Comparative Effects of Monocular and Stereopsis Training on Visual Acuity and Stereoacuity in Children With Amblyopia

Yan-Ru Chen,[1] Pin-Xian Li,[1] Hui-Fang Zhang,[2] Xiang-Yun Liu,[2] and Jun-Yun Zhang[1]

[1]School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Brain-Computer Interface and Mental Health Modulation, Peking University, Beijing, China
[2]Department of Ophthalmology, Tengzhou Central People's Hospital, Tengzhou, Shandong Province, China

Correspondence: Xiang-Yun Liu, Department of Ophthalmology, Tengzhou Central People's Hospital, 181 Xingtan Rd., Tengzhou, Shandong Province 277599, China; zhuanghqqq@126.com.
Jun-Yun Zhang, School of Psychological and Cognitive Sciences, Peking University, #5 Yiheyuan Rd., Haidian District, Beijing 100871, China; zhangjunyun@pku.edu.cn.

Received: December 31, 2025
Accepted: August 5, 2026
Published: August 31, 2026

Citation: Chen YR, Li PX, Zhang HF, Liu XY, Zhang JY. Comparative effects of monocular and stereopsis training on visual acuity and stereoacuity in children with amblyopia. *Invest Ophthalmol Vis Sci.* 2026;67(10):69. https://doi.org/10.1167/iovs.67.10.69

Purpose. To evaluate changes in visual acuity (VA) and stereoacuity in children with amblyopia following monocular or stereopsis training delivered alongside standard clinical care and to examine factors associated with training-related improvements in visual outcomes.

Methods. Forty-three children with amblyopia (7.3–14.8 years; 37 anisometropic, five strabismic, and one mixed) completed approximately 29 sessions of either monocular training (grating acuity or motion discrimination targeting the amblyopic eye, $n = 23$) or binocular stereopsis training (dichoptic disparity discrimination, $n = 20$). All participants continued standard clinical management, including optical correction and prescribed patching. Pre- and post-training assessments included amblyopic-eye VA, interocular acuity difference (IOD), and Randot stereoacuity.

Results. Both training protocols produced significant task-specific learning. Amblyopic-eye VA improved significantly in both groups, with no evidence of differential effects between training approaches. Stereoacuity also improved in both groups, with significantly greater gains following stereopsis training than monocular training. Exploratory analyses indicated that poorer baseline amblyopic-eye VA was associated with larger VA gains; however, this association did not survive correction for multiple comparisons. Stereoacuity improvement was not significantly associated with baseline VA, IOD, age, or changes in VA.

Conclusions. Visual training combined with standard clinical care improved amblyopic-eye VA and stereoacuity in children with amblyopia. Although both training approaches yielded comparable gains in VA, stereopsis training produced larger improvements in stereoacuity, supporting its potential role in addressing residual binocular deficits after conventional treatment.

Keywords: amblyopia, perceptual learning, stereopsis training, binocular vision, visual plasticity

Amblyopia is a neurodevelopmental visual disorder arising from abnormal binocular experience during early childhood, most commonly due to anisometropia, strabismus, or form deprivation.[1] It is the leading cause of visual impairment in children, affecting approximately 2% to 4% of the population.[2,3] Clinically, amblyopia is characterized by reduced visual acuity (VA), impaired contrast sensitivity, and deficits in stereopsis, often accompanied by other visual and oculomotor abnormalities such as fixation instability, perceptual distortions, and accommodative deficits.[2,4–6] Increasing evidence suggests that amblyopia reflects disrupted binocular development, with long-lasting consequences for cortical processing of input from both eyes.[7–11]

Patching therapy, typically involving occlusion or penalization of the fellow eye, remains the standard first-line treatment for young children with amblyopia.[12] Although patching improves VA in the amblyopic eye (AE), its effects on stereopsis are limited, and many patients remain stereoblind despite intensive treatment.[13] Even when near-normal VA is achieved, residual stereo deficits are common.[14] In addition, adherence to patching is often suboptimal,[15] and monocular occlusion may further exacerbate interocular suppression and disrupt binocular balance.[16,17] Together, these limitations have motivated increasing interest in adjunctive approaches that target both monocular and binocular visual function.

Perceptual learning is one such approach, in which repeated visual training leads to experience-dependent improvements in visual performance. Early work primarily focused on monocular training of the AE using tasks such as Vernier acuity, positional judgments, contrast detection, and letter recognition in both adults and children.[18,19] For example, we previously showed that intensive monocular grating–

acuity training yielded modest but significant improvements in VA and associated gains in stereoacuity in children with amblyopia.[20] However, although such approaches can enhance AE sensitivity, they do not directly address binocular imbalance, and improvements in stereoacuity are often limited.[6,21]

To overcome these limitations, binocular training paradigms have been developed to directly target interocular imbalance and promote binocular integration.[6] These approaches typically involve dichoptic or signal combination tasks in which information from the two eyes must be integrated to complete the perceptual task.[22–27] Such training has shown promise in improving both VA and stereoacuity in amblyopia across both adult and pediatric populations.[6,28,29] Specifically, our previous work demonstrated that dichoptic de-masking training, where observers discriminate the contrast of a Gabor stimulus presented to the AEs while resisting dichoptic noise masking from the fellow eyes, can improve and, in some cases, restore stereoacuity in children with amblyopia, particularly in those with mild deficits.[30]

More recently, stereopsis-specific training paradigms have been developed that directly target disparity processing mechanisms.[31–35] For example, Ding and Levi[31] introduced a stereo-depth discrimination training paradigm that produced significant improvements in stereoacuity in adults with long-standing amblyopia. These approaches have further motivated the development of VR- and game-based stereoscopic interventions, which offer engaging platforms for pediatric training.[36] However, substantial variability in training protocols, participant characteristics, and outcome measures across studies has limited a clear understanding of how different perceptual learning approaches differentially influence VA and stereoacuity in children with amblyopia.[37–40]

Despite growing interest in binocular approaches, relatively few studies have directly compared monocular and stereopsis-based training effects on both VA and stereoacuity in children receiving standard clinical care. In particular, it remains unclear whether training that explicitly engages binocular disparity processing yields differential effects on these two key clinical outcomes. To address this question, the present study evaluated changes in VA and stereoacuity in children with amblyopia who completed either monocular AE training or stereopsis training while continuing standard clinical management. We further examined associations between baseline visual characteristics and training-induced improvements to identify potential predictors of treatment response.

Methods

Participants

Forty-three children with amblyopia (37 anisometropic, five strabismic, and one mixed anisometropic/strabismic), 7.3 to 14.8 years old, participated in the study. Participants were randomly assigned to either a monocular training group (n = 23; 12 boys, 11 girls; mean age = 10.2 ± 1.9 years; 20 anisometropic, two strabismic, one mixed) or a stereopsis training group (n = 20; 10 boys, 10 girls; mean age = 10.3 ± 2.2 years; 17 anisometropic, three strabismic).

Amblyopia was defined as best-corrected visual acuity (BCVA) in the AE worse than 0.1 logMAR, with an interocular acuity difference of ≥0.1 logMAR. Anisometropia was defined as an interocular refractive difference of ≥1.00 diopter (D) in spherical or cylindrical error. Strabismus was defined as a constant ocular deviation of 5 to 50 prism diopters at either near or distance fixation.

All participants underwent comprehensive ophthalmologic examinations, and appropriate refractive correction was provided when necessary. Prior and ongoing clinical management varied across participants and included spectacle correction, patching therapy, or a combination of both. Some children were newly diagnosed or had received little or no prior treatment because of poor compliance. These participants were prescribed refractive correction and had worn their spectacles for at least 1 month before enrollment. During the study, all participants continued their prescribed clinical treatments, including spectacle wear and/or patching when indicated.

Demographic and clinical characteristics, including treatment history, are summarized in Tables 1 and 2. The monocular and stereopsis training groups did not differ significantly in treatment history (glasses only: 8 vs. 7; patching only: 1 vs. 1; patching plus glasses: 8 vs. 4; untreated: 2 vs. 4; newly diagnosed: 4 vs. 4; Fisher's exact test, $P = 0.76$), prior treatment duration, and current patching regimen (all $P > 0.05$). Given the absence of systematic between-group differences and the modest sample size, these variables were not included as covariates in the primary analyses.

The study was approved by the Ethics Committee of Tengzhou Central People's Hospital and the Institutional Review Board of Peking University. Written informed consent was obtained from parents or legal guardians.

Study Design

Participants completed three study phases: a pre-test assessment, a training phase, and a post-test assessment (Fig. 1). To minimize expectancy effects, outcome assessors were unaware of the specific study hypotheses, and participants were not informed of the predicted superiority of either training condition. Visual function was assessed before and after training and included BCVA measurements for the AE and fellow eye (FE), as well as clinical stereoacuity measured using the Randot Stereotest (Stereo Optical, Chicago, IL, USA).

