Perceptual Learning Improves Stereoacuity in Amblyopia

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Purpose. Amblyopia is a developmental disorder that results in both monocular and binocular deficits. Although traditional treatment in clinical practice (i.e., refractive correction, or occlusion by patching and penalization of the fellow eye) is effective in restoring monocular visual acuity, there is little information on how binocular function, especially stereopsis, responds to traditional amblyopia treatment. We aim to evaluate the effects of perceptual learning on stereopsis in observers with amblyopia in the current study.

Methods. Eleven observers (21.1 ± 5.1 years, six females) with anisometropic or ametropic amblyopia were trained to judge depth in 10 to 13 sessions. Red–green glasses were used to present three different texture anaglyphs with different disparities but a fixed exposure duration. Stereoacuity was assessed with the Fly Stereo Acuity Test and visual acuity was assessed with the Chinese Tumbling E Chart before and after training.

Results. Averaged across observers, training significantly reduced disparity threshold from 776.7″ to 490.4″ ($P < 0.01$) and improved stereoacuity from 200.3″ to 81.6″ ($P < 0.01$). Interestingly, visual acuity also significantly improved from 0.44 to 0.35 logMAR (approximately 0.9 lines, $P < 0.05$) in the amblyopic eye after training. Moreover, the learning effects in two of the three retested observers were largely retained over a 5-month period.

Conclusions. Perceptual learning is effective in improving stereo vision in observers with amblyopia. These results, together with previous evidence, suggest that structured monocular and binocular training might be necessary to fully recover degraded visual functions in amblyopia.

Keywords: perceptual learning, stereoacuity, amblyopia

弱视的立体视知觉学习

席洁，贾武力，封利霞，吕忠林，黄昌兵

目的：弱视是导致单眼和双眼视力降低的一种常见眼科疾病。弱视的传统治疗方式有光学矫正和“遮盖”疗法，这些方法能有效的恢复弱视患者的单眼视锐度，但是对双眼视觉功能特别是立体视的恢复并不理想。本研究考察了知觉学习对弱视患者立体视功能恢复的可能作用。

方法：研究被试为 11 名屈光参差性或屈光不正性弱视被试（21.1±5.1 岁，5 男 6 女）。知觉训练使用的刺激为进行红绿互补处理的三张纹理图片。训练中，刺激以固定时间在屏幕上呈现，要求被试佩戴红绿眼镜并完成深度判断任务。训练前后使用 Titmus 立体视检查图测量被试的立体视锐度，并使用 E 视力表检查被试的视锐度。

结果：训练显著降低了 11 名弱视被试的视差辨别阈值（平均从 776.7″ 降低到 490.4″），Titmus 测量表明立体视锐度也显著提高（从 200.3″ 到 81.6″）。立体视训练还可在一定程度上改善弱视眼的视锐度（平均 0.9 行）。对 3 名被试的追踪研究表明，立体视锐度和视锐度的改善可维持至少 5 个月。

结论：本研究结果证明知觉学习能够改善弱视的立体视功能。研究结果还提示，研究者应考虑同时使用单眼和双眼视觉功能训练以全面恢复弱视被试的视觉功能。

Amblyopia, defined as degradation of spatial vision in the absence of any detectable structural or pathologic ocular abnormalities, is a developmental disorder that is caused by early abnormal visual experiences, specifically a lack of coordinated and balanced registration between the images in the two eyes, most commonly due to uncorrected strabismus, anisometropia, or cataract-induced form deprivation.[1,2] Amblyopia impacts not only monocular vision, such as visual acuity,[3–5] vernier acuity,[5–7] contrast sensitivity,[3,8–10] spatial distortion,[4,11,12] and spatial interactions,[7,13,14] but also binocular functions, including binocular combination,[15–18] interocular interaction,[19–21] and stereopsis.[22–24]

Although early administrations of conventional refractive corrections, patching, Bangerter filters, or atropine penalization over the fellow eye are effective in restoring monocular visual acuity in young children with amblyopia, their effects on restoring binocular functions are mixed in young and older children with amblyopia.[25–29] Several studies have reported that occlusion or refractive correction itself can induce improved stereoacuity only in a subset of amblyopic subjects.[25,26,29] For example, Stewart et al.[26] recently investigated changes of stereoacuity in patients receiving amblyopia treatments comprised by refractive adaptation and occlusion phases. They found that 38% of their patients who received refractive adaptation and 29% who received occlusion improved their stereoacuity by at least one octave. However, other studies reported failed attempts to normalize binocular functions in amblyopia.[27,28] For example, Wallace et al.[28] found that 248 children (3- to 13-years old) with anisometropic amblyopia showed subnormal stereoacuity after conventional treatment (patching or Bangerter filters), although their visual acuities improved to normal or near-normal levels. Scheiman et al.[27] found that deficient binocular function cannot be improved by patching or application of atropine sulfate in the fellow eye among 7- to 12-year-old children.

