

Quantifying Nasotemporal Asymmetry of Interocular Suppression in Alternating Strabismus After Correction

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PURPOSE. This study identifies and characterizes the nasotemporal hemifield difference of interocular suppression in subjects who have been successfully treated for strabismus.

METHODS. Interocular suppression in the nasal and temporal hemifields were measured using two methods, namely, binocular phase combination and dichoptic motion coherence, both entailed suprathreshold stimuli. We tested 29 clinical subjects, who had strabismus (19 with exotropia and 10 with esotropia) but regained good ocular alignment (within 10 prism diopters) after surgical or refractive correction, and 10 control subjects.

RESULTS. Both the hemifield binocular phase combination and the hemifield dichoptic motion coherence tests revealed similar nasotemporal asymmetry of interocular suppression. Subjects with previous exotropia showed deeper suppression in the nasal hemifield, and those with previous esotropia showed deeper suppression in the temporal hemifield. This finding was consistent with the hemifield suppression theory. Furthermore, there was deeper suppression but less imbalance of nasotemporal asymmetry in the hemifield dichoptic motion coherence test. Finally, clinical stereopsis and the nasotemporal asymmetry of suppression ($P < 0.05$ in both tests) were negatively correlated in subjects with previous exotropia and measurable stereopsis.

CONCLUSIONS. Hemifield asymmetry of interocular suppression in corrected strabismus can be measured by using static and dynamic suprathreshold stimuli. Thus, the evaluation of binocular vision in strabismus should focus on both the magnitude and the pattern of interocular suppression.

Keywords: interocular suppression, hemifield, strabismus

Strabismus is a condition where the eyes are not properly aligned. Strabismus leads to abnormal binocular function,^{1–3} such as defective stereopsis, interocular suppression, and abnormal retinal correspondence.⁴ Although surgery or refractive correction may restore near-normal ocular alignment, abnormal binocular vision usually persists after interventions.^{5,6}

Interocular suppression is common in patients with strabismus.^{4,7} It develops during childhood to prevent image confusion and diplopia.⁴ In early studies, methods such as Bagolini striated glasses,⁸ colored or polarizing filter mirrors,^{9–11} red glasses,¹² and binocular perimeters^{13–15} were used to measure suppression, but the various measuring methods yielded incongruent results. Sireteanu et al.^{11,16,17} found hemifield asymmetry of suppression in strabismic amblyopia and in alternating strabismus, although in the latter case monocular acuity and contrast increment threshold were largely similar between the two hemifields except for the far periphery. Economides et al.¹⁸ measured interocular suppression by a red–green contrast detection method and found nearly complete suppression of the region in the strabismus eye that corresponded to the foveal region in the fixating eye. This result was replicated using a red–blue

dichoptic visual field test and a fixation switch paradigm in exotropia.^{19,20} In contrast, Pratt-Johnson et al.^{21,22} argued that suppression applies to the entire visual field in the deviated eye that was overlapped with the contralateral eye in an all-or-nothing fashion.^{18,23,24}

There are at least two remaining issues regarding interocular suppression in strabismus. First, although there exist several clinical tests^{25–37} based on dissociation methods that measure the suppression regions, these tests do not reveal the residual excitatory binocular function when contrast in the dominant eye is decreased.^{32,38,39} Recently, some methods such as binocular contrast matching have been developed to measure both the sizes and the depths of suppression regions, but consistent and agreeing results have yet been yielded.³² Second, although suppression usually persists after strabismus correction,⁵ the relationship between hemifield asymmetry and binocular visual functions, such as stereopsis,⁴⁰ remains unclear. In the attempt to answer these questions, we adopt the binocular phase combination test and the dichoptic motion coherence test to study nasotemporal asymmetry in interocular suppression.

Both the binocular phase combination and the dichoptic motion coherence tests use suprathreshold stimuli and

measure interocular suppression when images from both eyes are combined. In the binocular phase combination test, two horizontal sinusoidal gratings of equal contrast but out-of-phase are fed into the two eyes. To see one image, the contrast of one set of grating bars has to be decreased and the amount of contrast decrease is defined as the effective contrast ratio. This ratio indicates interocular suppression in amblyopia and strabismus.^{41,42} The dichoptic motion coherence test^{33,42,43} measures suppression by separating a group of moving dots into signal (coherently moving dots) and noise (randomly moving dots). While the signal's contrast is kept constant, the noise's contrast is adjusted. The noise's contrast at which observers barely perceive motion is noted as an index for interocular suppression. These two tests are pertinent and efficient for measuring residual binocular function in subjects with binocular abnormalities.