Participants in the monocular training group completed either a grating acuity task or a motion direction discrimination task using only the AE and received an average of 28.5 ± 6.5 training sessions (mean ± SD). Eighteen children completed the grating acuity task at a viewing distance of 4 meters. To control for potential effects of viewing distance, five children in the monocular group completed the motion discrimination task at a viewing distance of approximately 1 meter, matching the stereopsis training condition. Both tasks were based on the same perceptual learning framework targeting monocular visual processing and were therefore combined into a single monocular-training condition for the primary analyses. Exploratory subgroup analyses were conducted to evaluate potential task-specific effects. Participants in the stereopsis training group completed a stereopsis training task and received an average of 28.9 ± 8.7 training sessions.

For both groups, training sessions were conducted two to five times per week, depending on participant availability, over an average period of approximately 2.5 months. The number of completed staircases varied across participants and sessions, and a typical session lasted approximately 1 hour. The total number of training sessions did not differ

Investigative Ophthalmology & Visual Science

Table 1. Characteristics of Amblyopic Children in Monocular Training Group

Observer	Age (Y)	Sex	Diagnosis	Strabismus	Eye	Refractive Correction	VA (logMAR)		Stereoacuity (Arcsec)		Treatment History	Prior Treatment Duration (Mo)	Current Patching Regimen (h/d)
							Pre	Post	Pre	Post			
M1	10.8	Female	A	None	AE (L)	+2.00	0.70	0.30	F	200	Glasses	12	8
					FE (R)	Plano	0.00	0.00					
M2	8.5	Male	A	None	AE (R)	+7.00	0.52	0.30	F	400	Patching and glasses	48	8
					FE (L)	+7.50/−1.25 × 160	0.22	0.10					
M3	10.8	Male	A	None	AE (L)	+2.75/−1.00 × 160	0.70	0.60	F	F	Glasses	5	8
					FE (R)	Plano	0.00	0.00					
M4	8.7	Male	A	None	AE (L)	+4.25/−1.00 × 20	0.52	0.10	F	100	Untreated	0	8
					FE (R)	+0.75	0.00	0.00					
M5	11.3	Male	A	None	AE (R)	+4.00	0.40	0.30	F	200	Glasses	24	6
					FE (L)	Plano	0.00	−0.08					
M6	9.8	Male	A	None	AE (L)	+1.50/−3.25 × 180	0.60	0.40	200	200	Glasses	12	8
					FE (R)	−0.75	0.10	0.10					
M7	8.8	Male	A	None	AE (L)	+3.25/−0.50 × 25	0.52	0.30	F	400	Newly diagnosed	0	8
					FE (R)	Plano	0.00	0.00					
M8	13.0	Female	A	None	AE (L)	+4.00	0.40	0.22	F	200	Glasses	5	6
					FE (R)	Plano	0.00	0.00					
M9	10.7	Male	A	None	AE (L)	+3.50	0.30	0.10	50	50	Patching and glasses	6	6
					FE (R)	Plano	0.00	−0.08					
M10	8.0	Female	A	None	AE (R)	+3.50/−0.75 × 153	0.10	0.00	50	40	Patching and glasses	9	6
					FE (L)	+2.00	0.00	0.00					
M11	12.5	Female	A	None	AE (R)	+4.00/−0.75 × 75	0.22	0.00	F	200	Patching and glasses	84	6
					FE (L)	+4.25	−0.08	−0.08					
M12	14.0	Male	A	None	AE (R)	+5.25/−1.00 × 115	0.30	0.10	F	40	Patching and glasses	6	6
					FE (L)	−0.50	−0.08	−0.08					
M13	9.2	Female	S	Esotropia	AE (L)	+3.25/−1.50 × 180	0.22	0.10	50	50	Glasses	72	2
					FE (R)	+2.50	0.10	0.00					

Table 1. Continued

Observer	Age (Y)	Sex	Diagnosis	Strabismus	Eye	Refractive Correction	VA (logMAR)		Stereoacuity (Arcsec)		Treatment History	Prior Treatment Duration (Mo)	Current Patching Regimen (h/d)
							Pre	Post	Pre	Post			
M14	7.8	Female	A	None	AE (L)	+2.50 × 100	0.30	0.10	F	F	Untreated	0	6
					FE (R)	Plano	0.00	−0.18					
M15	12.5	Male	A	None	AE (L)	+4.75/−2.75 × 80	0.40	0.10	400	100	Patching and glasses	60	6
					FE (R)	+4.25/−1.00 × 170	0.10	0.00					
M16	12.8	Male	A	None	AE (R)	+3.25/−1.00 × 110	0.52	0.30	F	F	Newly diagnosed	0	8
					FE (L)	−1.50	0.00	−0.08					
M17	9.9	Female	A	None	AE (R)	+4.00/+2.00 × 75	0.30	0.22	200	50	Newly diagnosed	0	6
					FE (L)	+4.00/+1.75 × 90	0.10	0.10					
M18	7.7	Female	A & S	Esotropia	AE (L)	+2.75/−0.75 × 50	1.00	0.70	F	100	Patching and glasses	60	8
					FE (R)	+1.00/−0.50 × 175	0.00	0.08					
M19	7.8	Male	A	None	AE (R)	+5.25/−0.75 × 152	0.10	0.10	50	50	Glasses	60	2
					FE (L)	+3.50/−1.25 × 8	0.00	0.00					
M20	9.6	Female	A	None	AE (L)	+2.00	0.22	0.10	200	40	Patching	12	2
					FE (R)	Plano	−0.08	−0.08					
M21	10.6	Female	A	None	AE (L)	+4.00/−1.00 × 3	0.40	0.22	F	F	Patching and glasses	5	6
					FE (R)	Plano	0.00	0.00					
M22	8.7	Female	S	Exotropia	AE (L)	+5.25/−1.25 × 2	0.60	0.22	F	140	Newly diagnosed	0	8
					FE (R)	Plano	0.00	0.00					
M23	11.7	Male	A	None	AE (L)	+5.50/−1.00 × 10	0.52	0.40	F	400	Glasses	6	8
					FE (R)	−2.50	0.00	0.00					

Diagnoses included anisometropic (A) and strabismic (S) amblyopia. Eyes were classified as AE or FE, and as left (L) or right (R). Stereoacuity was assessed using the Randot Stereotest; participants who failed the test are indicated with an "F." Strabismus was diagnosed using a cover test at 33 cm. Participants M1 to M18 completed the grating acuity task, and participants M19 to M23 completed the motion discrimination task.

Table 2. Characteristics of Amblyopic Children in Stereopsis Training Group

Observer	Age (Y)	Sex	Diagnosis	Strabismus	Eye	Refractive Correction	VA (logMAR)		Stereoacuity (Arcsec)		Treatment History	Prior Treatment Duration (Mo)	Current Patching Regimen (h/d)
							Pre	Post	Pre	Post			
S1	10.9	Female	A	None	AE (L)	+1.50	0.22	0.10	200	140	Patching	36	6
					FE (R)	−1.00	0.00	−0.08					
S2	9.5	Female	A	None	AE (R)	+2.50/+0.75 × 95	0.40	0.22	200	140	Patching and glasses	6	6
					FE (L)	Plano	0.10	0.10					
S3	7.5	Female	A	None	AE (L)	+5.00/−0.50 × 164	0.22	0.10	70	20	Glasses	4	6
					FE (R)	+1.00/−1.00 × 3	0.00	0.00					
S4	8.7	Female	A	None	AE (R)	+4.25/−0.50 × 1	0.26	0.10	140	30	Untreated	0	6
					FE (L)	+1.75/−0.50 × 9	0.00	0.00					
S5	11.2	Male	A	None	AE (R)	+5.00/−3.50 × 200	0.22	0.10	F	40	Glasses	24	6
					FE (L)	+2.50/−1.00 × 170	0.00	0.00					
S6	8.6	Male	A	None	AE (L)	+5.50/−1.00 × 155	0.10	0.00	F	25	Patching and glasses	12	2
					FE (R)	+1.75/−0.50 × 10	0.00	0.00					
S7	7.3	Female	S	Esotropia	AE (L)	+3.00/−0.75 × 175	0.60	0.10	F	70	Glasses	4	8
					FE (R)	+3.00/−1.25 × 180	0.22	0.00					
S8	8.4	Male	S	Esotropia	AE (L)	Plano	0.52	0.30	140	70	Untreated	0	8
					FE (R)	Plano	0.00	0.00					
S9	9.0	Male	A	None	AE (L)	+2.00/−1.00 × 155	1.00	0.70	F	140	Newly diagnosed	0	8
					FE (R)	Plano	0.00	0.00					
S10	14.2	Male	S	Esotropia	AE (R)	Plano	0.60	0.40	F	70	Untreated	0	8
					FE (L)	Plano	0.10	0.10					
S11	10.0	Male	A	None	AE (R)	−1.00	0.10	0.00	70	25	Newly diagnosed	0	8
					FE (L)	+1.00/−0.50 × 180	0.00	0.00					
S12	13.3	Male	A	None	AE (L)	+1.50/−0.50 × 2	0.40	0.30	F	40	Patching and glasses	36	6
					FE (R)	−0.50 × 180	0.00	0.00					
S13	11.5	Female	A	None	AE (L)	+6.00/−0.75 × 79	0.52	0.40	200	140	Glasses	8	8
					FE (R)	−1.50/−0.50 × 7	0.10	0.10					
S14	14.8	Female	A	None	AE (R)	−3.00/−0.50 × 178	0.22	0.22	F	70	Newly diagnosed	0	6
					FE (L)	+3.00/−4.00 × 179	0.00	0.00					
S15	9.0	Male	A	None	AE (L)	Plano	0.92	0.70	100	20	Newly diagnosed	0	8
					FE (R)	Plano	0.22	0.22					
S16	9.6	Female	A	None	AE (R)	+3.00/−0.50 × 1	0.22	0.22	F	20	Glasses	5	6
					FE (L)	Plano	0.00	0.00					
S17	12.9	Male	A	None	AE (R)	+6.00/−1.25 × 176	0.30	0.10	F	100	Glasses	24	6
					FE (L)	+1.75/−0.50 × 167	0.00	0.00					
S18	7.9	Female	A	None	AE (R)	+3.00/−3.50 × 170	0.22	0.10	F	40	Glasses	6	4
					FE (L)	+0.50/−0.50 × 160	−0.08	−0.08					
S19	11.5	Female	A	None	AE (L)	+2.75	0.70	0.52	F	50	Untreated	0	6
					FE (R)	−0.75	0.10	0.10					
S20	9.9	Male	A	None	AE (L)	+5.50/−1.00 × 155	0.60	0.30	F	200	Patching and glasses	4	8
					FE (R)	+1.75/−0.50 × 10	0.00	0.00					

See Table 1 for definitions and assessment methods.

