

Dichoptic Attentive Motion Tracking is Biased Toward the Nonamblyopic Eye in Strabismic Amblyopia

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PURPOSE. To determine whether attention is biased toward the nonamblyopic eye under binocular viewing conditions in adults with anisometropic or strabismic amblyopia. We first determined whether attention could be allocated preferentially to one eye in visually normal observers performing a dichoptic attentive motion tracking task. We then assessed dichoptic attentive motion tracking in amblyopia.

METHODS. Participants performed a multiple-object tracking task under the following three viewing conditions: target dots to the dominant eye and distractor dots to the nondominant eye (DE condition), vice versa (NDE condition), or all dots to both eyes (binocular condition). Interocular attentional asymmetry scores were computed as the difference in accuracy between DE and NDE conditions. An interocular contrast difference favoring the amblyopic eye was used for all conditions to neutralize amblyopic eye suppression. To test for confounding effects of suppression, participants completed a separate dot enumeration task under dichoptic presentation conditions to obtain an interocular enumeration asymmetry score.

RESULTS. Participants with normal vision demonstrated similar accuracy between the DE and NDE conditions and exhibited slightly impaired performance under dichoptic compared with binocular viewing conditions. Participants with strabismic/mixed amblyopia had significantly higher interocular attentional asymmetry than participants with normal vision or with anisometropic amblyopia, whereby attention was biased toward the nonamblyopic eye. The latter two groups did not exhibit a bias in interocular attention. No interocular asymmetries for the enumeration task were observed for any group.

CONCLUSIONS. A nonamblyopic eye bias in the interocular allocation of attention may contribute to the binocular vision impairments caused by strabismic amblyopia.

Keywords: amblyopia, strabismus, visual attention, suppression, binocular vision

Abnormal binocular visual experience during early childhood, typically due to a large difference in refractive error between the eyes (anisometropia) or a deviated eye (strabismus), can disrupt visual development and cause amblyopia. Amblyopia is characterized clinically by decreased visual acuity in the affected eye that cannot be entirely accounted for by refractive error or pathology.^{1,2} Beyond the reduction in visual acuity, amblyopia also causes a broad range of visual deficits ranging from impairments in contrast sensitivity³⁻⁷ to the global processing of motion and form.⁸⁻¹⁷ A number of these deficits also extend to the nonamblyopic fellow eye.^{8,12,14,18-21}

Beyond the loss of monocular visual function, amblyopia also impairs binocular vision, in part because visual information from the amblyopic eye is suppressed from conscious awareness when both eyes are viewing.²²⁻²⁷ Suppression can affect large areas of the amblyopic eye visual field^{28,29} and may play an important role in the visual deficits experienced by patients with amblyopia.^{22,25,30} Stronger suppression is associated with poorer visual acuity in the amblyopic eye^{25,31,32} and treatments that aim to reduce suppression improve amblyopic eye visual acuity to some extent,³³⁻⁴⁰ although randomized clinical trial evidence for this approach is mixed.⁴¹⁻⁴³

The abnormal patterns of interocular excitation and inhibition that may contribute to suppression are evident within early visual areas of amblyopic primates.⁴⁴⁻⁴⁹ However, it has recently been suggested that abnormal allocation of visual attention between the two eyes may also play a role in suppression.⁵⁰ Using electroencephalography, Hou and colleagues⁵⁰ observed a reduced effect of attentional modulation in areas V1, V4, and V5 when participants with strabismic amblyopia viewed monocularly with their amblyopic eye. Importantly, they also found a strong positive correlation between the extent of the attentional modulation deficit in V1 and the strength of amblyopic eye suppression. Reduced attentional modulation was also observed for fellow eye viewing in V4 and V5, but not V1. Similarly, another study identified differences in event-related potential waveforms during processing of the Stroop task for children with amblyopia relative to controls.⁵¹ Other studies have used psychophysics to investigate attentive processing in amblyopia under monocular viewing conditions, with mixed results. Impairments have been reported in multiple-object tracking,^{52,53} conjunction visual search,⁵⁴ and attentional blink tasks,⁵⁵ suggesting an attention deficit associated with not just



the amblyopic but also the fellow eye, that affects both spatial and temporal components of visual attention. On the other hand, studies using attentive cueing paradigms in humans^{56,57} and primates⁵⁸ have reported that attentional modulation is comparable to a normal visual system. Thus, the extent of any attentional deficit in amblyopia remains unclear. This may be due to previous studies employing monocular presentation of visual stimuli. Presumably, if attentional allocation is abnormal between the eyes, it would be most evident under dichoptic viewing conditions.

In normal vision, attention can be allocated independently to each eye and modulate binocular combination of monocular information. Monocular cues presented under dichoptic viewing conditions can attract visual attention^{59,60} and can affect perceptual dominance in binocular rivalry paradigms, even though they cannot be discriminated from binocular cues.^{61–64} Therefore, it is conceivable that a biased allocation of attention between the eyes may contribute to interocular suppression and the loss of binocular vision in amblyopia.

