Visual Psychophysics and Physiological Optics

Temporal Contour Integration Deficits in Children With Amblyopia

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Purpose. Contour integration, the process of combining local visual fragments into coherent paths or shapes, is essential for visual perception. Although prior research on amblyopia has focused primarily on spatial domain deficits in contour integration, this study investigates how amblyopia affects contour integration over time and examines the relationship between temporal contour integration deficits and visual functions.

Methods. Nineteen amblyopic children (mean age, 10.9 ± 2.4 years; 17 anisometropic, 2 anisometropic/strabismic mixed) and 26 visually normal children (mean age, 10.5 ± 1.8 years) participated in this study. Temporal contour integration was assessed by measuring the accuracy of detecting tilted contour paths, formed by collinear Gabor elements with similar orientations, under slit-viewing conditions. Performance was evaluated for amblyopic eyes (AEs) and fellow eyes (FEs) at two spatial frequencies (1.5 cpd and 3 cpd). The slit width, orientation jitter of contour elements, and stimulus movement speed were systematically varied across separate runs. Visual acuity and Randot stereoacuity were assessed before testing.

Results. AEs exhibited significant deficits in temporal contour processing compared with FEs. Specifically, AEs required larger slit widths to achieve performance levels comparable to FEs, with more severe amblyopia (i.e., worse AE visual acuity) necessitating even larger slit widths for temporal contour integration. Temporal contour integration deficits in AEs were most pronounced under conditions of complete Gabor collinearity or moderate stimulus movement speeds (6.4°/s). No significant differences were observed between FEs and control eyes. Notably, the temporal contour integration ability between the two eyes quantified as the AE/FE ratio of slit width thresholds showed no correlation with interocular acuity differences, stereoacuity, or spatial contour integration deficits.

Conclusions. Amblyopic children demonstrate significant deficits in temporal contour integration in AEs, which seem to be independent of spatial contour integration deficits. The severity of these temporal deficits increases with worse AE visual acuity. These findings suggest that amblyopia is associated with temporal deficits in visual integration, in addition to the well-documented spatial deficits, highlighting the need for a more comprehensive understanding of amblyopic visual processing.

Keywords: amblyopia, anisometropia, contour integration, temporal integration, slit viewing

Amblyopia is a developmental visual disorder typically caused by strabismus, anisometropia, or selective deprivation of vision during early childhood. It is attributed to complex neural deficits in both the striate and extrastriate cortices,[1] resulting in significant unilateral visual loss, particularly in children. Amblyopia is associated with deficits in multiple spatial visual functions, including reduced visual acuity,[2] impaired contrast sensitivity,[3,4] diminished stereopsis,[5,6] and compromised global shape perception.[7,8] Although most research has focused on visual function deficits in the amblyopic eye (AE), emerging evidence suggests that the fellow eye (FE) may also exhibit visual function impairments compared with normal control eyes.[9,10]

Amblyopia not only impairs spatial processing, but also affects temporal processing. These temporal deficits include reduced temporal contrast sensitivity,[11,12] abnormal motion-defined form perception,[13,14] impaired global motion perception,[13,15,16] temporal instability,[17]

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ments.[16,19,20,25,26] For instance, Kiorpes et al.[26] demonstrated in amblyopic monkeys that motion sensitivity losses were uncorrelated with spatial contrast sensitivity losses.

Contour integration, the process of integrating physically discontinuous visual fragments into a perceived contour, is a fundamental aspect of higher-level visual processing.[27] In a seminal study, Field et al.[28] used a snake-like contour path composed of Gabor elements embedded in a noise background to demonstrate the critical role of continuity among neighboring elements in contour integration. Both spatial and temporal parameters of contour integration are frequently examined through local mechanisms, such as collinear facilitation, where the contrast sensitivity to a low-contrast Gabor target is enhanced by spatially separated collinear flankers.[29–31] These findings suggest that local interactions between neighboring elements underlie contour integration. Similar to collinear facilitation, contour integration is thought to involve excitatory horizontal connections between cells with similar orientation preferences within the primary visual cortex (V1),[28,32–36] supported by neurophysiological evidence.[37–43] Neuroimaging studies have further implicated both striate and extrastriate cortices, including V2, V4v, and the lateral occipital complex, contributing to contour integration.[44,45] Recent research indicates that contour integration involves both bottom-up and top-down (reentrant) processes.[46–49]