In the present study, we attempted to improve degraded stereo vision in observers with anisometropic or ametropic amblyopia through perceptual learning. Although it is known that stereopsis is critical for human visual perception, such as perceiving the three-dimensional (3D) layout of our surroundings, reading, hand–eye coordination, and camouflaged object detection,[30–32] attempts to directly improve stereopsis in amblyopia have been astonishingly scarce.

In the past decades, many studies found that training or practice of a specific visual task can improve performance of amblyopes in a variety of low-level visual tasks, including contrast detection with[33] and without flankers,[34,35] identification of contrast-defined and luminance-defined letters,[36,37] and positional acuity.[38,39] These effects of perceptual learning demonstrate substantial plasticity in the child and even adult brain.[40] While significant perceptual learning of stereopsis has been well documented in adults with normal vision,[41–44] improvement of stereopsis in amblyopes has been mostly evaluated following perceptual learning of other tasks.[39,45–50] For example, Hess et al.[51] found that, stereopsis was established after intensive training of dichoptic motion coherence discrimination in eight out of nine adult strabismic amblyopes. Li et al.[39] also found that two amblyopic children, one with strabismus and the other with anisometropia, who had no gross stereopsis at the beginning of their study, demonstrated measurable stereopsis after intensive monocular training on a position-discrimination task.

Two recent studies employed paradigms that directly targeted stereoacuity to evaluate the potential of perceptual learning in restoring stereo vision in amblyopia. Ding and Levi[52] trained one adult with anisometropic amblyopia and three adults with strabismic amblyopia, who were all stereoblind or stereoanomalous before training, to perform a stereo-depth judgment task with sine-wave gratings. After training, all subjects showed significant improvement in stereopsis in psychophysical tests although their monocular vernier acuities remained unchanged. Astle et al.[53] performed a case study on two adult anisometropic amblyopes with initial monocular training (to improve visual acuity in the amblyopic eye) and then stereo training. They reported that 9 days of detecting depth in random dot stereograms (RDS) improved stereoacuity to the normal level in both subjects. Interestingly, the improvement in stereoacuity was established independently of visual acuity amelioration. These results, together with the reported failure to normalize binocular functions in amblyopia after treatment focusing on monocular vision,[27,28] suggest that different treatments might be necessary to recover both stereoacuity and visual acuity in adult amblyopia.

In the present study, we trained stereo depth perception in 11 observers with anisometropic amblyopia or amblyopia associated with high ametropia. High ametropia was defined as hypermetropia greater than 5 diopters (D) or astigmatism greater than 2 D in the absence of anisometropia or strabismus.[54] Seven of the observers were novice and the other four received prior monocular contrast detection training. We used red–green glasses to present texture anaglyphs with different disparities but fixed exposure duration to the two eyes and trained subjects to detect stereo depth with feedback. Stereoacuity and visual acuity of both eyes were measured and compared before and after training. We focused on anisometropic or ametropic amblyopes because they are the predominant group, and other types of amblyopia (e.g., strabismic amblyopia), may be rather different in terms of the underlying mechanisms.[6,51,55] Our aim was to evaluate the effects of our training method (e.g., anaglyphs made of textures and displayed with a fixed-duration) on stereo vision and visual acuity in adults with anisometropic or ametropic amblyopia.

METHODS

Observers

The 11 participants in this experiment were 11- to 27-year-old (21.1 ± 5.1 years) observers with natural-occurring anisometropic or ametropic amblyopia. Among them, four observers (A1–A4) received monocular training prior to the study[34]; the other seven (A5–A11) were novice observers. All 11 observers wore glasses in their daily life (at least 1 year), five of which were prescribed by the third author of the paper (L-XF) and the other six by other doctors/experienced optometrists. Before they took part in the experiment, the third author (L-XF) carefully diagnosed them for potential ocular pathological defects and strabismus, and determined their refraction through mydriatic optometry (under cycloplegia). Corrective lens were prescribed based on their refraction and subjective trial of lens, if necessary. Subjects A3 and A6 were prescribed new glasses and wore the new glasses for at least 1 week before data collection. All other subjects wore their own glasses. The corneal light reflex test, cover–uncover test and alternate cover test were used to assess the patients' ocular alignment. Tropia or phoria was not found among these subjects. Detailed characteristics of these observers, including their sex, age, optical correction, and corrected visual acuity are listed in Table 1. None of the 11 observers had previous experience with stereograms made of anaglyph images and stereo training. All observers wore their corrective lenses during training.