We used a dichoptic multiple-object tracking task to directly address the question of whether interocular suppression in amblyopia involves an attentional bias in favor of the fellow eye.⁵⁰ By presenting target elements to only one eye and distractors to the other eye, we determined whether attention was biased toward one eye or allocated equally across both eyes. In Experiment 1, we tested whether dichoptic viewing affected multiple-object tracking in binocularly normal controls. In Experiment 2, we measured dichoptic multiple-object tracking performance in controls and participants with anisometropic and/or strabismic amblyopia. We considered the two amblyopia groups separately because a previous study of attentional modulation within the visual cortex only involved strabismic amblyopia.⁵⁰ Interocular contrast balancing^{32,65–70} and an enumeration control task were used to ensure that the stimulus elements presented to each eye were continuously visible in the amblyopia group. If a bias in the interocular balance of attention does play a role in suppression of the amblyopic eye, we would expect participants with amblyopia to have worse multiple-object tracking task performance when the target dots are presented to the less attended (amblyopic) eye versus the more attended (fellow) eye. We hypothesized that if such an attentional imbalance was a fundamental component of amblyopia, it would still be present after interocular contrast balancing was used to ensure that dots were equally visible to each eye.

METHODS

Participants

Experiment 1 involved 12 participants with normal vision (8 female; mean age 25 ± 2.8 years), and Experiment 2 involved 17 participants with amblyopia (9 anisometropic amblyopia, 8 strabismic/mixed amblyopia, mean age 37 ± 13.5 years) as well as 15 controls with normal vision (14 female; mean age 23 ± 1.5 years; only 1 of whom also participated in Experiment 1). Participants with normal vision had best-corrected visual acuity better than 0.1 logMAR (20/25), with no greater than 1 logMAR line difference between the eyes, and no history of binocular vision disorders. Inclusion in the amblyopia group required the following: (1) at least a 2 logMAR line difference in best-corrected visual acuity between the eyes (all participants had AE acuity worse than 0.2 logMAR with exception of A12, who had received successful treatment), (2) either anisometropia (>1 diopter difference in spherical equivalent between the eyes or >1.5 diopters of cylinder in one eye) and/or strabismus (including history of strabismus surgery), (3)

normal ocular and general health. All participants, except for author AC, were naïve to the experimental hypothesis and were reimbursed with \$15 for their time. Participants provided written informed consent to take part in the study, and the study protocol was approved by the institutional ethics committee, in accordance with the Declaration of Helsinki.

Apparatus

Stimuli were presented on an ASUS 27" VG278 3D monitor (1280×720 resolution, 120-Hz refresh rate; Taipei, Taiwan), which was synchronized to the alternation rate of a pair of NVIDIA 3D VISION LCD shutter glasses (Santa Clara, CA, USA). Participants viewed the screen (subtending $48^\circ \times 27^\circ$) through the shutter glasses at a distance of 67 cm. Stimuli were presented using MATLAB (The MathWorks, Natick, MA, USA) and Psychtoolbox.^{71,72}

Procedure

All participants were screened at the School of Optometry and Vision Science, University of Waterloo by author AC, who assessed visual acuity (electronic Early Treatment Diabetic Retinopathy Study chart), binocular status (distance and near cover test), and stereoacuity (Randot Stereotest; Stereo Optical Co. Inc., Chicago, IL, USA). Refraction was conducted if an eye exam had not been completed within the last 2 years. Participants wore their optimal refractive correction either through their habitual corrective lenses or a trial frame. Clinical details for individuals with amblyopia are summarized in the Table. Sensory eye dominance was determined for all participants using an established dichoptic motion coherence paradigm, assigning the eye with a lower dichoptic motion coherence threshold as the dominant eye.^{65,66} This dichoptic global motion task was then used to identify the balance point contrast required for normal binocular combination. Each participant viewed the experimental stimuli at 100% contrast with their nondominant or amblyopic eye, and at their balance point contrast for the dominant or fellow eye. Any ocular misalignments were accounted for subjectively with the alignment of a central Nonius cross prior to the start of each task.

Participants performed a multiple-object tracking task (similar to that employed by Giaschi et al.⁷⁵ and illustrated in Figs. 1A and 1B) that involved tracking four target dots among six identical distractor dots (Experiment 1) or tracking three target dots among seven distractor dots (Experiment 2). This change was made because participants with amblyopia had difficulty tracking four dots, so we opted for a task that allowed for near normal overall performance. Previous work has noted this tracking deficit, whereby participants with amblyopia demonstrated 75% accuracy tracking a mean of four dots with the fellow eye and 3.7 dots with the amblyopic eye, as compared with 5.16 dots in control participants.⁵² At the start of each trial, 10 stationary dots (1° in diameter, presented within a Gaussian envelope) were presented and the target dots were highlighted in green for 2 seconds. The dots then moved at $10^\circ/s$ within a $14^\circ \times 14^\circ$ field along random but nonoverlapping trajectories. Participants tracked the dots for 5 seconds while fixating a central cross. Using a partial report procedure, participants indicated whether a highlighted dot was a target dot at the end of each trial. Audio feedback was given after each trial.