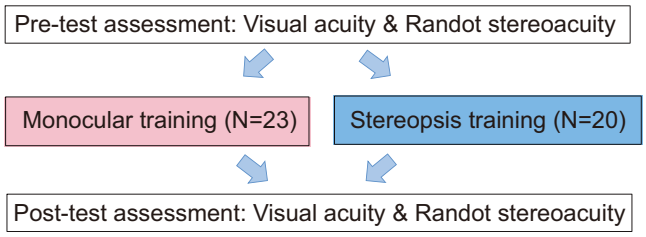

Figure 1. Study design. Participants completed pre-test assessments of VA and Randot stereoacuity and were then assigned to either a monocular training group or a stereopsis training group. Following approximately 2.5 months of training, all participants completed post-test assessments.

significantly between the monocular and stereopsis training groups ($P = 0.84$, independent-samples t-test).

Apparatus and Stimuli

All stimuli were generated using Psychtoolbox-3[41,42] and presented on a 21-inch G520 CRT monitor (resolution, 2048 × 1536 pixels; pixel size, 0.19 × 0.19 mm; refresh rate, 75 Hz; Sony, Tokyo, Japan). The monitor had a mean luminance of 50 cd/m^2, and luminance output was linearized using an 8-bit lookup table. Eighteen children in the monocular training group completed the grating acuity task (Fig. 2A left), and five children completed the motion direction discrimination task (Fig. 2A right).

The grating acuity task was adapted from our previous monocular perceptual learning paradigms in amblyopia.[20] High-contrast square-wave gratings oriented ±45° from vertical were presented monocularly to the AE at a viewing distance of 4 meters, with the fellow eye occluded. Stimuli consisted of binary luminance patterns within a fixed square aperture (500 × 500 pixels). Spatial frequency was manipulated by varying stripe width (half-cycle width), and aperture size remained constant throughout the experiment.

The motion discrimination task was adapted from our previous perceptual learning studies of motion processing.[43] Stimuli were presented monocularly to the AE at a viewing distance of 1 meter, with the fellow eye occluded. The stimuli consisted of a band-limited dynamic luminance noise pattern displayed within a circular aperture (6.5° diameter) surrounded by an annular mask. Motion was gener-

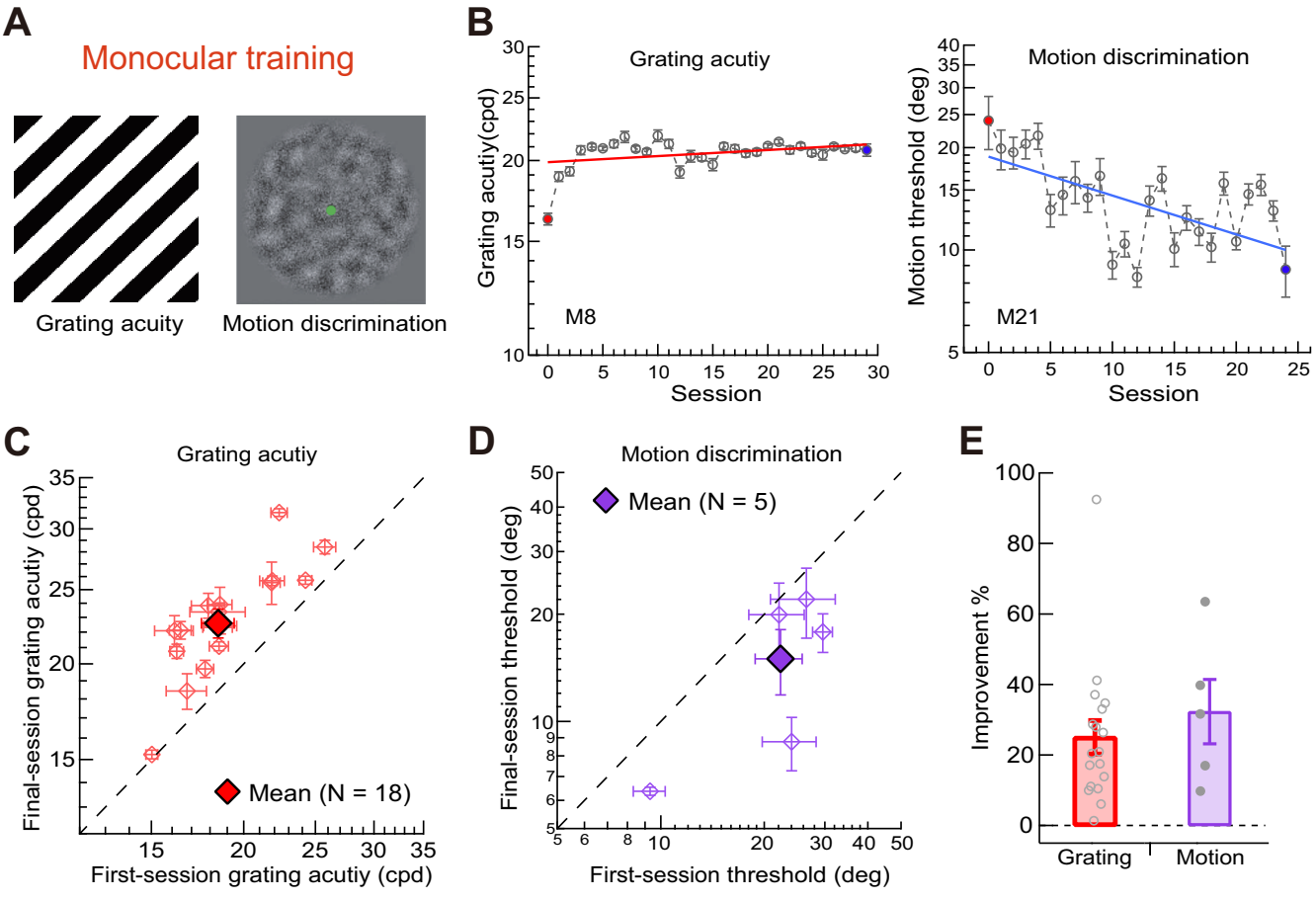

Figure 2. Stimuli and behavioral results of monocular training. (**A**) Stimuli used in the monocular training tasks: grating acuity (*left*) and luminance-defined motion direction discrimination (*right*), presented to the AE. (**B**) Representative learning curves from two participants (M8 and M21) performing the grating acuity task (*left*) and motion direction discrimination task (*right*). Filled circles denote thresholds from the first and final training sessions. *Gray lines* indicate linear regression fits to the session-by-session training data. (**C**) Grating acuity measured during the first and final training sessions. Data points above the unity line indicate improved performance. *Large symbols* represent group means, and *small symbols* represent individual participants. (**D**) Motion direction discrimination thresholds measured during the first and final training sessions. Data points below the unity line indicate improved performance. *Large symbols* represent group means, and *small symbols* represent individual participants. (**E**) Proportional improvement in the trained tasks, expressed as percentage change from the first to the final training session. *Small circles* represent individual participants. *Error bars* indicate ±1 SEM.

