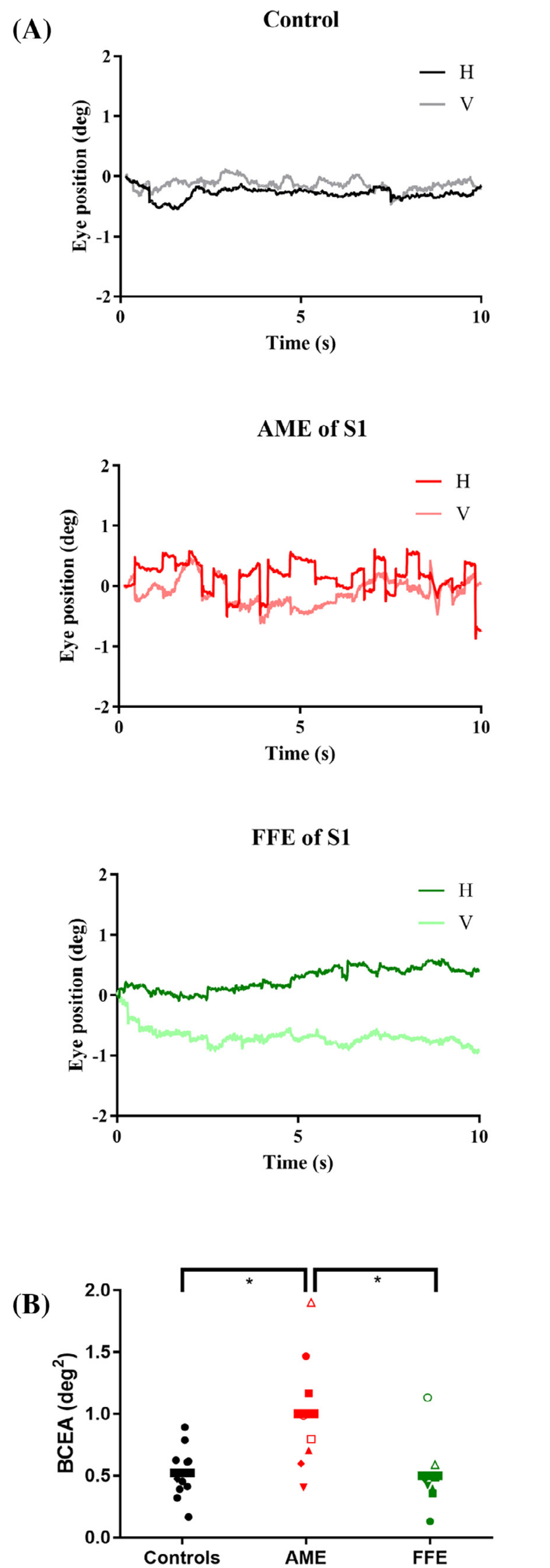

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Fig. 2. A) Sample horizontal (darker line) and vertical (lighter lines) eye positions of the amblyopic eye (red) and the fellow eye (green) of observer S1 from the amblyopia group and a control participant. Eye movement recordings were monocular and therefore the traces for each eye of observer S1 are from different trials. B) BCEA values for control eyes (n = 12) and each eye of patients with amblyopia (n = 8). In Fig. 2B, the horizontal line represents the mean and the data points represent the value for each participant. * symbol represents statistical significance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

microsaccadic amplitude at the simulated visual acuity of 0.7 logMAR, the largest visual acuity reduction that we tested. This suggests that even greater simulated acuity reductions may start to affect FEM in controls.