In Experiment 1, a monocular awareness task (illustrated in Fig. 1C) was used to assess whether participants were aware of which eye a stimulus of interest was being presented to. In a $14^\circ \times 14^\circ$ field, a single dot moving at $10^\circ/s$ was presented to only one eye among four static dots displayed to the other eye.

TABLE. Clinical Details for Amblyopic Participants

ID	Age/Sex	Type	VA (FE)	VA (AE)	Stereoacuity	Ocular Deviation (Near)	Refraction	Clinical History
A01	24/F	A	20/20	20/100	>500"	NS, 12Δ X(T)	OD: +6.50 DS OS +0.50 DS	Unknown history
A02	43/M	M	20/20	20/40	>500"	8Δ constant RET	OD: +7.00/−2.75 × 030 OS: +5.00/−1.75 × 170	Dx at 4 yo, sx for RET at 4 yo, patched, vision therapy
A03	43/M	M	20/15	20/60	>500"	NS, ortho	OD: +2.75/−2.50 × 175 OS: +1.75/−0.50 × 060	Dx at 4 yo, for ET, patched
A04	54/F	S	20/20	20/60	>500"	12Δ constant LET	OD: +4.00 DS OS: +4.25/−0.50 × 140 ADD +2.25 D	Patched
A05	28/M	A	20/20	20/70	500"	4Δ X(T)	OD: +5.00 DS OS: +3.75 DS	Poor compliance with patching
A06	28/M	A	20/20	20/50	>500"	NS, ortho	OD: +3.00/−0.25 × 140 OS: plano	No patching or surgery
A07	23/F	M	20/15	20/30	250"	6Δ constant LXT	OD: pl/−0.25 × 179 OS: +4.50/−1.50 × 064	Dx at 3–4 yo, patched
A08	25/F	A	20/20	20/150	>500"	NS, ortho	OD: pl/−0.25 × 005 OS: +4.50/−3.00 × 058	Dx at 10 yo, no patching, training or surgery
A09	51/F	A	20/20	20/50	>500"	NS, 6Δ X(T)	OD: +0.75 DS OS: −2.25/−0.75 × 161 ADD +1.75 D	Dx at 8 yo, Rx given but did not wear until 25 yo
A10	25/M	M	20/15	20/40	>500"	6Δ constant RET	OD: +1.25/−0.75 × 170 OS: −1.75/−0.75 × 002	Dx at 1 yo, minimal patching and training
A11	38/F	A	20/15	20/30	250"	NS, ortho	OD: +1.00 DS OS: +4.50/−1.00 × 025	Dx 4 yo, patched, FT Rx wear
A12	21/M	A	20/15	20/25	250"	NS, ortho	OD: +0.25/−0.25 × 153 OS: +3.75/−2.00 × 180	Dx 14 yo, inconsistent patching, no sx or training, FT Rx wear
A13	41/M	M	20/20	20/60	>500"	18Δ constant RET	OD: +4.00/−1.25 × 090 OS: +0.75/−0.50 × 090	Dx 11–12 yo, wore Rx for 2 y, but discontinued
A14	47/F	M	20/15	20/40	>500"	14Δ constant RET	OD: +4.50/−0.50 × 171 OS: +2.75/−0.25 × 155 ADD +1.75 D	FT Rx wear, patched, no sx
A15	46/F	A	20/15	20/40	>500"	NS, 10Δ E(T)	OD: −0.50 DS OS: +1.25/−0.75 × 105	No patching or sx
A16	68/M	M	20/20	20/100	>500"	12Δ constant LET	OD: +2.25/−0.25 × 140 OS: +5.75 DS ADD +2.50 D	Wore Rx since 25 yo, no patching/training/sx
A17	26/F	A	20/20	20/50	>500"	NS, 4Δ E(T)	OD: −1.00/−0.50 × 150 OS: +0.75/−1.25 × 165	Wore Rx since 12 yo, minimal patching, no training/sx

VA, visual acuity; Dx, diagnosed; A, anisometropia; S, strabismus; M, mixed; NS, nonstrabismic, E(T), esophoria; X(T), exophoria; RET, right esotropia; LXT, left exotropia; OD, right eye; OS, left eye; Δ, prism dioptre; yos, years old; F, female; M, male.

Participants were asked to identify which eye was viewing the moving dot using a key press. No feedback was provided, and participants were monitored to ensure they were viewing the display with both eyes open. The moving dot was presented to either eye with equal probability, and each participant completed 48 trials.