Investigative Ophthalmology & Visual Science

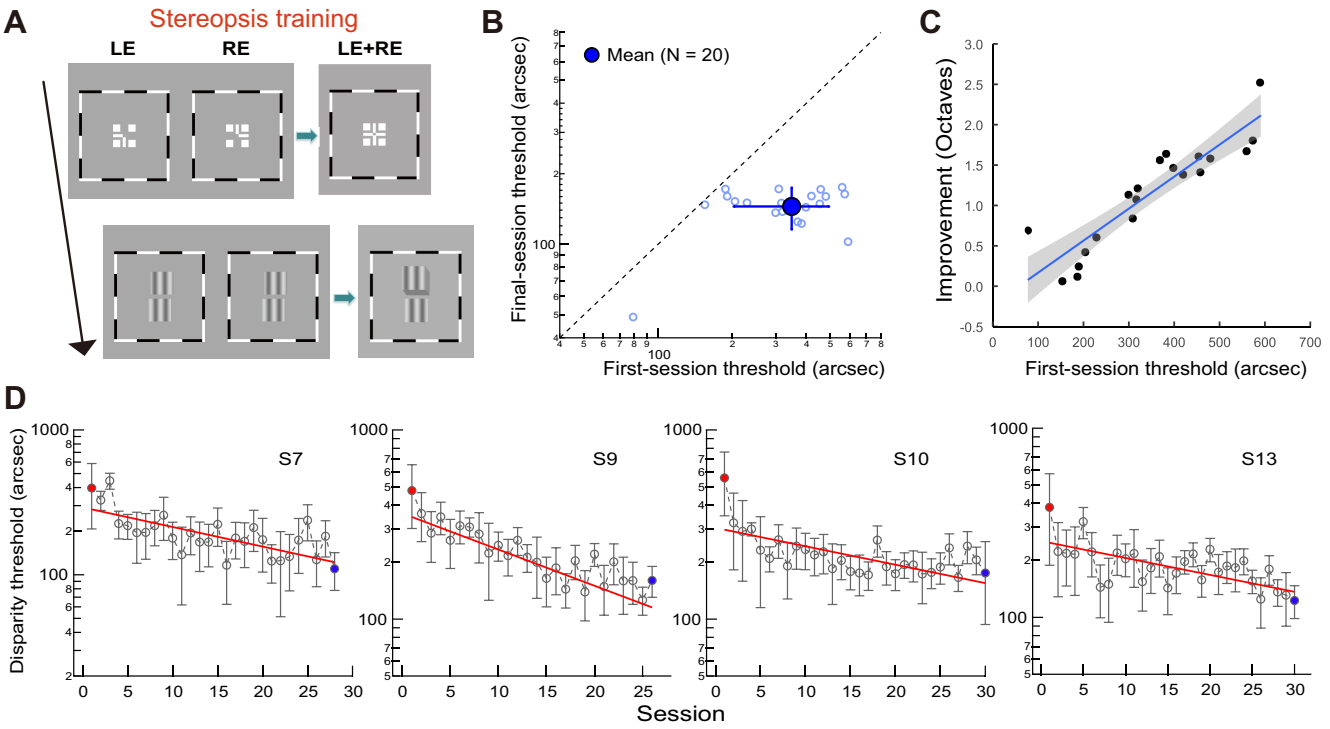

Figure 3. Stimuli and behavioral results of stereopsis training. (**A**) Stereoscopic stimuli used during training. Stimuli were presented dichoptically to the amblyopic and fellow eyes via a mirror stereoscope. On each trial, participants judged whether the upper grating patch appeared nearer or farther relative to the lower zero-disparity reference patch. (**B**) Disparity thresholds measured during the first and final training sessions. Data points below the unity line indicate improved performance (i.e., reduced disparity thresholds at the final session). *Large symbols* represent group means, and *small symbols* represent individual participants. *Error bars* indicate ±1 SEM. (**C**) Relationship between first-session disparity threshold and training-induced improvement expressed in octaves. Each *circle* represents one participant. The *solid line* indicates the linear regression fit, and the shaded area represents the 95% confidence interval. (**D**) Representative learning curves from four participants: three with no measurable clinical Randot stereoacuity at pre-test (S7, S9, and S10) and one with measurable stereoacuity at pre-test (S13; 200 arcsec). *Filled circles* denote thresholds from the first and final training sessions. *Red lines* indicate linear regression fits to session-by-session data.

ated by translating a pre-generated noise texture across successive frames at 4°/s using a sliding-window procedure. The resulting motion was defined by systematic luminance displacement over time and therefore represented a first-order (luminance-defined) motion stimulus.

The stereopsis training stimuli were adapted from Ding and Levi.[31] At the beginning of each trial, dichoptic fusion frames were presented through a mirror stereoscope to facilitate stable binocular alignment. The fusion frames were identical except for complementary monocular half-cross cues, which fused perceptually into a complete cross. When stable fusion had been achieved, stereoscopic stimuli consisting of two vertically aligned pairs of sinusoidal gratings were presented dichoptically to the amblyopic and fellow eyes (Fig. 3A). Each grating patch had a contrast of 48% and spatial frequency of 0.93 cycles per degree (cpd) and subtended 2.4° × 2.4°. The lower grating pair served as a zero-disparity reference, whereas the upper pair served as the target and contained variable binocular disparity. This configuration allowed participants to judge whether the target appeared nearer or farther than the reference. Disparity was generated by introducing horizontal offsets between the left- and right-eye images of the target pair while maintaining zero disparity in the reference pair. Crossed disparities specified a target appearing nearer than the reference, whereas uncrossed disparities specified a target appearing farther away. This relative disparity design reduces dependence on absolute depth judgments relative to the screen plane. To minimize positional adaptation, a small random horizontal jitter was applied on each trial. The vertical separation between the centers of the target and reference pairs was 26 arcmin. The effective viewing distance was 0.93 meter, determined by the optical path length of the stereoscope.

Procedures

Grating Acuity Task. Stimuli remained visible until a response was made. Participants performed a two-alternative forced-choice (2AFC) orientation-discrimination task, indicating whether the grating was tilted to the left or right of vertical. Thresholds were estimated using a 3-down/1-up adaptive staircase procedure converging on approximately 79.4% correct performance. The staircase operated in log space with a fixed step size of 0.05 log units. Stripe width (half-cycle width of the square-wave grating) was constrained to a range of approximately 1 to 100 pixels. Each staircase terminated after 10 reversals, and the threshold was defined as the geometric mean of the last six reversals. Thresholds were converted to spatial frequency (cpd) based on the 4-meter viewing geometry.

Motion Direction Discrimination Task. Participants completed a temporal 2AFC motion-discrimination task using a 3-down/1-up adaptive staircase. Each trial

consisted of two sequential motion intervals presented in randomized order. One interval contained a reference motion direction (35° or 125°, counterbalanced across participants), and the other contained a test stimulus differing in direction by a variable amount. Each stimulus lasted 800 ms with a 200-ms interstimulus interval. Participants indicated which interval moved in a more clockwise direction.

The direction difference was adaptively controlled using a staircase operating in log space (0.05 log-unit step size), with values constrained between approximately 0.2° and 40° (upper bound defined by pilot testing). Each staircase terminated after 10 reversals, and the threshold was calculated as the geometric mean of the last six reversals.

Stereopsis Task. Each trial began with fusion stimuli to ensure stable binocular alignment. After fusion, participants judged whether the upper grating pair appeared nearer or farther relative to a zero-disparity reference below. Stimuli remained visible until a response was made. Disparity thresholds were estimated using a 3-down/1-up staircase in log space (0.05 log-unit step size). Disparity magnitude was sampled per trial and randomly assigned as crossed or uncrossed. Values ranged from 1 to 50 pixels, corresponding to approximately 42 to 2100 arcsec at a viewing distance of 0.93 m. Each staircase terminated after eight reversals, with the threshold defined as the geometric mean of the last six reversals. Eight reversals were chosen based on pilot testing to balance reliability and task duration in children.

Disparity was implemented as horizontal pixel offsets between the two eyes and converted to visual angle units based on viewing geometry. Because disparity was discretized at integer-pixel resolution, sensitivity at very small disparities was constrained by quantization. On the first training day, participants completed a familiarization block using large disparities to ensure task understanding. In all tasks, responses were made via key press with no response time limit, and auditory feedback was provided following incorrect responses.

Visual Function Assessment

Monocular VA was measured using the Chinese tumbling E chart, which consists of 14 lines with optotype sizes ranging from 1.0 to −0.3 logMAR in 0.1-logMAR steps. Testing was conducted at a viewing distance of 5 meters with the nontested eye occluded. Participants identified the orientation of the optotype opening, and VA was recorded in logMAR units. Stereoacuity was assessed using the Randot Stereotest under standard room illumination. The test consists of contoured circle targets spanning 10 disparity levels, ranging from 400 to 20 arcsec. Participants viewed the test plates at a distance of 40 cm while wearing polarized glasses. Stereoacuity thresholds were recorded in arcsec.

Data Analysis

Training Outcomes. Training-induced improvement was quantified using measure-specific indices. For each task, the first-session and final-session thresholds were defined as the mean thresholds obtained in the first and last training sessions, respectively. For the monocular training tasks, improvement was expressed as the relative change in threshold. Because improved grating acuity corresponds to higher spatial-frequency thresholds, grating acuity improvement was calculated as (final-session threshold − first-session threshold)/first-session threshold. In contrast, because improved motion discrimination corresponds to lower discrimination thresholds, motion discrimination improvement was calculated as (first-session threshold − final-session threshold)/first-session threshold. For the stereopsis training task, improvement was quantified as the reduction in disparity threshold expressed in octave units and calculated as $\log_2$(first-session threshold/final-session threshold), such that a value of 1 indicates that the final threshold was reduced to half of the initial threshold.