We also trained five normal observers for 10 sessions with the same task and setups to assess whether training can also reduce disparity threshold in normal vision. The five observers went through the same screening examination as the

Table 1. Observer Characteristics

Observer	Sex	Age, y	Treatment History	Eye	Correction	Acuity, logMAR	Exposure Time, s
A1*	F	16	Glasses for 1 y, no patching	AE (R)	+3.50 DS	0.62	5
				DE (L)	−1.00 DS	−0.10	
A2*	F	17	Glasses for 8 y, no patching	AE (L)	+7.00 DS/+1.5 DC × 90	0.66	2.5
				DE (R)	+1.25 DS	−0.22	
A3*	M	20	Glasses for 10 y, no patching	AE (L)	+5.00 DS	0.28	1
				DE (R)	−1.75 DS	−0.16	
A4*	M	11	Glasses for 2 y, patching for 2 y	AE (L)	+3.00 DS/+2.00 DC × 90	0.26	2
				DE (R)	+3.00 DS/+2.00 DC × 85	−0.10	
A5	M	19	Glasses for 4 y, no patching	AE (R)	+9.00 DS/+0.37 DC × 90	0.45	3
				DE (L)	+10.00 DS/+0.50 DC × 95	0.18	
A6	F	27	Glasses for 4 y, no patching	AE (R)	−3.50 DS	0.38	5
				DE (L)	−2.50 DS	0	
A7	M	24	Glasses for 12 y, patching duration unknown	AE (L)	2.74 DS/+1.5 DC	0.30	0.1
				DE (R)	0	−0.05	
A8	F	21	Glasses for 13 y, patching from age 8, duration unknown	AE (L)	+5.00 DS	0.30	1
				DE (R)	+1.00 DS	−0.10	
A9	F	25	Glasses for 12 y, no patching	AE (R)	+4.00 DS/+0.50 DC × 90	0.72	0.3
				DE (L)	0.50 DC × 90	−0.10	
A10	F	25	Glasses for 3 y, no patching	AE (L)	+1.25 DS/+1.25 DC × 90	0.36	2
				DE (R)	0	−0.22	
A11	M	27	Glasses for 9 y, no patching	AE (R)	+4.50 DS	0.48	0.5
				DE (L)	−2.75 DS	0.08	

Exposure Time: exposure duration of the two anaglyph images, derived from a pilot experiment (see Methods). Visual acuity was assessed with crowded Chinese Tumbling E chart. The stimuli were presented binocularly and the exposure time was the same for both eyes. AE, amblyopic eye; DE, dominant eye; L, left eye; R, right eye.

* These four observers had monocular training experience before the stereo experiment.

amblyopic group did. They did not have any organic ocular disease and had normal or corrected-to-normal visual acuity and stereoacuity. Briefly, disparity threshold decreased from 914.0″ to 262.0″, a reduction of 74.0% (SE: ±16.5%) averaged across the observers. Please refer to the Supplementary Material for detailed characteristics of these observers, their improvements, and learning curves.

The research protocol was approved by the ethics committee of the Institute of Psychology, Chinese Academy of Sciences (Beijing, China) and all research activities adhered to the tenets of the Declaration of Helsinki. Informed written consent was obtained from all observers before the experiment.

Apparatus and Stimuli

The experiments were controlled by a desktop computer running Visual C++ (Microsoft, Inc., Redmond, WA, USA). The stimuli were presented on a SONY G520 color monitor (P22 phosphor; Sony, Tokyo, Japan) driven by the internal graphics card of the computer with a spatial resolution of 1600 × 1200 pixels and a refresh rate of 75 Hz. At a viewing distance of 100 cm, each pixel subtends 41.3″. Observers wore red–green anaglyph glasses which only passed red patterns in the stimuli to the left eye and green patterns to the right eye.

The stimuli used in this experiment were three different textures (18.36° × 2.75°; Fig. 1A). We started with black and white textures with pixel gray levels at 150 ± 46.43, 113 ± 52.74, 94 ± 57.41 (mean ± SD). To generate anaglyphs, we removed the blue component of the textures in a pixel-wise fashion, dissected the remaining texture into the red and green components, and shifted the red component relative to its green counterpart according to the desired disparity.