Amblyopic individuals exhibit abnormal performance in both lateral interactions[50–54] and spatial contour integration.[55–61] For example, Polat et al.[50] found that collinear flankers facilitated the detection of low-contrast Gabor targets in control subjects, whereas this facilitatory effect was absent or even reversed in individuals with strabismic and/or anisometropic amblyopia. Similarly, studies investigating contour detection in noise revealed that contour visibility in strabismic amblyopia was degraded by random orientation offset from the contour path, confirming the critical role of collinearity in contour integration.[55,61] Interestingly, Hess and Demanins[62] reported no contour integration deficits in most adults with anisometropic amblyopia using a contour detection task. In contrast, Levi et al.[57] identified mild but genuine contour integration deficits in adults with anisometropic amblyopia using a contour discrimination test. Recently, we demonstrated that children treated for anisometropic amblyopia still exhibited contour integration deficits, particularly at higher spatial frequencies, even after compensating for low-level deficits such as reduced contrast sensitivity and degraded shape perception in AEs.[60] These findings suggest that contour integration deficits in amblyopia may arise from impairments in both low-level and high-level visual processing.

Visual systems can integrate information over time to perceive an object's shape, even when it moves behind a narrow slit.[63] Although most studies have focused on spatial contour integration, Kuai et al.[64] were the first to investigate the mechanisms of temporal contour integration systematically. They developed a contour integration task under slit viewing conditions, in which stimuli moved horizontally behind a vertical slit, allowing only a small portion of the stimuli to be visible at any given time. They found that young adults with normal visual acuity demonstrated robust contour detection, even when the slit permitted only one viewable contour element. This finding suggests that, unlike spatial contour integration, horizontal connections in V1 may not be necessary for temporal contour integration.[32,65] Using functional magnetic resonance imaging, Kuai et al.[64] further demonstrated that temporal contour processing primarily involved higher dorsal visual areas (e.g., V3B and MT) and higher ventral visual areas lateral occipital complex, but not early visual areas (e.g., V1 and V2). These findings suggest that the neural mechanisms underlying the Gestalt rule of continuity in contour integration are at least dissociated partially between spatial and temporal domains, with temporal contour integration relying more heavily on higher-order visual regions.

Despite extensive research on spatial contour integration in amblyopia, the impact of amblyopia on temporal contour integration remains poorly understood, particularly in children. Furthermore, it is unclear whether performance differences exist between the FEs and normal control eyes in temporal contour integration. In this study, we adopted the slit-viewing task developed by Kuai et al.[64] to examine temporal contour integration in 19 amblyopic children. We compared the performance of detecting tilted contour paths composed of collinear Gabor elements under slit viewing conditions among the AEs, FEs, and normal control eyes. Additionally, we investigated the influence of Gabor orientation collinearity and stimulus movement speed on temporal contour integration in amblyopic and normal vision children. We also explored the relationships between temporal contour integration deficits and other visual functions, including monocular visual acuity, binocular stereoacuity, and spatial contour integration.

Methods

Participants

Amblyopia was defined as a best-corrected visual acuity in the AE of less than 0.1 logMAR and an interocular acuity difference of no less than 0.1 logMAR.[66] This clinical definition of amblyopia was adopted as part of our inclusion and exclusion criteria. Anisometropia was defined as a difference of 1.00 diopters (D) or more in the myopic, hyperopic, or astigmatic refractive error between the observer's two eyes. Strabismus was defined as a 5 to 50 prism diopter angular deviation between two eyes at either near or far viewing distances.