Reducing fellow fixing eye visual acuity to match amblyopic eye visual acuity on a patient by patient basis did not alter fellow fixing eye BCEA ($t_7 = 0.06$; $p = 0.9$). Furthermore, even when the fellow fixing eye visual acuity was matched, the fellow fixing eye BCEA values were significantly smaller (more stable) than those of the AME ($t_7 = 3.16$; $p = 0.02$; Fig. 6A). Similarly, fellow fixing eye microsaccadic amplitude was not affected by the simulated visual acuity reduction ($t_7 = -0.042$; $p = 0.68$), and fellow fixing eye microsaccadic amplitude remained significantly smaller than that of the amblyopic eye when visual acuity was matched between the two eyes ($t_7 = 2.93$; $p = 0.03$) [Fig. 6B]. Similarly, no significant change was noted for microsaccadic frequency – AME vs. FFE ($t_7 = 0.11$; $p = 0.91$); AME vs. FFE with simulated VA ($t_7 = 0.64$; $p = 0.54$); FFE vs. FFE with simulated VA ($t_7 = 0.37$; $p = 0.72$) [Fig. 6C].

4. Discussion

4.1. Visual acuity and fixation stability

The purpose of the experiment was to test for a causal relationship between reduced visual acuity and reduced stability of FEM in controls and observers with amblyopia. Prior to inducing visual acuity deficits with convex lenses, we observed that amblyopic eye fixation was significantly less stable (larger BCEA) than that of fellow fixing eye and control eyes, in agreement with previous studies (Chung et al., 2015; González et al., 2012; Raveendran et al., 2014; Shaikh et al., 2016; Shi et al., 2012; Subramanian et al., 2013). Our observation of greater amblyopic eye microsaccadic amplitude is also consistent with previous work (Chung et al., 2015). We then observed that simulating reduced visual acuity with convex lenses did not significantly affect fixation stability or microsaccadic amplitude in control eyes or the fellow eyes of participants with amblyopia. Overall, our results suggest that reduced visual acuity alone cannot explain the fixation stability impairment associated with amblyopia.

4.2. Simulation of visual acuity deficits

In this study, we used convex lenses to simulate reduced visual acuity in observers with normal vision or amblyopia. We acknowledge that brief, simulated visual acuity impairments involving retinal blur are not directly equivalent to the visual acuity loss associated with amblyopia, which is chronic and involves abnormal neurodevelopment (Kiorpes, 2006; Levi, 2006). However, because the purpose of this study was to understand the effect of reduced visual acuity per se on FEM, we considered optical blur to be an acceptable way of manipulating visual acuity.

We used a relatively brief period of optical defocus to avoid blur adaptation effects (Khan, Dawson, Mankowska, Cufflin, & Mallen, 2013), which would complicate matching of visual acuity between the amblyopic and fellow eyes of participants with amblyopia. However, it is possible that blur adaptation causes a reduction in fixation stability and that visual acuity deficits after blur adaptation are a closer analogue to the visual acuity deficits associated with amblyopia. These possibilities remain to be addressed by future studies.