In a given trial, one texture was selected randomly and displayed in two locations, one above and one below the fixation point (radius = 0.11°; Fig. 1B). Images in the two

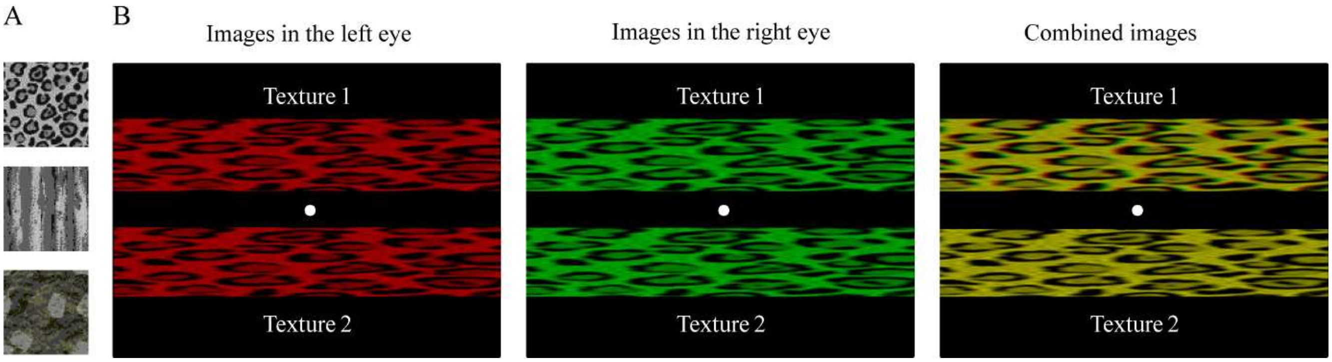

Figure 1. **(A)** Three textures used in the experiment. **(B)** Schematic illustration of stereo training task. In this example, the *red* component of the upper texture was shifted to right relative to its *green* counterpart to create an uncrossed disparity; the lower texture has zero disparity. The correct response is to press the down key in the keyboard to indicate the lower texture is the nearer one.

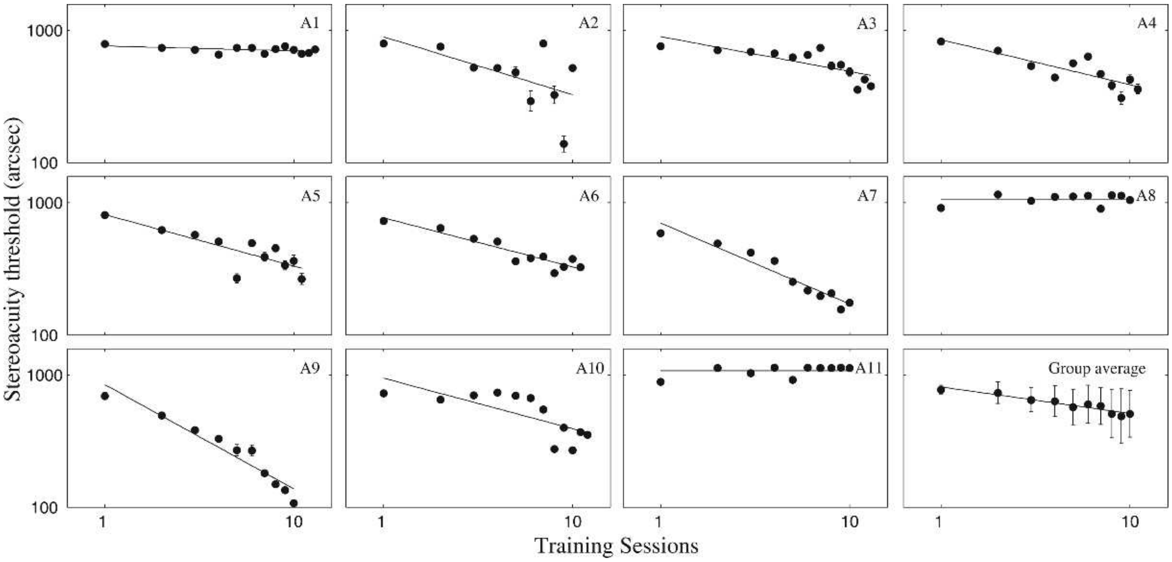

Figure 2. Individual and group average learning curves. Stereo training significantly reduced disparity threshold for 9 of 11 amblyopic observers over 10 to 13 training sessions. The group data were computed by averaging across the 10 common sessions of the 11 observers. Data were fitted with a Log-linear function. *Error bars*: ±1 SE.