Clinical Outcome Measures. For visual function assessments, improvement metrics were defined according to the properties of each measure. VA and interocular differences were calculated as absolute pre–post changes (in logMAR units). Clinical Randot stereoacuity improvement was quantified using the same octave metric: $\log_2$(pretest/post-test). For participants who failed the Randot Stereotest, a value of 500 arcsec was assigned, representing performance below the measurable range. Sensitivity analyses using alternative ceiling values and ordinal approaches yielded comparable results (see Results).

Statistical Analysis. Statistical analyses were performed using JASP 16.3. Within-group pre–post comparisons were conducted using paired-samples *t*-tests. One-sample *t*-tests were used to test whether training-induced changes differed from zero. Between-group differences (monocular vs. stereopsis training) were assessed using independent-samples *t*-tests and mixed-design analyses of variance (ANOVAs). Baseline group comparisons were performed using independent-samples *t*-tests for continuous variables and Fisher's exact tests for categorical variables. Pearson correlation analyses were performed to examine associations among participant characteristics, baseline visual function, and training-induced improvements. False discovery rate (FDR) correction was applied to all correlation analyses to control for multiple comparisons.

Results

Monocular Training

Children assigned to the monocular training group ($n = 23$) completed an average of 28.5 ± 6.5 training sessions targeting the AE. Participants performed either the grating acuity task ($n = 18$) or the motion direction discrimination task ($n = 5$). Figure 2B presents representative learning curves from both tasks, illustrating examples of training-related improvements over the course of practice.

For the grating acuity task, AE grating acuity increased significantly from 18.5 ± 4.0 cpd to 22.6 ± 4.2 cpd ($t_{17} = -7.91$; $P < 0.001$; Cohen's $d = -1.86$; log $BF_{10} = 10.57$) (Fig. 2C). Consistent with this effect, most individual data points were distributed above the unity line (Fig. 2C). The proportional gain was significantly greater than zero, with a mean improvement of 25.0% (SD = 20.2%; $t_{17} = 5.24$; $P < 0.001$; Cohen's $d = 1.24$; log $BF_{10} = 6.01$) (Fig. 2E). For the motion discrimination task, motion thresholds decreased significantly from 22.3° ± 7.8° to 15.0° ± 7.0° ($t_4 = 2.80$; $P = 0.049$; Cohen's $d = 1.25$; log $BF_{10} = 0.82$) (Fig. 2D). The proportional improvement was likewise significantly greater than zero, averaging 32.3% (SD = 21.1%; $t_4 = 3.43$; $P = 0.026$; Cohen's $d = 1.54$; log $BF_{10} = 1.25$) (Fig. 2E). Together, these findings indicate that monocular training produced significant improvements in performance on the trained visual functions.

Stereopsis Training

Children assigned to the stereopsis training group (n = 20) completed an average of 28.9 ± 8.7 training sessions using a mirror stereoscope. On each trial, participants judged whether the upper grating patch appeared nearer or farther relative to a lower zero-disparity reference patch (Fig. 3A). Figure 3D shows representative learning curves from four participants, including three children with no measurable clinical Randot stereoacuity at pre-test and one child with a baseline Randot stereoacuity of 200 arcsec.

Disparity thresholds decreased significantly across training, from 348.2 ± 145.3 arcsec in the first training session to 145.2 ± 29.3 arcsec in the final training session (t_{19} = 6.47; P < 0.001; Cohen's d = 1.45; log BF_{10} = 8.69 (Fig. 3B). Individual data points were predominantly distributed below the unity line, consistent with lower disparity thresholds at the final session. The mean reduction in disparity threshold was 1.15 ± 0.64 octaves, corresponding to a proportional improvement of 50.7% ± 22.4%, both significantly greater than zero (octave change: t_{19} = 8.08; P < 0.001; Cohen's d = 1.81; log BF_{10} = 11.57).

To examine whether learning-related improvements depended on baseline stereo sensitivity, we assessed the relationship between first-session disparity threshold and octave improvement. Baseline thresholds were strongly associated with improvement magnitude (Pearson r = 0.90; P < 0.001; log BF_{10} = 10.43; Spearman ρ = 0.93) (Fig. 3C), indicating that participants with poorer initial stereo sensitivity tended to exhibit larger training-related gains. Together, these results indicate substantial improvements in stereoscopic depth discrimination following stereopsis training.

Visual Acuity and Stereoacuity Changes Following Monocular and Stereopsis Training

Visual Acuity Outcomes. Figure 4 illustrates changes in the two primary clinical outcome measures, VA and Randot stereoacuity, following monocular and stereopsis training. At pre-test, the two groups did not differ significantly in age, AE VA, or Randot stereoacuity (all P > 0.05, independent-samples t-tests), nor in diagnosis type or treatment-related variables (Fisher's exact tests, P = 0.53 and P = 0.76, respectively), indicating comparable baseline characteristics. AE VA improved in both groups following training, but FE VA remained stable. AE VA improved from 0.43 ± 0.04 to 0.23 ± 0.04 logMAR in the monocular group and from 0.42 ± 0.06 to 0.25 ± 0.05 logMAR in the stereopsis group (Fig. 4A).

A three-way mixed ANOVA with time (pre vs. post) and eye (AE vs. FE) as within-subject factors and training type (monocular vs. stereopsis) as a between-subject factor, revealed significant main effects of time ($F_{1,41}$ = 95.75; P < 0.001; η_p^2 = 0.70) and eye ($F_{1,41}$ = 120.30; P < 0.001; η_p^2 = 0.75). Neither the main effect of training type nor any interaction involving training type reached significance (all P > 0.65), indicating comparable VA improvements across groups. Sensitivity analyses excluding newly diagnosed or untreated participants yielded similar results, with no effect of training type (P = 0.46; η_p^2 = 0.02; log BF_{incl} = −0.38) and no significant interaction involving training type (P = 0.77; η_p^2 = 0.003; log BF_{incl} = −0.72).

Within the monocular training group, no difference in VA improvement was observed between the grating acuity and motion discrimination subgroups (P = 0.85; Cohen's d = −0.10; log BF_{10} = −0.83), although this comparison was limited by the small motion subgroup (n = 5).

Interocular VA difference. A two-way mixed ANOVA on interocular acuity difference (IOD) showed a significant main effect of time ($F_{1,41}$ = 89.34; P < 0.001; η_p^2 = 0.69, log BF_{incl} = 20.53), reflecting reduced interocular differences after training. Neither the main effect of training type nor the interaction between time and training type was significant (both P > 0.67) (Fig. 4B). Within the monocular group, no significant difference was observed between training subgroups (P = 0.78; Cohen's d = 0.14; log BF_{10} = −0.82).

Stereoacuity Outcomes. Both groups showed significant improvements in Randot stereoacuity, with greater gains observed in the stereopsis training group. The monocular training group improved by 1.00 ± 1.07 octaves, with mean stereoacuity decreasing from 378.3 ± 38.5 arcsec at baseline to 215.7 ± 36.5 arcsec post-training, corresponding to a 38.0% reduction in the group mean stereoacuity. In comparison, the stereopsis training group improved by 2.38 ± 1.26 octaves, with stereoacuity decreasing from 356.0 ± 184.2 arcsec to 72.5 ± 11.9 arcsec, corresponding to a 73.1% reduction in the group mean stereoacuity (Figs. 4C, 4D). The improvement was significantly greater in the stereopsis training group than in the monocular training group (t_{41} = −3.88; P < 0.001; Cohen's d = −1.19; log BF_{10} = 4.27) (Fig. 4D). Among participants with unmeasurable baseline Randot stereoacuity, 11 of 15 in the monocular group and all 12 in the stereopsis group achieved measurable stereoacuity at post-test.

Sensitivity analyses addressing ceiling effects yielded consistent findings. Excluding participants with unmeasurable baseline stereoacuity reduced statistical significance (P = 0.16), although the estimated effect remained in the same direction (Cohen's d = −0.74; log BF_{10} = −0.15). Analyses using alternative ceiling substitutions (800 and 1000 arcsec) produced consistent results (both P < 0.05; Cohen's d = −0.86 and −0.71, respectively). Similar conclusions were obtained when stereoacuity levels were analyzed as ordinal categories rather than using the numerical threshold value (Mann–Whitney U test, U = 81; P < 0.001; rank-biserial correlation = −0.648).

Exploratory analyses revealed no significant differences in Randot stereoacuity improvement between the grating acuity and motion discrimination training tasks (P = 0.58; Cohen's d = −0.29; log BF_{10} = −0.74), nor between anisometropic and strabismic participants (P = 0.70; Cohen's d = 0.17; log BF_{10} = −0.89). These analyses were limited by small subgroup sizes (motion, n = 5; strabismus, n = 6). Overall, both training approaches produced comparable improvements in VA and interocular balance, whereas stereopsis training yielded substantially greater improvements in clinical stereoacuity.