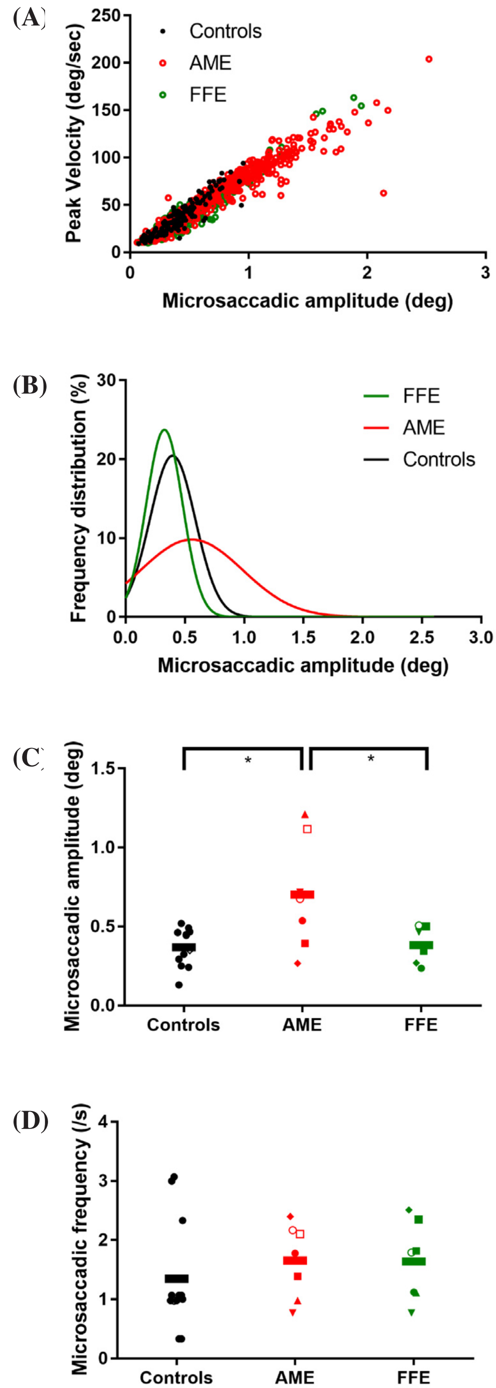

Fig. 3. Microsaccadic amplitude and frequency for control eyes (n = 12) and each eye of patients with amblyopia (n = 8). Panel A shows the summary main sequence data for all participants. Panel B shows the summary distribution of microsaccadic amplitude for all participants (data were fitted with Gaussian functions; amplitude bin range 0–2.6° in 0.1° steps). Panel C shows mean microsaccadic amplitudes for each group. Panel D shows mean microsaccadic frequency. Abbreviations: AME – amblyopic eyes and FFE – fellow fixing eyes. In Fig. 3C & D, the horizontal line represents the mean and the data points represent the value for each participant. * symbol represents statistical significance.

Convex lenses act as a low pass filter and thus reduce visual acuity. Therefore, our results suggest that BCEA and microsaccadic amplitude

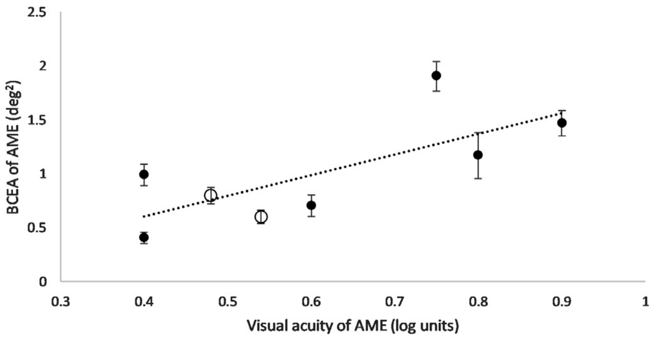

Fig. 4. Relationship between amblyopic eye visual acuity and BCEA. The empty-circles indicate the two participants with mixed amblyopia. Reduced fixation stability was associated with reduced visual acuity. Abbreviations: AME – amblyopic eyes. Data points represent mean and the error bars represent within-subject variability.