locations were both red–green anaglyphed but disparity, either crossed or uncrossed, was only endowed to the anaglyph in one of the two locations. The fixation dot and one of the two images (zero-disparity) were referred as the zero planes. Each anaglyph was trimmed to eliminate edges that contain information from only one eye when the two anaglyphs are combined in binocular vision. Observers were asked to indicate which one of the two textures appeared to be nearer and respond with the up or down key on the keyboard. During training, a brief tone followed each correct response. The response also initiated the next trial. Three textures were presented randomly with the constraint that no more than three consecutive trials used the same texture.

Design and Procedure

The experiment consisted of pretraining assessment, stereopsis training at one exposure duration and posttraining assessment. We also conducted a follow-up test of stereoacuity and visual acuity in three observers 5 months after posttraining assessment.

In both pre- and posttraining assessments, stereoacuity and visual acuity were measured for all observers. Stereoacuity was assessed with the Fly Stereo Acuity Test. Two versions of the Titmus Fly Test were used, one with 10 circles ranging from 800 to 40 arcsecs (Stereo Fly SO-001; Stereo optical Co., Inc., Chicago, IL, USA) for observers A1, A2, A3, A5, and A6, and the other with 10 circles ranging from 400 to 20 arcsecs (Fly Stereo Acuity Test; Vision Assessment Corporation, Elk Grove Village, IL, USA) for the other six subjects. We administered the tests according to the manufacture's guidance and lessons learned from the literature. In a bright room (without direct lighting on the testing material), subjects looked directly at the test material at a viewing distance of 40 cm (strictly tape measured). Subjects were first made familiar with the task using the easiest fly of 3000″ and then reported which circle was out of the plane of the other three (zero plane) in turn (easy–hard). Lighting level was kept almost the same across tests. We confirmed that subjects relied on stereopsis to accomplish the test by rotating the testing material by 90° in three subjects. Visual acuity was assessed with the Chinese Tumbling E Chart,[56] which has 14 lines, with the size of the optotypes ranging from 1 to –0.3 logMAR and changing by 0.1 log unit from line to line. Subjects were required to report the orientation (the opening) of the letter "E." Visual acuity is defined as the logMAR associated with 75% correct identification. The order of tests in the pre- and posttraining measurements was counterbalanced.

Before training, we conducted a pilot experiment to determine the suitable exposure duration for each observer. We varied the exposure duration of the three anaglyphs from 10, 5, 4, 3, 2.5, 2, 1.5, 1, 0.5, 0.3, to 0.1 second in a descending order and obtained rough estimates of the disparity thresholds with approximately 50 trials in each condition. We then chose the exposure duration that corresponded to a disparity threshold around 0.23° (20 pixels) as the display duration during training. The disparity of 0.23° was chosen because the stereo task was demanding but still accomplishable in that condition, leaving enough room for subjects to improve. The display duration for each observer was listed in Table 1. The same task was used in the pilot and training experiments.

Stereo training took an average of 11 sessions (ranged from 10–13, 1 session/d; 8–60 min/session), during which the exposure time was fixed while disparity was changed based on observers' performance. Each training session consisted of three 80-trial blocks. In each block, disparity threshold was measured by a two-down, one-up staircase procedure in which two consecutive correct responses resulted in a reduction of disparity [$D_{n+1} = 0.9\ D_n$] and one wrong response resulted in an increase in disparity [$D_{n+1} = 1.1\ D_n$], converging to a performance level of 70.7% correct. All disparities were expressed in units of pixels and rounded to their closest integer values. A reversal resulted when the staircase changed its direction (changing from increasing to decreasing disparity or vice versa). According to standard psychophysical practice, the first three (if there were an odd number of total reversals) or four (if even) reflections were discarded and the average of the remaining reversals were taken as the threshold. The starting disparity was set at 20 pixels (0.23°) for the first session. It was set as the threshold of the previous session in subsequent sessions.

Table 2. Pre- and Posttraining Titmus Stereoacuity

				Retention*	
Observer	**Pre**	**Post**	**Improvement, %**	**Retest**	**%**
A1†	400″	200″	50.0	300″	66.7
A2†	140″	80″	42.9	80″	100
A3†	140″	100″	28.6	67″	148
A4†	100″	20″	80		
A5	200″	100″	50.0		
A6	400″	200″	50.0		
A7	100″	25″	75		
A8	63″	20″	68.3		
A9	100″	20″	80		
A10	160″	63″	60.6		
A11	400″	50″	87.5		

* Retention after 5 months for three retested observers.