In Experiment 2, an enumeration task was also performed at each participants' contrast balance point to ensure that participants with amblyopia were not suppressing the dots presented to the amblyopic eye. Dot parameters were the same as the multiple-object tracking task (dots moving at 10°/s in a 14° × 14° field), except the target dots were presented in red and remained red throughout the entire 5-second viewing period. Participants were asked to report the number of red dots (either 3 or 5) that were present with a key press on a number pad. Target dots were split between the dominant and nondominant eyes in either a 2:1 or 3:2 ratio, or all targets and distractors were presented to both eyes as catch trials. Splitting the target dots between the eyes allowed us to determine by numeric report whether amblyopic eye dots were being

suppressed. Participants also provided a subjective yes/no report of whether any of the dots disappeared during the trial. This provided an indirect measure of transient suppression. Participants performed 60 trials in this self-paced task.

The multiple-object tracking and enumeration tasks were performed across three conditions in the following randomized order: (1) binocular viewing, (2) dichoptic viewing with target dots presented to the dominant eye (DE condition) and distractor dots to the other eye, and (3) dichoptic viewing with target dots presented to the nondominant eye (NDE condition) and distractor dots to the other eye. In both experiments, participants were given 12 practice trials prior to completing 120 test trials, with an opportunity to take a break every 60 trials.

Statistical Methods

The one-sample Kolmogorov-Smirnov test was used to test for normality. Data that were not normally distributed were analyzed with nonparametric statistics. For the multiple-object

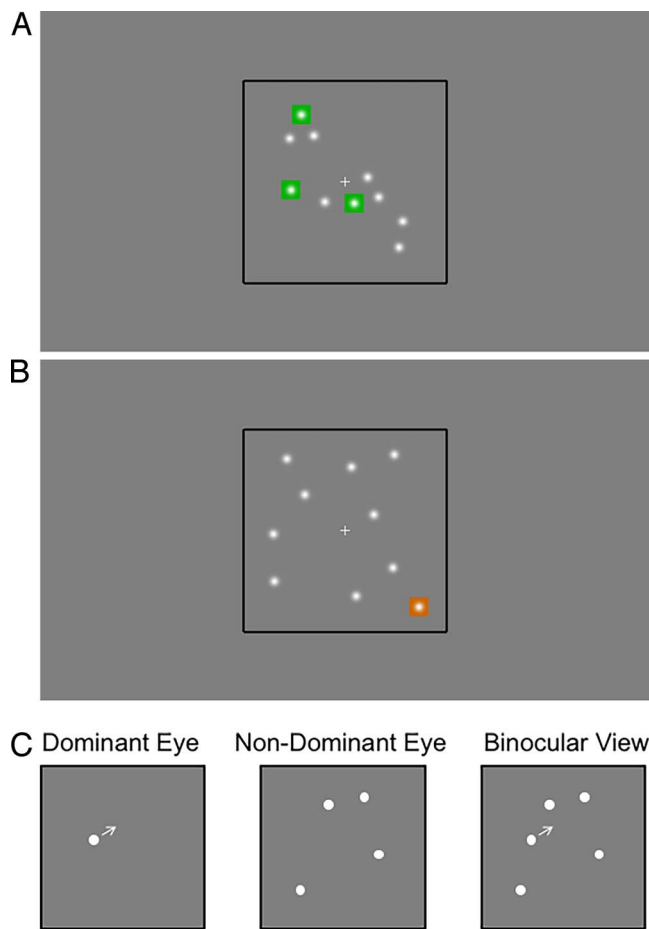


FIGURE 1. (A) The multiple-object tracking task, consisting of four (Experiment 1) or three (Experiment 2) target dots to be tracked (highlighted in green) among distractor dots. (B) The two-alternative force choice (2-AFC) partial report screen. Participants reported whether the highlighted dot was a target dot. (C) The monocular awareness task. Participants reported the eye that was presented with the moving dot. All dots were presented within a Gaussian envelope.

tracking task in Experiment 1, ANOVA was used to assess the effect of viewing condition. Pairwise *t*-tests were used for post-hoc analysis. Multiple comparison corrections were not applied due to the limited sample size. For the monocular awareness task in Experiment 1, a one-sample *t*-test was used to test whether task performance differed from chance.