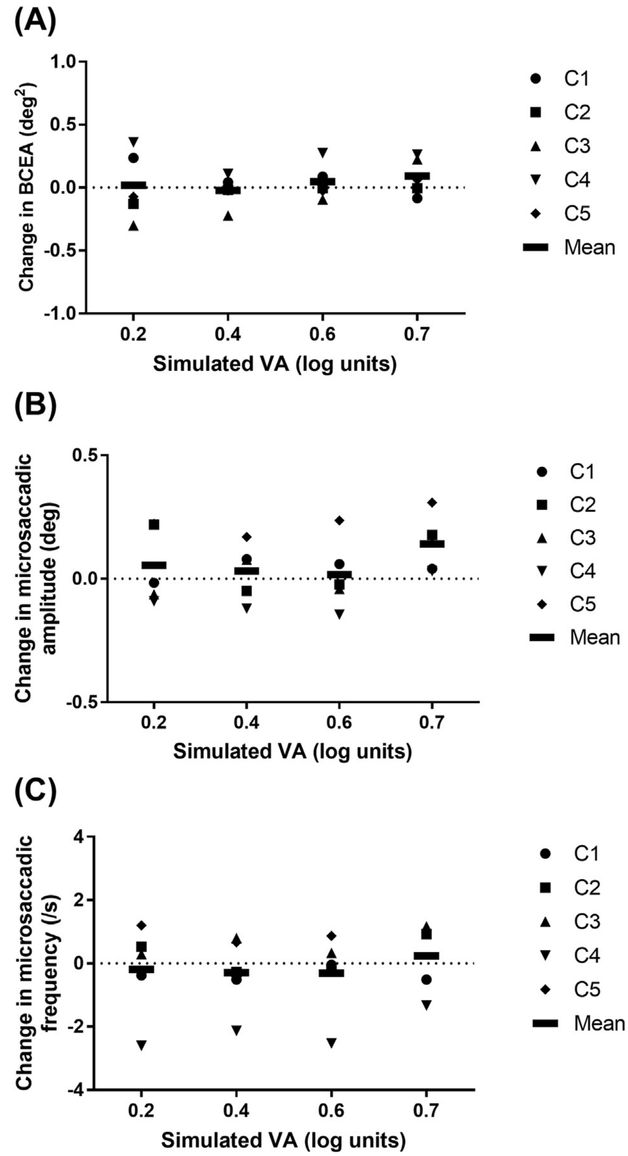

Fig. 5. The effect of simulated VA deficits on BCEA (Panel A), microsaccadic amplitude (Panel B) and microsaccadic frequency (Panel C) in control eyes. The Y-axis shows change in BCEA, microsaccadic amplitude or frequency from the 0 logMAR condition. Positive values indicate less stable fixation, increased microsaccadic amplitude or frequency with a simulated VA deficit. The dashed horizontal line indicates no change. In each figure, the horizontal line represents the mean and the data points represent the value for each participant.

are not sensitive to the high spatial frequency content of visual stimuli. This idea is consistent with the finding that microsaccadic amplitudes are similar when viewing low and high spatial frequency stimuli (Mostofi, Boi, & Rucci, 2015). Ukwade and Bedell (1993) also evaluated the effect of optical blur on the stability of FEM and reported that dioptric blur had no consequential effect on fixation stability (Ukwade & Bedell, 1993). Our results extend those of Ukwade and Bedell by demonstrating that fixation stability remains constant across a wide range of blur-induced visual acuity reductions in observers with normal vision and those with amblyopia.

4.3. Amblyopia etiology and fixation stability

It is currently unclear whether amblyopia etiology affects FEM. Although more substantial FEM impairments have been observed for strabismic than anisometropic amblyopia (Subramanian et al., 2013), this is not consistent across all studies (Chung et al., 2015). For example, a recent study with a relatively large sample size reported that amblyopia etiology was not a significant predicting factor for BCEA (Chung et al., 2015). Our study was not designed to address this question and involved detailed, repeated measures in a relatively small sample of participants with amblyopia. However, we did observe significantly elevated amblyopic eye BCEA relative to controls in an amblyopia group consisting primarily of participants with anisometropic amblyopia (6/8 participants). The significant difference from controls remained when the two participants with strabismic amblyopia were removed from the analysis [mean ± SD BCEA; Controls ($0.52 \pm 0.2\,deg^2$) vs. anisometropic amblyopic eye ($1.13 \pm 0.5\,deg^2$, $t = 3.05$, $p = 0.01$). This is in agreement with studies indicating that FEM can be affected by anisometropic amblyopia (Shi et al., 2012).