Correlates of Training-Induced Improvements

To identify factors associated with improvement in the two primary clinical outcome measures (VA and Randot stereoacuity), we examined relationships among participant characteristics, baseline visual function, and training-induced improvements across both training groups. Greater VA improvement was associated with poorer pre-test AE VA (r = 0.34; P = 0.026; log BF_{10} = 1.14) (Fig. 5A). In contrast, VA improvement was not significantly associated

Investigative Ophthalmology & Visual Science

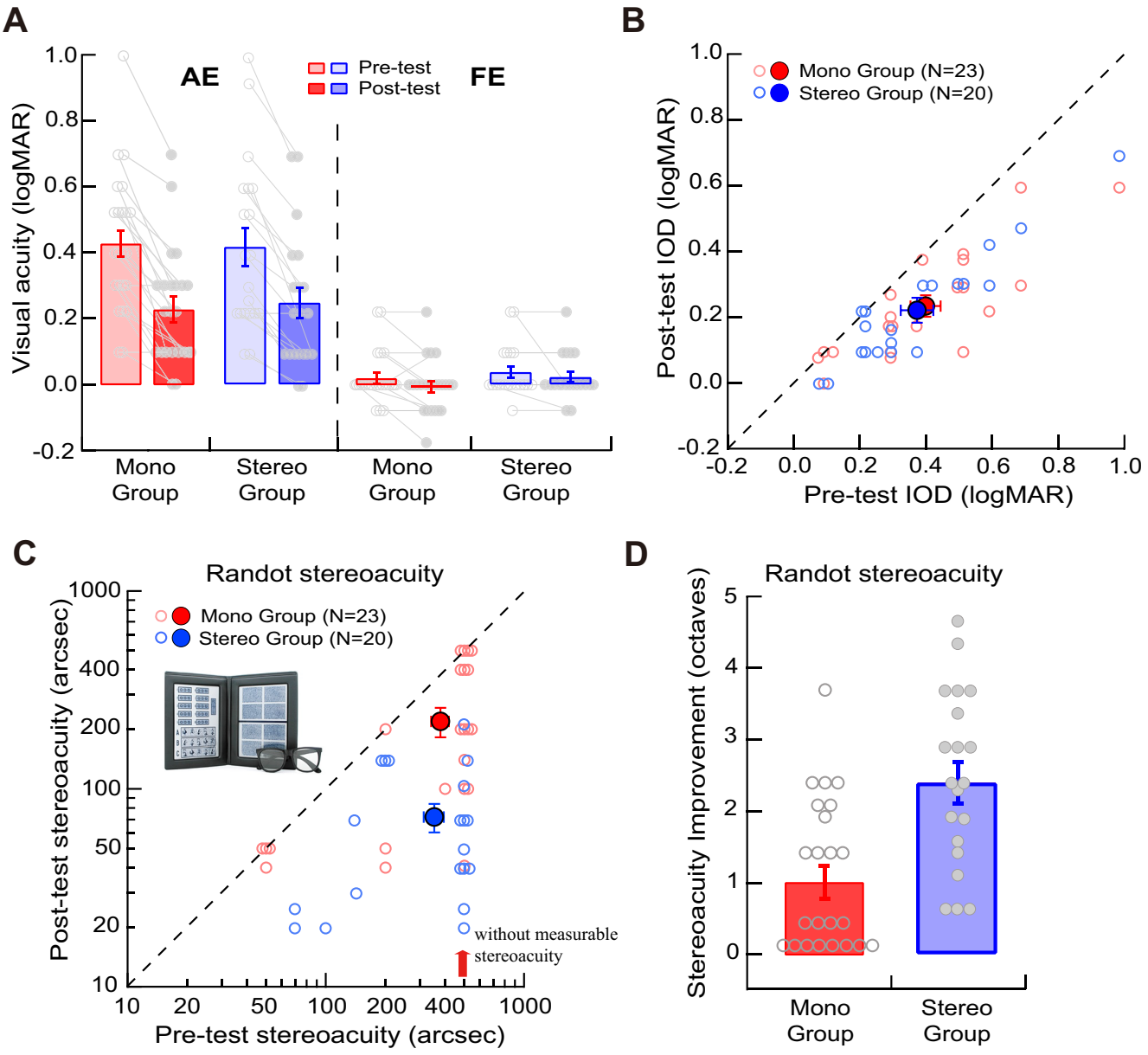

Figure 4. Effects of monocular and stereopsis training on VA and Randot stereoacuity. (**A**) VA (logMAR) of the AE and FE before and after training in the monocular and stereopsis training groups. Individual participants are shown as *circles*, and *lines* connect pre-test and post-test values. (**B**) IOD at pre-test and post-test. Data points below the unity line indicate reduced IOD following training. (**C**) Randot stereoacuity at pre-test and post-test. Data points below the unity line indicate improved stereoacuity (i.e., lower thresholds). Participants who did not achieve measurable stereoacuity on the Randot Stereotest were assigned a value of 500 arcsec, reflecting performance below the measurable range of the test. In **B** and **C**, *large circles* represent group means and *small circles* represent individual participants. (**D**) Randot stereoacuity improvement (octave scale) in the monocular and stereopsis training groups. *Small circles* represent individual participants. *Error bars* indicate ±1 SEM.

with pre-test IOD ($r = -0.26$; $P = 0.089$, log $BF_{10} = 0.21$) (Fig. 5B) or age ($r = -0.17$; $P = 0.27$; log $BF_{10} = -0.53$) (Fig. 5C). Randot stereoacuity improvement (octave scale) was not significantly associated with pre-test AE VA ($r = 0.11$; $P = 0.47$; log $BF_{10} = -0.84$) (Fig. 5D), pre-test IOD ($r = -0.04$; $P = 0.79$; log $BF_{10} = -1.04$) (Fig. 5E), VA improvement ($r = 0.03$; $P = 0.85$; log $BF_{10} = -1.06$) (Fig. 5F), reduction in IOD ($r = 0.09$; $P = 0.57$; log $BF_{10} = -0.93$) (Fig. 5G), or age ($r = 0.15$; $P = 0.34$; log $BF_{10} = -0.67$) (Fig. 5H).

We further examined whether improvement attained during training predicted changes in clinical outcomes. Within the stereopsis training group, training-task improvement was not significantly associated with improvement in either Randot stereoacuity ($r = -0.38$; $P = 0.09$; log $BF_{10} = 0.36$) or VA ($r = 0.16$; $P = 0.50$; log $BF_{10} = -0.56$). Similarly, within the monocular training group, improvement on the training tasks was not significantly associated with improvements in clinical outcome measures (all $P > 0.70$). Because these analyses were exploratory, FDR correction

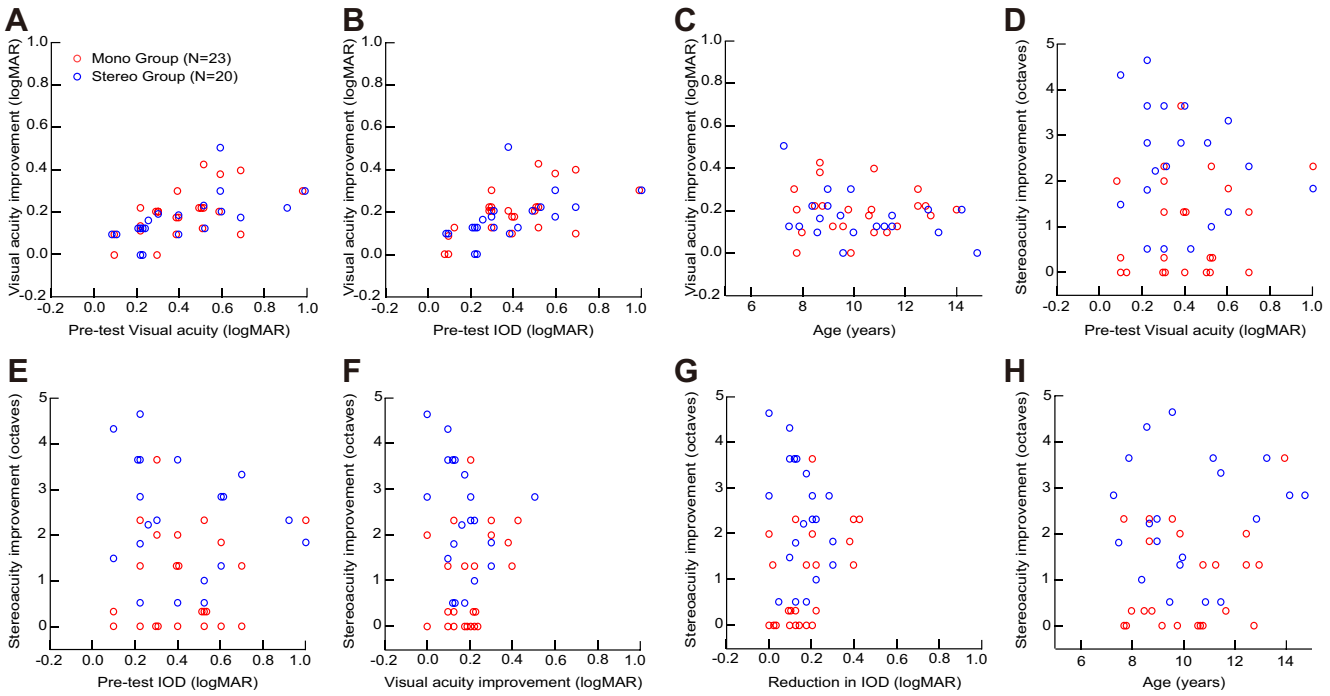

Figure 5. Correlates of training-induced improvements in clinical outcomes. (**A–C**) Improvement in AE VA as a function of pre-test AE VA (**A**), pre-test IOD (**B**), and age (**C**). (**D–H**) Randot stereoacuity improvement, expressed in octave units, $\log_2$(pre-test stereoacuity/post-test stereoacuity), as a function of pre-test AE VA (**D**), pre-test IOD (**E**), AE VA improvement (**F**), IOD reduction (**G**), and age (**H**). Each *circle* represents an individual participant.

was applied. The association between poorer baseline AE VA and greater VA improvement did not survive FDR correction, and no other correlations reached significance after correction.