Nineteen amblyopic children aged 8.0 to 16.5 years (13 boys and 6 girls; mean age, 10.9 ± 2.4 years; 17 anisometropic and 2 anisometropic/strabismic mixed) met the inclusion criteria, and their data were included in the analysis (detailed clinical information is provided in Table). Three additional children participated in the study but were excluded from the analysis because they did not meet the inclusion criteria: one was a successfully treated patient with refractive amblyopia (<0.1 logMAR best-corrected visual acuity in the weak eye after treatment), and the other two were strabismic patients with 0.1 logMAR best-corrected visual acuity in the weak eye and a 0.1 logMAR interocular acuity difference. All participants underwent ophthalmological examinations and were refracted by a registered optometrist before testing. Participants who had been prescribed refractive correction were required to wear their glasses throughout the experiment.

Twenty-six children aged 8 to 13 years (12 boys and 14 girls; mean age, 10.5 ± 1.8 years) with normal or corrected-to-normal visual acuity and normal stereoacuity (mean, 33.2 ± 11.7 arcsec) participated as control groups (n = 11, n = 10, and n = 7 for experiments 1, 2, and 3, respectively; 1 observer participated in all 3 experiments).

Table. Characteristics of Amblyopic Children

Observer	Age (Y)	Sex	Diagnosis	Strabismus	Eye	Refractive Correction	Best-Corrected Visual Acuity (logMAR)	Severity	Stereoacuity (Arcsec)	Past Treatment	Experiments
S1	13.0	Male	A	None	AE (R)	+3.25/−2.00 × 170	0.92	Sev	F	Glasses	1
					FE (L)	+3.00/−1.25 × 165	0.22				
S2	10.8	Female	A	None	AE (L)	+2.00	0.82	Sev	F	Corrective surgery	2
					FE (R)	+4.25	0.40				
S3	11.0	Male	A	None	AE (R)	+3.50/−1.25 × 140	0.60	Mod	70	Patching glasses	1, 2, and 3
					FE (L)	−0.25/−1.00 × 5	0.22				
S4	12.3	Female	A	None	AE (L)	+2.00	0.22	Mild	200	Patching glasses	1 and 2

±0.25 square size in both horizontal and vertical directions from the grid center. To avoid density cues, the center-to-center horizontal distance between neighboring contour Gabor elements was randomized between 0.9 and 1.1 times the average interelement distance (AIED), which was equal to the size of the square. The stimulus pattern was regenerated for each trial. Within the same trial, a random stimulus image (without any contour path) was generated by randomly shuffling the positions of all Gabors in the contour stimulus image (Fig. 1A, middle).

Procedures

For amblyopic children, we measured contour detection performance for AEs and FEs separately using a two-interval forced-choice method of constant stimuli. In experiment 1, two stimul590.9(o)0(rced-c790.⊠10362(a)e0(rced8.2(esD⊠⊠(d0(rces)-239.4(4.1(o)-381.(4.1(o)-382.5(t):-239(t8d)-37ne0(rced8.)-320.-.1(ion)⊠I or repeated-measures ANOVA were employed for within-group comparisons (e.g., AEs vs. FEs). One-way ANOVA was used to compare performance between the amblyopic group and the normal control group. Pearson's r correlation was applied to assess the potential influence of visual functions (e.g., visual acuity, stereoacuity) on temporal contour integration deficits in amblyopic children.

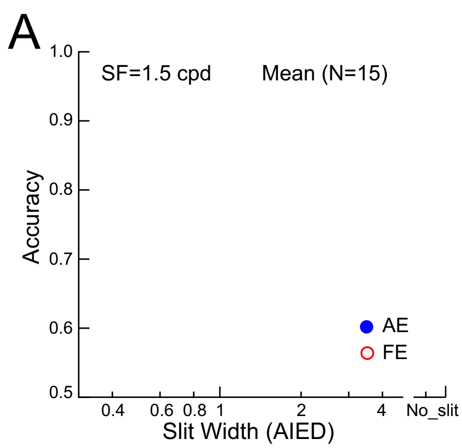
Results

Temporal Contour Integration in Amblyopic Children and Children With Normal Vision

In experiment 1, we investigated the temporal contour integration ability of amblyopic children using Gabor element arrays moving at a speed of 6.4°/s behind five slit widths (0.4, 0.8, 1.0, 2.0, and 4.0 times the AIED). To assess performance across different spatial scales, Gabor elements with spatial frequencies of 1.5 and 3 cpd were used, achieved by setting the viewing distance to 0.5 and 1.0 meter, respectively.