4.4. The relationship between visual acuity and fixational eye movements

In agreement with most (Chung et al., 2015; Shaikh et al., 2016; Srebro, 1983; Subramanian et al., 2013), but not all (González et al., 2012) prior studies of FEM in amblyopia, we also observed a significant correlation between amblyopic eye visual acuity and amblyopic eye fixational stability. Our finding that acute simulated visual acuity deficits did not influence FEM suggests that this relationship was not due to a reduction in visual acuity per se. Possible causal explanations for the relationship between amblyopic eye visual acuity and fixation stability that remain to be tested include: 1) reduced fixation stability causes the visual acuity loss, in agreement with inferences made from previous work (Chung et al., 2015), 2) reduced fixation stability is caused by long term adaptation to impaired visual acuity (Shi et al., 2012), perhaps in order to enhance processing of low spatial frequencies (Agaoglu, Sheehy, Tiruveedhula, Roorda, & Chung, 2018; Shi et al., 2012) and, 3) FEM and visual acuity are affected independently by amblyopia, but both scale with amblyopia severity. Although technically challenging, future work should investigate whether partial stabilization of the retinal image in the amblyopic eye improves visual acuity.

5. Conclusion

Reduced fixation stability could not be induced in controls or the fellow eyes of observers with amblyopia by reducing visual acuity with optical defocus. This suggests that reduced visual acuity per se may not be the cause of fixational eye movements impairments in amblyopia.

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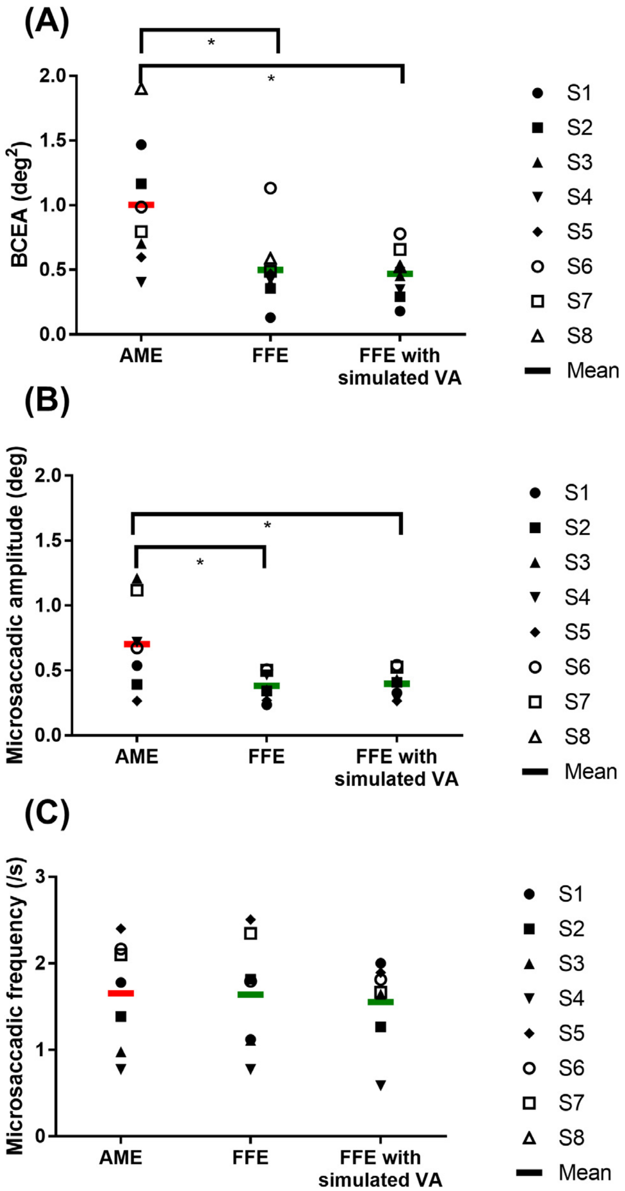

Fig. 6. The effect of simulated visual acuity deficits on BCEA (Panel A), microsaccadic amplitude (Panel B) and microsaccadic frequency (Panel C) in the fellow fixing eyes of observers with amblyopia. Blur-induced reductions in visual acuity did not alter fixation stability, microsaccadic amplitude or microsaccadic frequency of the fellow eye. Abbreviations: AME – amblyopic eyes and FFE – fellow fixing eyes. In each figure, the horizontal line represents the mean and the data points represent the value for each participant. * symbol represents statistical significance.

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