† These four observers had previous monocular training experience.

Table 3. Pre- and Posttraining Visual Acuity

		Visual Acuity, logMAR						
			Monocular Training		Stereo Training		Retention*	
Observer	**Eye**	**Initial**	**Post**	**Imp, %**	**Post**	**Imp, %**	**Retest**	**%**
A1†	AE	0.85	0.62	40.8	0.57	11.9	0.54	105.7
	DE	0.08	−0.10	33.3	−0.16	12.5	−0.16	100
A2†	AE	0.85	0.66	35.2	0.56	21.7	0.57	97.3
	DE	−0.16	−0.22	14.3	−0.16	−16.7	−0.10	87.5
A3†	AE	0.58	0.28	50.0	0.23	10.5	0.20	106.2
	DE	−0.05	−0.16	22.2	−0.16	0	−0.16	100
A4†	AE	0.34	0.26	18.2	0.23	5.6		
	DE	−0.05	−0.10	11.1	−0.10	0		
A5	AE	0.45			0.28	32.1		
	DE	0.18			0.11	13.3		
A6	AE	0.38			0.30	16.7		
	DE	0			0.04	−10		
A7	AE	0.30			0.28	5		
	DE	−0.05			−0.05	0		
A8	AE	0.30			0.26	10		
	DE	−0.10			−0.10	0		
A9	AE	0.72			0.38	54.7		
	DE	−0.10			−0.16	12.5		
A10	AE	0.36			0.26	21.7		
	DE	−0.22			−0.22	0		
A11	AE	0.48			0.48	0		
	DE	0.08			0.08	0		

The visual acuity was assessed by crowded Chinese Tumbling E chart. Imp, improvement.

* Retention after 5 months for three retested observers.

† These four observers had monocular training experience before the stereo experiment.

Statistical Analysis

Pre- and posttraining disparity threshold, visual acuity and Titmus stereoacuity were compared using paired *t*-tests. For each observer, the percent improvement for all the three measures (disparity threshold, visual acuity and stereoacuity measured with Titmus Fly test) was calculated as:

$$I = \frac{Measure_{pretraining} - Measure_{posttraining}}{Measure_{pretraining}} \times 100\%. \qquad (1)$$

For each observer, the magnitude of improvement for stereoacuity measured with the Titmus Fly test was also calculated as:

$$I = 20\log10\frac{Measure_{pretraining}}{Measure_{posttraining}}\,\mathrm{dB}. \qquad (2)$$

The learning curve (i.e., disparity threshold as a function of training session [in log unit] for each observer and the group average) was fit with a linear function:

$$D = D_0 + a\log(Session) \qquad (3)$$

where D denotes disparity threshold and a is the slope of the learning curve.

RESULTS

Stereo Training

As illustrated in Figure 2, disparity threshold decreased significantly in 9 of 11 amblyopic observers over training sessions. Averaged across observers, disparity threshold decreased from 776.7″ to 490.4″, a reduction of 36.9% (SE: ±10.8%; $t[10] = 3.493$, $P < 0.01$). The average slope of the learning curve was –290.2″ per log unit of training session ($P < 0.001$). Specifically, the four observers with prior monocular training (A1–A4) improved from 781.9″ to 457.5″, with an average reduction of 41.5% (±12.7%); the other seven novices improved from 773.7″ to 509.2″, with an average reduction of 34.2% (±16.1%). There was no significant difference in terms of the magnitude of improvement in the two subgroups ($P > 0.5$).

Stereoacuity and Visual Acuity Tests

Training improved Titmus stereoacuity from 200.3″ to 81.6″, an average reduction of 59.3% ($t[10] = 4.264$, $P < 0.01$, or 7.80 dB; Table 2). The improvement was 50% (SE: ±10.8%) for the four observers with prior monocular training (210″–105″, or 6.02 dB), and 64.9% (SE: ±5.5%) for the seven without monocular training (194.7″–68.3″, or 9.10 dB), without significant difference in the magnitude of improvement ($P > 0.1$). A previous study[57] indicated that the appropriate criterion for normal stereopsis is stereoacuity less than 40″. According to this criterion, observers 4, 7, 8, and 9 achieved normal stereoacuity following training.