The mean accuracy of amblyopic observers is shown in Figures 2A and 2D. Contour detection accuracy increased with larger slit widths for both AE and FE. High accuracy levels (≥0.8) were achieved at a slit width of 4 times the AIED, comparable with the performance observed when no aperture or slit was present (i.e. the entire Gabor array was visible). A three-way repeated measures ANOVA, with Gabor spatial frequency (1.5 and 3 cpd), eye (AEs vs. FEs), and slit width (0.4, 0.8, 1.0, 2.0, and 4.0 times the AIED) as factors, revealed significant main effects of the eye, $F(1, 11) = 20.60$, $P < 0.001$, $\eta_p^2 = 0.65$, and slit width, $F(4, 44) = 54.04$, $P < 0.001$, $\eta_p^2 = 0.65$, indicating pronounced differences in contour detection accuracy between AEs and FEs. Notably, at the 0.4 AIED slit width, where only one Gabor element or part of it was visible at any time, AEs demonstrated accuracy significantly above chance level (0.5) for both spatial frequencies: 1.5 cpd (accuracy = 0.61 ± 0.08, $t_{14} = 5.95$, $P < 0.001$, Cohen's $d = 1.54$) and 3 cpd (accuracy = 0.61 ± 0.08, $t_{12} = 5.08$, $P < 0.001$, Cohen's $d = 1.41$, one sample t test).

To quantify interocular performance differences, we calculated the AE/FE ratio of accuracy for each slit width