For Experiment 2, three analyses were conducted on the multiple-object tracking accuracy data. First, the three different viewing conditions were compared within each group using Wilcoxon signed ranks tests. Second, the binocular condition results were compared between the three groups to assess whether any group exhibited a general multiple-object tracking deficit. Because the binocular condition accuracy data were normally distributed, a univariate ANOVA with a factor of group (control versus anisometropia versus strabismic) was conducted. Third, an interocular asymmetry score was computed for each group by subtracting NDE from DE accuracy to enable between-group comparisons in the allocation of attention between the two eyes. Asymmetry scores were analyzed using the independent samples Kruskal-Wallis test and post-hoc testing was conducted using Mann-Whitney *U* tests. Asymmetry scores were also calculated for the enumeration task and analyzed in the same way. Spearman's rho correlation coefficients were used to investigate the

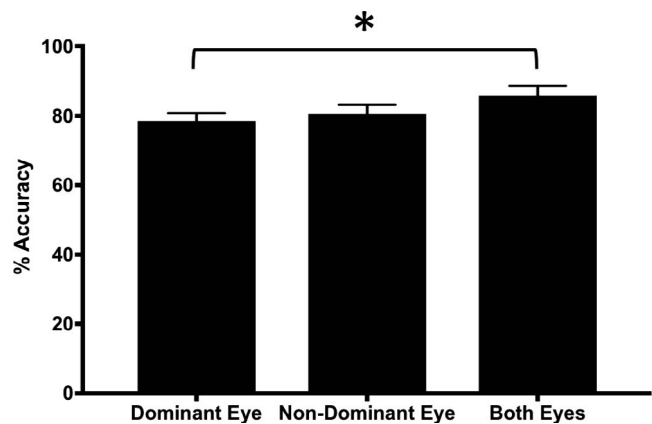


FIGURE 2. Mean percent accuracy on the multiple-object tracking task in Experiment 1. Participants with normal vision showed slightly improved tracking performance under binocular viewing conditions than dichoptic viewing conditions. Error bars denote ± 1 SEM.

association between NDE enumeration task accuracy and multiple-object tracking asymmetry scores.

RESULTS

Experiment 1

Multiple-object tracking performance (percent accuracy, mean \pm SE) was $86 \pm 3\%$ for binocular viewing, $79 \pm 2\%$ for the DE condition, and $81 \pm 3\%$ for the NDE condition (see Fig. 2). There was a significant main effect of viewing condition ($F_{2,11} = 4.2$, $P = 0.048$). Pairwise *t*-tests revealed a significant difference between performance under binocular viewing compared with the DE condition ($t_{11} = -2.96$, $P = 0.013$) and no significant difference between binocular viewing compared with the NDE condition ($t_{11} = -2.00$, $P = 0.07$). Performance between the DE and NDE conditions did not differ significantly ($t_{11} = -0.776$, $P = 0.45$). In the conscious monocular awareness task, participants were unable to consciously report which eye the signal was being presented to and did not perform significantly better than chance ($t_{11} = 1.03$, $P = 0.33$).

These results demonstrate that in participants with normal vision, dichoptic viewing with target dots presented to one eye, and distractor dots presented to the other eye did not benefit multiple-object tracking. In fact, dichoptic presentation slightly impaired task performance relative to binocular presentation. Furthermore, participants were not consciously aware of which eye was receiving target information and were unable to use this information to their advantage. As a whole, the results indicate that attention was allocated equally between the two eyes in participants with normal vision, even when task performance would have benefited from preferential allocation of attention to the eye that saw the target dots.

Experiment 2

Multiple-object tracking performance (Fig. 3A) was quantified as percent accuracy (mean \pm SE) for the normal group (DE $83 \pm 3\%$, NDE $80 \pm 4\%$, binocular $92 \pm 2\%$), anisometropia group (DE $81 \pm 6\%$, NDE $86 \pm 3\%$, binocular $78 \pm 6\%$), and strabismic/mixed group (DE $88 \pm 1\%$, NDE $65 \pm 5\%$, binocular $84 \pm 5\%$). Within each group, the multiple-object tracking accuracy scores for each viewing condition were compared with determine whether there was an effect of viewing