Discussion

The present study investigated changes in VA and stereoacuity in children with amblyopia who underwent visual training while continuing to receive standard clinical care. Both monocular and stereopsis training were associated with robust task learning and measurable improvements in clinical outcomes. Improvements in AE VA were observed in both groups, whereas larger gains in stereoacuity were observed in children who received stereopsis training. These findings suggest that, when combined with standard clinical care, training approaches that engage binocular processing may provide additional benefits for improving stereoscopic function in amblyopia.

Consistent with a large body of perceptual learning research, both monocular and binocular training improved AE VA.[18] Previous studies have shown that monocular training can enhance multiple aspects of visual function, including positional acuity, grating and letter acuity, and contrast sensitivity, primarily through improvements in visual processing efficiency within the amblyopic visual system.[20,44–46] Our findings extend this literature by demonstrating that stereopsis training, despite specifically targeting binocular processing, can produce VA improvements comparable to those achieved with monocular training. This result is consistent with recent reviews indicating that binocular interventions do not consistently outperform conventional monocular therapies in improving VA.[37–39,47]

One possible explanation is that amblyopia fundamentally reflects abnormal binocular interactions rather than solely a monocular deficit.[10,26] Interocular suppression from the fellow eye weakens the cortical representation of AE inputs and affects both monocular and binocular visual functions.[16] By engaging coordinated processing of disparity signals from the two eyes, stereopsis training may partially rebalance binocular interactions and enhance the effective contribution of AE signals during binocular combination.[27,31,48] Improved binocular balance may, in turn, facilitate more efficient utilization of AE inputs, leading to improvements in VA despite the absence of direct acuity training.[6] Thus, the VA improvements observed following stereopsis training may reflect transfer from binocular processing to monocular visual function, although the mechanisms underlying such transfer remain to be established.

In contrast to the comparable VA gains, stereopsis training produced substantially larger improvements in Randot stereoacuity. This finding is consistent with our previous work demonstrating that dichoptic training in adults with amblyopia yields additional stereoacuity gains beyond monocular training.[25] It also aligns with evidence that stereoscopic three-dimensional video game training produces greater improvements in stereoacuity than comparable two-dimensional training.[49] Neurobiological and psychophysical studies indicate that stereopsis depends on accurate integration of signals from both eyes and is particularly vulnerable to interocular suppression and abnormal disparity processing in amblyopia.[8,26,50–55] By engaging binocular mechanisms involved in stereoscopic perception, stereopsis training may strengthen the contribution of AE inputs to binocular combination and enhance

disparity processing.[21,29,56] This framework may help explain why training approaches that incorporate binocular stimulation appear particularly effective for improving stereoacuity.[40]

Notably, a subset of participants transitioned from unmeasurable to measurable stereoacuity on the Randot test following training. Although post-training stereoacuity in these participants generally remained relatively coarse, such transitions may nevertheless indicate clinically meaningful gains in stereoscopic function. Given the discrete disparity levels of the Randot test, some degree of measurement variability cannot be excluded, and these findings should therefore be interpreted with caution. However, the consistency of this pattern across both training groups argues against random measurement variability as the sole explanation. Consistent with the possibility that training-related improvements reflect enhanced binocular function, our previous work demonstrated that dichoptic de-masking training improved, and in some cases restored, stereoacuity in amblyopic children despite relatively limited changes in interocular acuity difference.[30] Together, these findings suggest that improvements in stereoacuity may reflect enhanced binocular processing, although the specific mechanisms remain to be determined.

Exploratory analyses did not identify reliable predictors of treatment response. Although poorer baseline AE VA was associated with larger VA gains at the uncorrected level, this association did not remain significant after correction for multiple comparisons. Similarly, stereoacuity improvement was not significantly related to baseline VA, interocular acuity difference, age, or changes in VA. In addition, learning attained during stereopsis training was not significantly associated with improvements in Randot stereoacuity. This lack of association may reflect differences between the training task and the Randot assessment in stimulus characteristics and measurement properties, such that they capture partially distinct aspects of stereoscopic processing. Alternatively, the present study may have had limited power to detect modest relationships between training-task learning and transfer to clinical measures. Although these analyses did not identify robust predictors of improvement, the overall pattern is consistent with the possibility that monocular and binocular deficits represent partially distinct aspects of amblyopia. Within this framework, gains in VA may depend more strongly on improvements in AE visual sensitivity, whereas gains in stereoacuity may rely on binocular mechanisms that are not fully reflected in conventional monocular clinical measures.[29]

These findings have several potential clinical implications. Participants continued to receive standard clinical treatment throughout the training period, including patching therapy, optical correction, or both. Consequently, the observed improvements likely reflect the combined effects of conventional clinical management and visual training rather than the independent efficacy of either component. Within this context, both training approaches were associated with significant improvements in AE VA, supporting the potential utility of perceptual learning-based interventions as adjunctive therapies. Notably, stereopsis training was associated with greater improvements in stereoacuity than monocular training under the same clinical conditions, suggesting additional benefits for residual binocular deficits that often persist despite conventional treatment.[14–37] Although binocular training may not be sufficient as a standalone intervention, combining binocular training with established clinical therapies may provide a more comprehensive rehabilitation approach, particularly for children who achieve satisfactory VA but continue to exhibit impaired stereopsis.[40]

Several limitations should be considered. First, participants continued to receive individualized clinical management during the training period, including optical correction and patching when clinically indicated. Because these treatments were not experimentally controlled, the present study cannot disentangle the effects of visual training from those of concurrent clinical care. This, together with the relatively short training duration and the absence of long-term follow-up, limited our ability to evaluate the durability of the observed improvements and the independent efficacy of the training paradigms. Second, most participants had anisometropic amblyopia, with relatively few cases of strabismic or mixed amblyopia. Although the two training groups were well matched at baseline, the predominance of anisometropic cases and the modest sample size may limit the generalizability of the findings and reduce statistical power to detect subtype-specific effects. Third, although the training protocols were based on previously validated paradigms[20,31,43] and employed a common adaptive staircase procedure, the tasks differed in their visual demands. In addition, differences in stimulus parameters and viewing distance across tasks may have introduced varying accommodative and vergence requirements,[57,58] which should be considered when interpreting differences in training effects. Finally, the mechanisms underlying training-related improvements in stereoacuity remain incompletely understood. Interocular acuity difference was used as an indirect index of binocular imbalance, but changes in this measure were not significantly associated with stereoacuity improvement. Moreover, neither interocular suppression nor eye movements, including vergence responses, were directly measured. As a result, the relative contribution of different binocular mechanisms to the observed improvements remains unclear. Future studies incorporating larger samples, controlled treatment protocols, extended follow-up periods, and direct assessments of interocular suppression and eye movements will be important for clarifying both the mechanisms and long-term efficacy of binocular training.

Acknowledgments

The authors extend their gratitude to Jian Ding for providing the experimental stimulus programs used in the stereopsis training task. We also thank Dennis Levi and Cong Yu for their insightful comments and valuable discussions. Our appreciation goes to Ms. Chao Man and Ms. Jing Liu for their assistance in data collection. Finally, we sincerely thank the participating children and their parents for their time and contributions to this study.

Supported by grants from the Natural Science Foundation of China (32371097 and 31970978 to JYZ) and the XZHMU-QL Joint Research Fund (QL-YB069 to XYL).