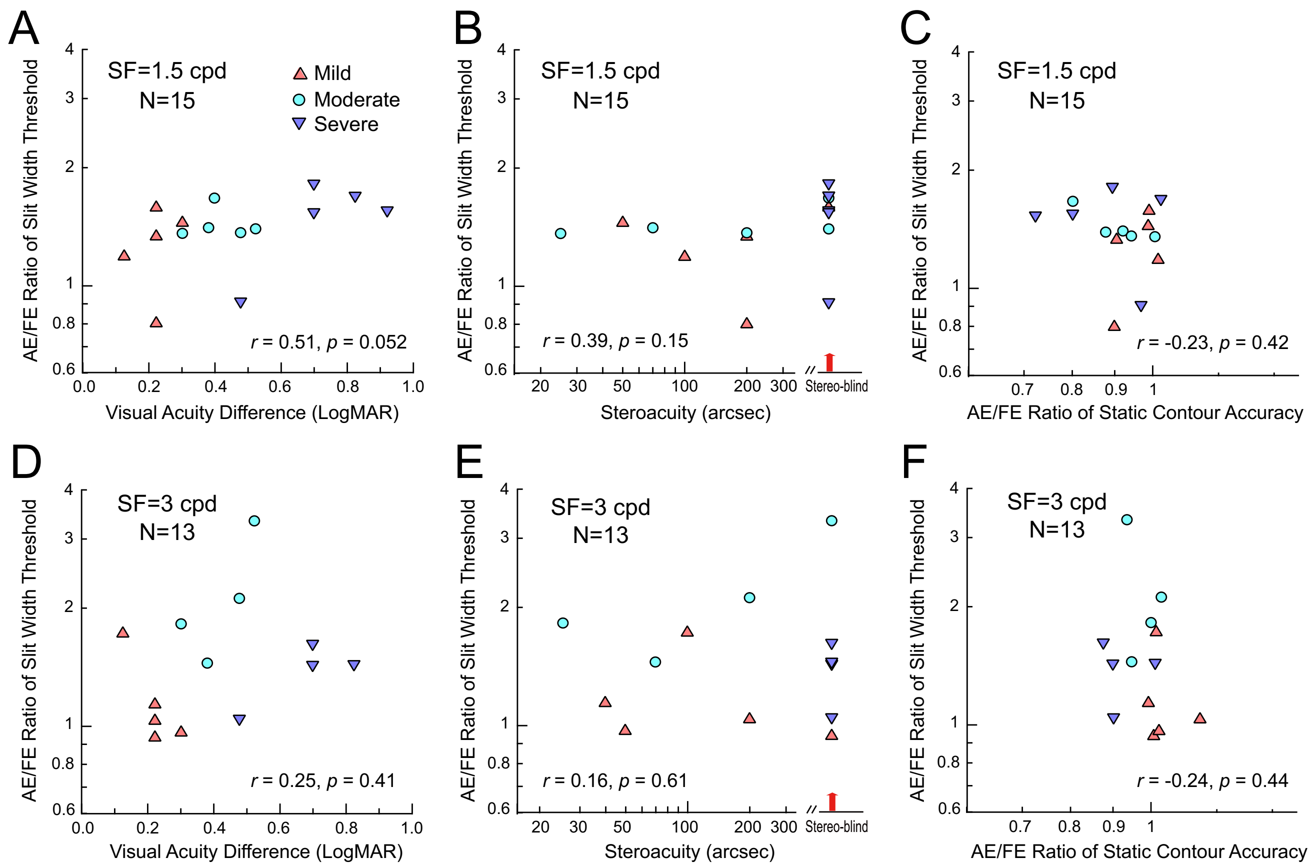


Figure 4. Relationship between temporal contour integration deficits and visual functions, as well as spatial contour integration deficits. (**A** and **D**) Visual acuity difference between AEs and FEs as a function of the AE/FE ratio of slit width thresholds at 1.5 cpd (**A**