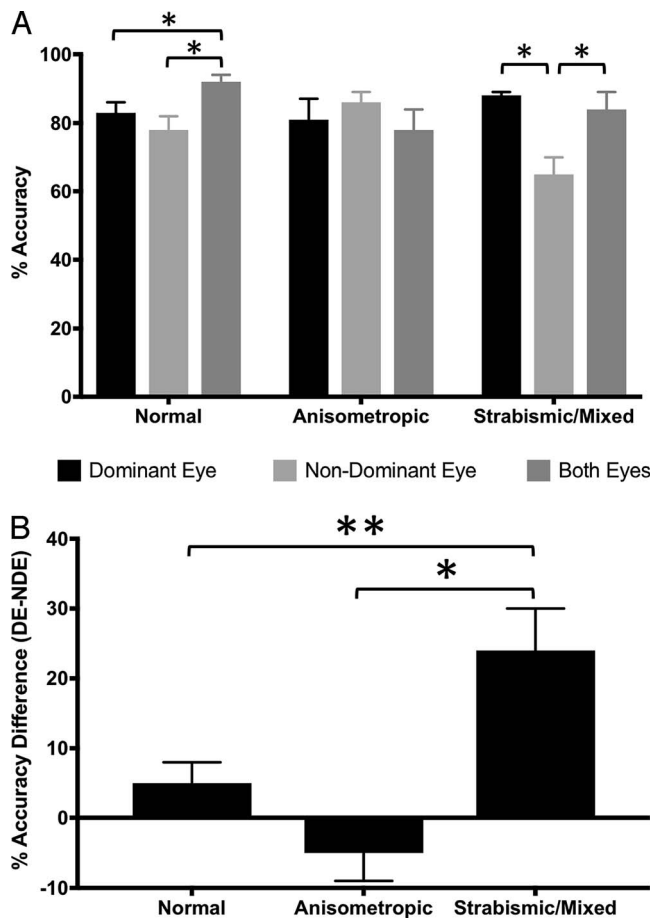


FIGURE 3. (A) Mean percent accuracy on the multiple-object tracking task for each group in Experiment 2. (B) Multiple-object tracking asymmetry scores calculated from the difference between FE and AE accuracy in the amblyopia groups and DE and NDE accuracy in controls). Interocular asymmetry scores were significantly higher in the strabismic/mixed amblyopia as compared with the anisometropic amblyopia or control groups. Error bars denote ± 1 SEM. FE, fellow eye; AE, amblyopic eye.

condition. For the normal vision group, no significant difference was found between the DE and NDE conditions ($W = 24.5$; $P = 0.3$), but both differed significantly from the binocular condition (DE versus binocular: $W = 117.5$, $P = 0.001$; NDE versus binocular: $W = 117.5$, $P = 0.001$). In the anisometropic amblyopia group, none of the pairwise comparisons were significant (DE versus NDE: $W = 25$, $P > 0.05$; DE versus binocular: $W = 8.5$, $P > 0.05$; NDE versus binocular: $W = 17$, $P > 0.05$). In the strabismic/mixed amblyopia group, there was no significant difference between the DE and binocular conditions ($W = 7.5$, $P > 0.05$). However, the NDE condition was worse than both the DE ($W = 3$, $P = 0.04$) and binocular ($W = 26$, $P = 0.04$) conditions. Each participant's multiple-object tracking task accuracy under the two dichoptic conditions can be seen in Figure 4.

Binocular multiple-object tracking accuracy was compared between groups in a separate analysis to evaluate whether the strabismic/mixed group had a general multiple-object tracking deficit compared with the other groups. There was a significant main effect of group ($F_{2,29} = 3.89$, $P = 0.03$). Pairwise t -tests showed that performance in the anisometropic amblyopia group was significantly worse than controls ($t_{9,49} = -2.34$, $P = 0.043$). There was no significant difference between the strabismic/mixed amblyopia and control groups ($t_{8,86} =$

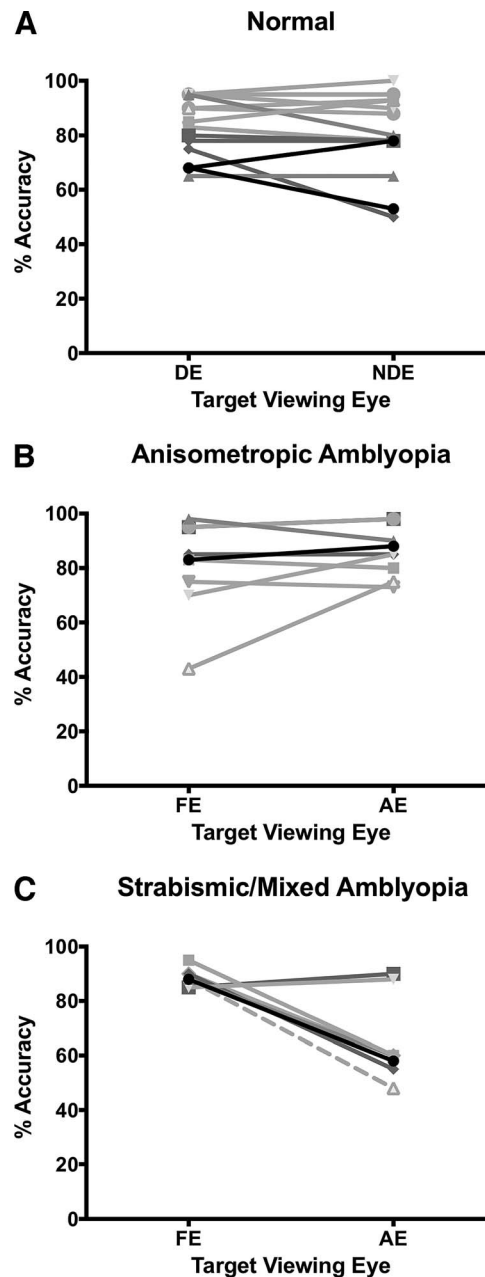


FIGURE 4. Individual participant multiple-object tracking task performance accuracy under each dichoptic condition for each group (A) controls with normal vision; (B) anisometropic amblyopia; (C) strabismic/mixed amblyopia). Participants with anisometropic amblyopia and binocularly normal had similar patterns of attentional allocation. Participants with strabismic/mixed amblyopia showed a significant deficit when target dots were presented to the amblyopic eye. Data points from the same participant across the two separate viewing conditions are connected with a line for ease of interpretation. The dashed line in (C) denotes participant A16, who reported intermittent diplopia sporadically during the multiple-object tracking task.