Disclosure: **Y.-R. Chen**, None; **P.-X. Li**, None; **H.-F. Zhang**, None; **X.-Y. Liu**, None; **J.-Y. Zhang**, None

References

1. Holmes JM, Clarke MP. Amblyopia. *Lancet*. 2006;367(9519):1343–1351.

2. Webber AL, Wood J. Amblyopia: prevalence, natural history, functional effects and treatment. *Clin Exp Optom*. 2005;88(6):365–375.
3. Pai A, Mitchell P. Prevalence of amblyopia and strabismus. *Ophthalmology*. 2010;117(10):2043–2044; author reply, 2044.
4. Barrett BT, Bradley A, McGraw PV. Understanding the neural basis of amblyopia. *Neuroscientist*. 2004;10(2):106–117.
5. Webber AL. The functional impact of amblyopia. *Clin Exp Optom*. 2018;101(4):443–450.
6. Levi DM. Rethinking amblyopia 2020. *Vision Res*. 2020;176:118–129.
7. Chino YM, Bi H, Zhang B. Normal and abnormal development of the neuronal response properties in primate visual cortex. In: Kaas J, Collins C, eds. *The Primate Visual System*. Boca Raton, FL: CRC Press; 2004.
8. Kiorpes L. Visual processing in amblyopia: animal studies. *Strabismus*. 2006;14(1):3–10.
9. Maurer D, McKee SP. Classification and diversity of amblyopia. *Vis Neurosci*. 2018;35:E012.
10. Birch EE. Amblyopia and binocular vision. *Prog Retin Eye Res*. 2013;33:67–84.
11. Wen W, Wang Y, Zhou J, et al. Loss and enhancement of layer-selective signals in geniculostriate and corticotectal pathways of adult human amblyopia. *Cell Rep*. 2021;37(11):110117.
12. Williams C. Amblyopia. *BMJ Clin Evid*. 2009;2009:0709.
13. Lee SY, Isenberg SJ. The relationship between stereopsis and visual acuity after occlusion therapy for amblyopia. *Ophthalmology*. 2003;110(11):2088–2092.
14. Wallace DK, Lazar EL, Melia M, et al. Stereoacuity in children with anisometropic amblyopia. *J AAPOS*. 2011;15(5):455–461.
15. Wang J. Compliance and patching and atropine amblyopia treatments. *Vision Res*. 2015;114:31–40.
16. Hess RF, Thompson B, Baker DH. Binocular vision in amblyopia: structure, suppression and plasticity. *Ophthalmic Physiol Opt*. 2014;34(2):146–162.
17. Narasimhan S, Harrison ER, Giaschi DE. Quantitative measurement of interocular suppression in children with amblyopia. *Vision Res*. 2012;66:1–10.
18. Levi DM, Li RW. Perceptual learning as a potential treatment for amblyopia: a mini-review. *Vis Res*. 2009;49(21):2535–2549.
19. Birch EE, Kelly KR, Wang JY. Recent advances in screening and treatment for amblyopia. *Optthalmol Ther*. 2021;10(4):815–830.
20. Liu X-Y, Zhang T, Jia Y-L, Wang N-L, Yu C. The therapeutic impact of perceptual learning on juvenile amblyopia with or without previous patching treatment. *Invest Ophthalmol Vis Sci*. 2011;52(3):1531–1538.
21. Levi DM, Knill DC, Bavelier D. Stereopsis and amblyopia: a mini-review. *Vision Res*. 2015;114:17–30.
22. Astle AT, McGraw PV, Webb BS. Recovery of stereo acuity in adults with amblyopia. *BMJ Case Rep*.2011;2011:bcr0720103143.
23. Ooi TL, Su YR, Natale DM, He ZJ. A push–pull treatment for strengthening the 'lazy eye' in amblyopia. *Curr Biol*. 2013;23(8):R309–R310.
24. Hess RF, Mansouri B, Thompson B. A binocular approach to treating amblyopia: antisuppression therapy. *Optom Vis Sci*. 2010;87(9):697–704.
25. Liu XY, Zhang JY. Dichoptic training in adults with amblyopia: additional stereoacuity gains over monocular training. *Vision Res*. 2018;152:84–90.
26. Hess RF, Thompson B. Amblyopia and the binocular approach to its therapy. *Vision Res*. 2015;114:4–16.
27. Li J, Thompson B, Deng D, Chan LYL, Yu M, Hess RF. Dichoptic training enables the adult amblyopic brain to learn. *Curr Biol*. 2013;23(8):R308–R309.
28. Alrasheed SH, Aldakhil S. Childhood amblyopia: a systematic review of recent management options. *Saudi J Ophthalmol*. 2024;38(3):201–213.
29. Levi DM. Learning to see in depth. *Vision Research*. 2022;200:108082.
30. Liu X-Y, Zhang Y-W, Gao F, Chen F, Zhang J-Y. Dichoptic perceptual training in children with amblyopia with or without patching history. *Invest Ophthalmol Vis Sci*. 2021;62(6):4.
31. Ding J, Levi DM. Recovery of stereopsis through perceptual learning in human adults with abnormal binocular vision. *Proc Natl Acad Sci USA*. 2011;108(37):E733–E741.
32. Vedamurthy I, Knill DC, Huang SJ, et al. Recovering stereo vision by squashing virtual bugs in a virtual reality environment. *Philos Trans R Soc Lond B Biol Sci*. 2016;371(1697):20150264.
33. Xi J, Jia W-L, Feng L-X, Lu Z-L, Huang C-B. Perceptual learning improves stereoacuity in amblyopia. *Invest Ophthalmol Vis Sci*. 2014;55(4):2384–2391.
34. Li RW, Antonucci MM, Li B, Yanyin C, Chat SW, Levi DM. Towards establishing a novel stereoscopic treatment for childhood amblyopia using 3-dimensional video games. *Invest Ophthalmol Vis Sci*. 2023;64(8):1450.
35. Li RW, Tran KD, Bui JK, Antonucci MM, Ngo CV, Levi DM. Improving adult amblyopic vision with stereoscopic 3-dimensional video games. *Ophthalmology*. 2018;125(10):1660–1662.
36. Asensio-Jurado L, Argilés M, Quevedo-Junyent L, Levi DM. Emerging therapies for improving stereoacuity in amblyopia. A systematic review and meta-analysis. *Vision Res*. 2026;239:108717.
37. Pineles SL, Aakalu VK, Hutchinson AK, et al. Binocular treatment of amblyopia: a report by the American Academy of Ophthalmology. *Ophthalmology*. 2020;127(2):261–272.
38. Roda M, Pellegrini M, Di Geronimo N, Vagge A, Fresina M, Schiavi C. Binocular treatment for amblyopia: a meta-analysis of randomized clinical trials. *PLoS One*. 2021;16(10):e0257999.
39. Tang AC, Wang X, Yang WJ, et al. Comparison between dichoptic and monocular training protocols for treating monocular amblyopia: a meta-analysis and systematic review. *Ophthalmic Epidemiol*. 2025;32(6):769–783.
40. Tsani Z, Ioannopoulos D, Androudi S, Dardiotis E, Papageorgiou E. Binocular treatment for amblyopia: a systematic review. *Int Ophthalmol*. 2024;44(1):362.
41. Pelli DG. The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision*. 1997;10(4):437–442.
42. Brainard DH. The Psychophysics Toolbox. *Spat Vis*. 1997;10(4):433–436.
43. Wang R, Wang J, Zhang J-Y, et al. Perceptual learning at a conceptual level. *J Neurosci*. 2016;36(7):2238–2246.
44. Li RW, Levi DM. Characterizing the mechanisms of improvement for position discrimination in adult amblyopia. *J Vis*. 2004;4(6):476–487.
45. Zhang J-Y, Cong L-J, Klein SA, Levi DM, Yu C. Perceptual learning improves adult amblyopic vision through rule-based cognitive compensation. *Invest Ophthalmol Vis Sci*. 2014;55(4):2020–2030.
46. Verghese P, McKee SP, Levi DM. Attention deficits in amblyopia. *Curr Opin Psychol*. 2019;29:199–204.
47. Tsirlin I, Colpa L, Goltz HC, Wong AMF. Behavioral training as new treatment for adult amblyopia: a meta-analysis and systematic review. *Invest Ophthalmol Vis Sci*. 2015;56(6):4061–4075.

48. Hess RF, Mansouri B, Thompson B. A new binocular approach to the treatment of amblyopia in adults well beyond the critical period of visual development. *Restor Neurol Neurosci*. 2010;28(6):793–802.
49. Li RW, Li BZ, Chat SW, Patel SS, Chung STL, Levi DM. Playing three-dimensional video games boosts stereo vision. *Curr Biol*. 2024;34(11):R524–R525.
50. Farivar R, Thompson B, Mansouri B, Hess RF. Interocular suppression in strabismic amblyopia results in an attenuated and delayed hemodynamic response function in early visual cortex. *J Vis*. 2011;11(14):16.
51. Kiorpes L. Understanding the development of amblyopia using macaque monkey models. *Proc Natl Acad Sci USA*. 2019;116(52):26217–26223.
52. Acar K, Kiorpes L, Movshon JA, Smith MA. Altered functional interactions between neurons in primary visual cortex of macaque monkeys with experimental amblyopia. *J Neurophysiol*. 2019;122(6):2243–2258.
53. Bi H, Zhang B, Tao X, Harwerth RS, Smith EL, 3rd, Chino YM. Neuronal responses in visual area V2 (V2) of macaque monkeys with strabismic amblyopia. *Cerebral Cortex*. 2011;21(9):2033–2045.
54. Wang Y, Zhang B, Tao X, Wensveen JM, Smith EL, 3rd, Chino YM. Noisy spiking in visual area V2 of amblyopic monkeys. *J Neurosci*. 2017;37(4):922–935.
55. Parker AJ. Binocular depth perception and the cerebral cortex. *Nat Rev Neurosci*. 2007;8(5):379–391.
56. Levi DM. Applications and implications for extended reality to improve binocular vision and stereopsis. *J Vis*. 2023;23(1):14.
57. Manh V, Chen AM, Tarczy-Hornoch K, Cotter SA, Candy TR. Accommodative performance of children with unilateral amblyopia. *Invest Ophthalmol Vis Sci*. 2015;56(2):1193–1207.
58. Lew WH, Stevenson SB, Coates DR. Stimulus dependence of interocular suppression. *Sci Rep*. 2021;11(1):9309.

Investigative Ophthalmology & Visual Science