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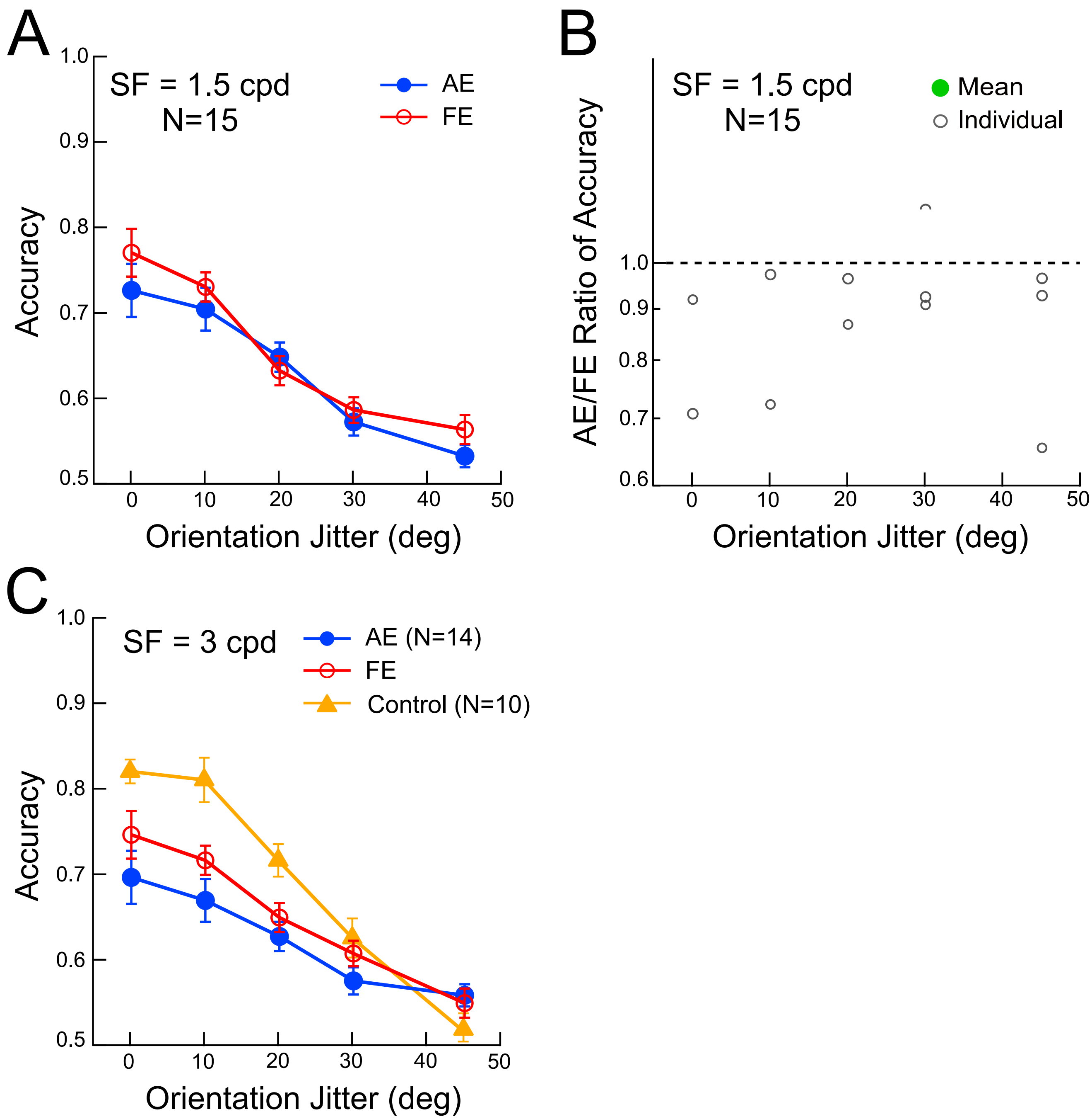
A
SF = 1.5 cpd
N=15
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FE
Accuracy
Orientation Jitter (deg)
B
SF = 1.5 cpd
N=15
Mean
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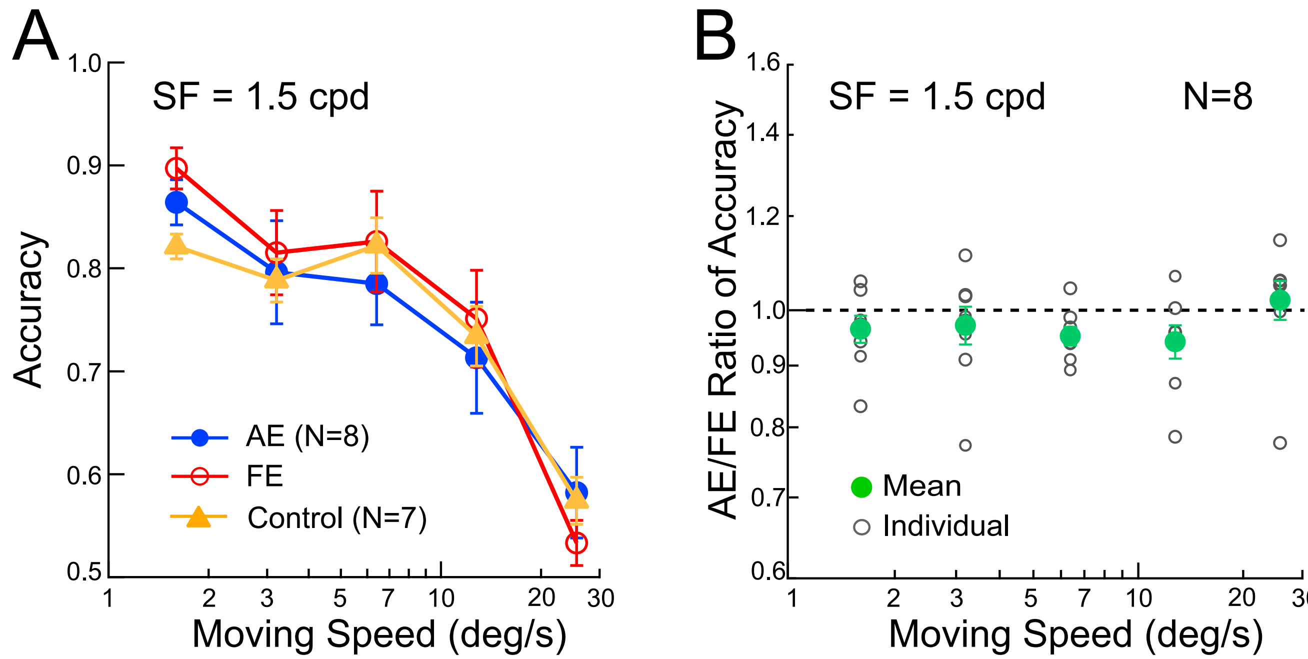

Figure 6. Effects of stimulus moving speed on temporal contour integration. (**A**) Mean accuracy of AEs, FEs, and normal control eyes as a function of stimulus moving speed. (**B**) AE/FE ratio of accuracy as a function of stimulus moving speed. Large dots: mean thresholds; small dots: individual thresholds. Error bars represent ±1 SEM.