-1.59 , $P = 0.15$), or between the anisometropic and strabismic/mixed amblyopia groups ($t_{15} = -0.77$, $P = 0.45$).

Asymmetry scores (normal $3 \pm 2\%$; anisometropia $-5 \pm 4\%$; strabismic/mixed $24 \pm 6\%$) varied significantly across groups as seen in Figure 3B ($H_2 = 8.4$, $P = 0.02$). Pairwise comparisons revealed a significant difference between the normal and strabismic/mixed groups ($U = 24$, $P = 0.02$), and between the anisometropia and strabismic/mixed groups ($U =$

60.5, $P = 0.02$). Asymmetry scores between the normal and anisometropia groups did not significantly differ ($U = 92$, $P > 0.05$).

To explore whether the differences in multiple-object tracking accuracy could be explained by suppression, we analyzed the contrast balance points for our participants with amblyopia. There was no significant difference in contrast balance points between the anisometropic amblyopia and strabismic/mixed amblyopia groups ($t_{12,9} = -0.11$, $P = 0.91$). Similarly, when the enumeration task was performed at each participants' contrast balance point, participants exhibited the following high accuracy (mean \pm SE) across all three groups: anisometropia DE $97 \pm 2\%$, NDE $96 \pm 2\%$, and binocular $99 \pm 1\%$; strabismic/mixed DE $89 \pm 3\%$, NDE $86 \pm 3\%$, and binocular $87 \pm 12\%$; and normal DE $99 \pm 0\%$, NDE $99 \pm 1\%$, and binocular $99 \pm 1\%$. Enumeration performance differed across the groups for both DE and NDE conditions ($H_2 = 10.5$, $P = 0.005$ and $H_2 = 13$, $P = 0.001$, respectively), but not for the binocular condition ($H_2 = 0.3$, $P = 0.86$). Pairwise comparisons showed a significant difference between the normal and strabismic/mixed groups (DE: $U = 19$, $P = 0.007$; NDE: $U = 11.5$, $P = 0.001$) and between the anisometropia and strabismic/mixed groups (DE: $U = 17$, $P = 0.05$; NDE $U = 14$, $P = 0.03$). No significant difference between the anisometropia and normal groups were found in the dichoptic conditions (DE: $U = 53$, $P > 0.05$; NDE: $U = 42$, $P > 0.05$). Analysis of the enumeration task interocular asymmetry scores revealed that the groups did not differ in interocular difference in enumeration task performance ($H_2 = 0.7$, $P = 0.72$).

Additionally, the multiple-object tracking task asymmetry scores did not correlate significantly with enumeration performance in the NDE condition ($\rho_{16} = -0.395$, $P = 0.12$), contrast balance point ($\rho_{16} = -0.08$, $P = 0.77$), or visual acuity difference between the eyes ($\rho_{16} = 0.131$, $P = 0.62$).

Participant A16 subjectively reported intermittent diplopia during the tracking task. When this participant was removed from the analysis, the asymmetry scores still varied significantly across groups ($H_2 = 7.06$, $P = 0.02$) and a significant difference between the binocularly normal and strabismic/mixed groups persisted (although the P value was very close to 0.05: $U = 26.5$, $P = 0.047$) as well as between the anisometropia and strabismic/mixed groups ($U = 51.5$, $P = 0.03$).

The results show that participants with anisometropic amblyopia had an equal distribution of attention between the two eyes, similar to those with normal vision. However, those with strabismic amblyopia displayed a significant deficit when targets were presented to their amblyopic eye and distractors their fellow eye, despite the dots being adequately visible to both eyes. This asymmetry cannot be attributed to suppression of dots presented to the amblyopic eye, as seen by the poor correlation between enumeration performance in the NDE condition and the asymmetry scores seen on the multiple-object tracking task. Similarly, a general motion tracking deficit cannot explain this effect, as task performance in the strabismic/mixed group under binocular viewing conditions did not differ from controls. Instead, these results suggest an imbalance in the allocation of attention to each eye for the multiple-object tracking task.