Training also significantly improved visual acuity in the amblyopic eyes (0.44–0.35 logMAR, ~0.9 lines, or 18.8% on average, $t[10] = 3.089$, $P < 0.05$) but not in the fellow eyes (average –0.05%, $t[10] = 0.667$, $P > 0.5$) relative to their prestereo training visual acuity (Table 3). The improvement was 13.2% (0.46–0.40 logMAR, ~0.6 lines, SE: ±2.1%) for the four observers with prior monocular training and 22.0% (0.43–0.32 logMAR, ~1.1 lines, SE: ±6.4%) for the seven without prior monocular training, without significant difference in the magnitude of improvement ($P > 0.1$). No observer improved to normal visual acuity after training.

To examine long-term retention of the training effects on stereoacuity and visual acuity, three observers (A1–A3) were retested 5 months after posttraining assessment for stereoacuity and visual acuity. Stereoacuity deteriorated from 200 to 300 arcsecs for A1, remained at 80 arcsecs for A2, and improved from 100 arcsec to 67 arcsec for A3. On average, the three observers retained 104.9% of training results in stereoacuity (Table 2) and 103.1% of visual acuity improvements in the amblyopic eyes (Table 3).

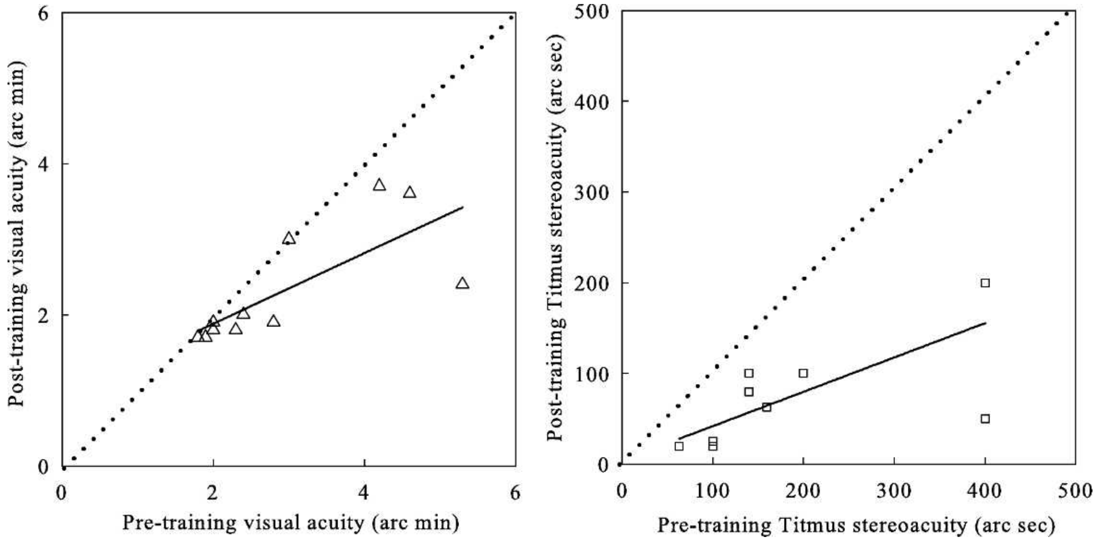

Figure 3. Posttraining measures of visual acuity and Titmus stereopsis versus pretraining counterparts. The *dashed line* is the identity line (slope = 1; i.e., no improvement).

Correlation Between Different Measures

In Figure 3, we plotted pretraining measures of visual acuity and Titmus stereopsis versus posttraining counterparts. Almost all data points are below the identity line, which indicates significant improvement. The best-fitting linear regression line for visual acuity ($r^2 = 0.56$, $P < 0.01$) has a slope of 0.47, suggesting greater visual acuity improvements for observers with worse initial acuities, consistent with previous reports.[35] The best-fitting linear regression for Titmus stereoacuity ($r^2 = 0.57$, $P < 0.01$) has a slope of 0.38, indicating the worse the initial stereoacuity, the greater the improvement.

We also performed Pearson's correlation analysis between the improvements on disparity threshold, Titmus stereoacuity, and visual acuity in the amblyopic eyes. Neither correlation between the improvements on Titmus stereoacuity and disparity threshold ($P > 0.5$) nor between the improvements on Titmus stereoacuity and visual acuity in the amblyopic eyes ($P > 0.5$) was significant. We also did not find significant correlation between the improvements on disparity threshold and visual acuity in the amblyopic eyes ($P = 0.094$; $R = 0.529$).