(seven of whom also participated in experiments 1 and 2) performed the contour detection task under five moving speed conditions: 1.6°/s, 3.2°/s, 6.4°/s, 12.8°/s or 25.6°/s. The slit width was fixed at 1 AIED, and the Gabor spatial frequency was set at 1.5 cpd. Seven visually normal children participated as the control group.

The mean accuracy of contour detection for each group is shown in Figure 6A. A two-way ANOVA with the eye (AEs vs. FEs) and moving speed (1.6°/s, 3.2°/s, 6.4°/s, 12.8°/s, and 25.6°/s) as repeated measures revealed no significant main effect on the eye (P = 0.24) but a significant main effect of the moving speed, $F(4, 28) = 18.48$, $P < 0.001$, $\eta_p^2 = 0.73$, indicating a significant decline in performance of both AEs and FEs as the moving speed increased. At 25.6°/s, a speed too fast for contour identification, the accuracy of AEs, FEs, and normal control eyes was barely above chance level. A one-way ANOVA with moving speed as a repeated measure and group (amblyopic vs. control) as a between-subject factor showed no significant main effect of group ($P = 0.99$). Similarly, no significant difference in accuracy was observed between FEs and normal control eyes ($P = 0.57$).

To examine the interocular difference in moving speed for amblyopic children specifically, we conducted one-sample t tests on the AE/FE accuracy ratio (Fig. 6B). A significant interocular difference was found at 6.4°/s (AE/FE ratio = 0.96, $t_7 = -2.68$, $P = 0.031$, Cohen's $d = -0.95$), but not at other moving speeds (Ps > 0.05). These findings suggest that interocular differences in temporal contour integration for amblyopic children are present at moderate moving speeds but not at very slow or very fast speeds. Notably, seven observers who performed the contour detection task under the same condition three times (across experiments 1–3) showed no significant improvement in performance (mean improvement from test 1 to test 3 = −0.44% ± 2.96%).

Discussion

In this study, we investigated spatial–temporal visual integration in amblyopic children by exploring dynamic contour integration under a slit viewing condition. Our results showed significant temporal contour deficits in AEs compared with FEs, whereas no differences were found between FEs and normal control eyes. Notably, temporal contour integration deficits in AEs were most pronounced under conditions of complete collinearity and moderate stimulus moving speeds. Furthermore, the temporal contour integration ability between AEs and FEs, defined as the AE/FE ratio of slit width thresholds, was uncorrelated with interocular acuity differences, stereoacuity, and spatial contour integration deficits.

Our study demonstrates that amblyopia exhibits deficits in temporal contour processing. Specifically, AEs required larger slit widths to achieve performance levels comparable to FEs, and children with worse AE visual acuity exhibited greater slit width requirements. These results align with prior studies documenting temporal deficits in amblyopic visual systems, including reduced temporal resolution,[25,72] degraded temporal contrast sensitivity,[11] increased temporal synchrony thresholds,[19,20] and an expanded temporal binding window.[73] Such spatiotemporal deficits may arise from delayed information processing in the AE,[74,75] as evidenced by reduced neural synchronization in the amblyopic visual cortex.[76] Additionally, these deficits likely reflect reduced processing efficiency in the amblyopic visual system, attributable partly to reduced template efficiency but, to a greater extent, to a higher fraction of internal noise.[15,26,77]

The lack of correlation between the AE/FE ratio of slit width thresholds and interocular acuity differences, stereoacuity, or spatial contour integration deficits supports

pating children and their parents for their contributions to this study.

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