DISCUSSION

The aims of this study were to determine whether interocular attention is biased in visually normal participants (Experiment 1), and whether interocular attention is biased in favor of the fellow eye in anisometropic and strabismic/mixed amblyopia (Experiment 2) when both eyes are viewing. Experiment 1 revealed that the normal visual system has an equal distribution

of attention between the two eyes when performing the multiple-object tracking task, and that dichoptic presentation of target dots to only one eye did not benefit task performance. In fact, splitting targets and distractors between the two eyes impaired performance, as we found an advantage of binocular over dichoptic stimulus presentation for multiple-object tracking accuracy. This is the opposite of what we would expect if attention could be biased in favor of the eye viewing only target elements during dichoptic viewing. Therefore, despite previous evidence that attentive processing of monocular information can be used in an advantageous manner to expedite stimulus detection in dichoptic tasks,^{59,60} we found that it does not benefit performance within a motion tracking paradigm.

Experiment 2 revealed an equal allocation of attention between the two eyes in anisometropic amblyopia and an attentional bias in favor of the fellow eye in strabismic amblyopia. These findings are consistent with relatively reduced attentional modulation for amblyopic eye viewing in strabismic amblyopia.⁵⁰ Our results are also broadly consistent with previous neuroimaging studies that have reported abnormalities within the motion processing and attentional networks that contribute to multiple-object tracking task performance in amblyopia.⁷⁴⁻⁸² However, other studies have observed normal performance on attentional tasks in amblyopia. For example, Roberts and colleagues⁵⁷ found normal accuracy and reaction times for a group of participants with amblyopia who performed involuntary and voluntary attentive cueing tasks under monocular viewing conditions. Furthermore, they found that the extent of attentional modulation did not correlate with amblyopia severity. However, when only considering the participants in their study who had at least a 2 logMAR line difference in acuity, those who remain (7/19 participants) predominantly had anisometropic amblyopia. The results of the current study are consistent with this previous study in finding no attentional deficit in anisometropic amblyopia.

An inspection of Figure 4 reveals variability in the control and strabismic/mixed groups with some participants exhibiting a bias toward the fellow/dominant eye and others showing no bias. This indicates that an attentional bias was not present in all participants with strabismic amblyopia and that a bias can also exist in controls. A study with a larger sample size is required understand this variability and to enable stronger conclusions to be drawn regarding the allocation of interocular attention in strabismic/mixed amblyopia.

Unlike controls, participants with amblyopia did not exhibit an advantage of binocular over dichoptic presentation. This effect may be related to previous work demonstrating that binocular summation may be impaired in amblyopia.^{5,83-85} However, the reason for a multiple-object tracking task advantage for binocular versus dichoptic presentation of the multiple-object tracking task remains to be explained. Similarly, the reason for an interocular attention asymmetry for the strabismic/mixed group and not the anisometropic group is unclear. Stronger dichoptic masking in strabismic relative to anisometropic amblyopia has been reported.⁸⁶ However, other studies have not observed differences in interocular suppression strength between strabismic/mixed and anisometropic amblyopia.^{25,28} In agreement with these latter studies, we did not find a difference in interocular suppression strength between the two amblyopia groups in terms of balance point contrast. In addition, once interocular suppression was neutralized with an appropriate interocular contrast balance, interocular asymmetries in enumeration task performance did not differ between groups, although the strabismic/mixed group did exhibit worse overall performance on this task than the other groups. If we assume that an interocular bias in

attention contributes to interocular suppression in amblyopia,⁵⁰ then our measurements reveal a residual attentional bias in strabismic/mixed amblyopia that is maintained when suppression is minimized.

To rule out the potential confound of a general motion tracking deficit in amblyopia, we examined multiple-object tracking performance under binocular viewing conditions to provide an index of multiple-object tracking accuracy without any interocular manipulations. Both amblyopia groups exhibited numerically poorer multiple-object tracking accuracy than controls in agreement with previous studies of monocular multiple-object tracking in amblyopia^{52,53,76}; however, the difference from controls only reached significance for the anisometropia group, perhaps due to limited sample size. Critically, the two amblyopia groups did not differ significantly from one another, confirming that the interocular attentional bias in the strabismic/mixed group could not be explained by a general tracking deficit. Both amblyopia groups had greater mean ages than the control group; however, the mean age of the two amblyopia groups did not differ. As all participants were adults with mature visual systems and healthy eyes, we do not anticipate age to have affected our results.

It has been proposed that the spatial attention deficits may be involved in the multiple-object tracking impairments in amblyopia,⁷⁶ whereby the spatial resolution of attention is coarser in the amblyopic eye.⁵⁶ This may cause crowding of dots presented to an amblyopic eye.⁸⁷⁻⁸⁹ Although we cannot eliminate crowding as a confounding factor in our study, contour interactions were minimized by the use of Gaussian blur on dot edges. It is also important to note that our target dots were generally perceived to be separate dots in the enumeration task. Although the strabismic/mixed group displayed poorer overall enumeration accuracy in both dichoptic conditions, no interocular differences were present and binocular performance was similar to the anisometropic and visually normal groups.

Overall, our results provide new evidence that an interocular imbalance in attention occurs in strabismic/mixed amblyopia. Interocular attention may be important to consider within the rapidly developing field of binocular amblyopia treatments.

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