DISCUSSION

In the current study, we demonstrated that 10 to 13 brief sessions of stereo training using textures stimuli at a fixed exposure time significantly reduced disparity threshold in 9 of 11 amblyopic observers. Training also significantly improved stereoacuity measured with the Titmus Fly Test and visual acuity in all observers, including the two who did not show improvement in the disparity threshold. Moreover, improvements in stereoacuity for two of the three retested observers were largely retained for at least 5 months, suggesting that stereo training induced genuine improvement of stereopsis in those observers.

Ten of the 11 observers showed improvement on visual acuity in the amblyopic eyes after stereo training, but the magnitude of the improvement did not significantly correlate with the magnitude of improvement on disparity threshold ($P = 0.094$). Similarly, Hess et al.[45] found binocular fusion training resulted in significant improvements in stereoacuity as well as Snellen acuity in the amblyopic eye, but the magnitudes of the improvements were not correlated. In their study, the training task of the nine strabismic amblyopic subjects was dichoptic motion detection near coherence thresholds. In the current study, the 11 anisometropic or ametropic amblyopic observers were directly trained to judge depth by manipulating the disparity of texture stimuli. Mechanisms underlying strabismic and anisometropic amblyopia are thought to be different.[6,51] It would be interesting to apply both training paradigms in different types of amblyopia.

Astle et al.[53] reported that their two observers did not show improvements in visual acuity, although their stereo vision reached normal level. They attributed the lack of correlation between the magnitudes of improvements in visual acuity and stereoacuity to the subjects' extensive monocular training experience before stereo training. In the current study, 4 of the 11 observers underwent a monocular contrast detection task over 10,000 trials prior to stereo training.[34] It is interesting to note that we still found some improvements in visual acuity in those subjects (0.05, 0.1, 0.05, and 0.03 logMAR), comparable to the improvements in the other seven subjects without prior monocular training experience (0.17, 0.08, 0.02, 0.04, 0.34, 0.1, and 0 logMAR), although there was no significant correlation between the magnitudes of improvements in visual acuity and disparity threshold in the 11 subjects. It would be useful to compare different combinations of monocular and stereo training tasks/paradigms in a large sample of subjects to test if recovery of visual acuity and stereoacuity is truly independent.

Two observers (A8 and A11) showed no change in stereoacuity threshold during training, but they showed a very large improvement in performance on the Titmus test. We note that the two tests differed significantly with each other in many ways and the results of the two measurements may not correlate with each other. The Titmus test used polarized broad-band circles that can be viewed freely and our psychophysical tests used texture red/green anaglyphs that were displayed with fixed exposure duration. And the viewing distance was 40 and 100 cm, respectively. We performed a Pearson's correlation analysis between the pretest Titmus stereoacuity and pretest disparity threshold and the posttest Titmus stereoacuity and posttest disparity threshold. Indeed neither correlation was significant ($P > 0.1$).

In previous studies, we found that for normal observers, both eyes contributed almost equally in binocular combination.[16,17] For amblyopic observers, stimulus of equal contrast was weighted much less in the amblyopic eye relative to the fellow eye. The effective contrast of the amblyopic eye in binocular combination was equal to approximately 11% to 28% of the same contrast presented to the fellow eye.[16] Stereo disparity threshold was on the other hand found to depend not only on image contrasts in the two eyes but also the ratio between them.[58–61] It would be interesting to match the effective contrasts in the fellow and amblyopic eyes in assessing stereoacuity. Future stereo training studies should also consider the effects of interocular suppression on stereo performance in amblyopia.

We have previously shown that the binocular deficits in contrast and phase perception in anisometropic amblyopia were jointly determined by the attenuation of the signal from the amblyopic eye and a disproportionally stronger inhibition from the fellow eye to the amblyopic eye based on the multipathway, contrast-gain control model (MCM) of binocular vision.[17] We later demonstrated that subject's disparity threshold can also be understood within the MCM framework, indicating both signal attenuation and interocular inhibition contributed to stereo information computation.[59] In this scenario, the observation of improved stereoacuity might reflect an enhancement of the signal in the amblyopic eye or a decrease of interocular suppression from the fellow eye to the amblyopic eye. On the other hand, Sowden et al.[41] has suggested that the improvements in stereoacuity in normal observers might not occur at an early level of visual processing. All these possibilities need to be further evaluated.

In summary, we found that training significantly improved stereoacuity in amblyopic observers but the improvement in stereoacuity and visual acuity was not significantly correlated with each other. Our results, together with others,[27,28,45,52,53] suggested that perceptual learning may be valuable in improving stereoacuity in observers with anisometropic amblyopia, and recovery of monocular visual acuity and stereo vision in amblyopia may need separate monocular and binocular treatments.

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