To measure hemifield suppression in subjects with a history of alternating strabismus, we modified these tests by presenting fixation crosses into the two eyes and moving the stimuli into specific retinal locations. Specifically, the modified hemifield binocular phase combination test was largely similar to the original version,^{41,42,44} which was designed for testing binocular combination in amblyopia, except that modulating the reference gratings' contrast is not required. The modified hemifield dichoptic motion coherence test deviated from the original test⁴⁵ only for the region being tested.

With this modification, we are able to quantitatively analyze interocular suppression and address several questions. First, does excitatory binocular interaction exist in the nonfoveal regions of subjects who have gone through strabismus correction? Second, does the hemifield asymmetry of interocular suppression persist after correction of strabismus? Third, is the asymmetry of suppression functionally related to stereopsis? If so, what is the nature of this relation?

METHODS

This research followed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of Zhongshan Ophthalmic Center, Sun Yat-sen University. Informed consent was obtained from subjects after explaining to them the purposes, procedures, risks, and benefits of this study.

Subjects

Nineteen subjects with previous exotropia (mean, 16.05 ± 6.80 years), 10 with previous esotropia (mean, 13.40 ± 4.95 years), and 10 normal controls (mean, 26.30 ± 2.26 years) participated in this study. Staff members at the Zhongshan Ophthalmic Center were recruited as normal subjects ($n = 10$; mean, 26.30 ± 2.26 years). Subjects with previous exotropia ($n = 19$; mean, 16.05 ± 6.80 years) and previous esotropia ($n = 10$; mean, 13.40 ± 4.95 years) were recruited. All subjects had visual acuity measured in each eye by the tumbling-E Early Treatment Diabetic Retinopathy Study chart, and all but one had a visual acuity of 20/20 (the one had a visual acuity of 20/25 in both eyes). Measured by the near alternate prism cover test, all subjects had less than 10 prism diopters of strabismic deviation. Binocular vision was assessed using Bagolini striated lens, a synoptophore, and a stereo acuity test (Vision Assessment Corporation Co., Elk

Grove Village, IL). None of the subjects had consecutive tropias or amblyopia. See the Table for details (More details can be seen in the Supplementary Table).

Apparatus

The experiments were conducted in a dim room. Experimental programs were executed on a personal computer running MATLAB (MathWorks, Inc., Natick, MA). Test stimuli were presented on a gamma-corrected liquid crystal display screen with a 1920 × 1080 resolution and 120 Hz refresh rate. Subjects put on 3D Shutter Glasses (3D Vision2 wireless glasses kit, NVIDIA, Santa Clara, CA) and viewed the display dichoptically with viewing distance of 57 cm.

Stimuli

In the binocular phase combination test (Fig. 1A), the stimuli were two horizontal sine-wave gratings (size: width = 5.7°; length = 5.7°) with different contrast ratios and phase relations of ±22.5°. The gratings were presented dichoptically within a high-contrast frame on a background of 35 cd/m². A fixation cross with complementary elements (two dots presented monocularly in the first and third quadrants and two in the second and fourth quadrants) was shown to assist fusion. Subjects adjusted the black reference line (1 pixel wide) to indicate their perceived phase after combining the gratings in the two eyes. We also used two configurations to remove possible bias. The contrast of the grating presented to the nondominant eye was fixed at 0.5, and the contrast ratios of the gratings presented to the dominant eye was set at 0, 0.1, 0.4, 1.0, 1.5, and 2.0 (for details, see the methods of Huang et al.⁴²). The stimuli were onscreen until the subjects responded. Subjects' responses were not timed.

In the hemifield binocular phase combination test (Fig. 1C), two similar target gratings (size: width = 1.9°; length = 5.7°) with different contrast ratios and phases relations of ±22.5° were presented dichoptically in the same visual field (eccentricity = 5°). Two probe gratings that were in-phase and had identical contrast were presented in the opposite hemifield to the target (eccentricity = 5°). The phases of the probe gratings could be adjusted to match those of the target gratings on the other hemifield.

The stimuli in the dichoptic motion coherence test (Fig. 1B) entailed 50 moving dots (mean diameter of 0.7°) with random initial positions inside a circular aperture (diameter = 11.4°). Following previous studies,^{35,46} we set the dots' moving speed at 3.36°/s and the duration of stimulus onset to be 1 second. Some dots (10%–15%)⁴⁷ were signal dots that moved in the same direction (either upward or downward), had high contrast (50% of Weber contrast) and were presented in one eye; other dots were noise dots that moved in heterogeneous directions, had varying contrast, and were presented in the other eye.

In the hemifield dichoptic motion coherence test (Fig. 1D), the diameter of the aperture of dots presentation was decreased to 5.2° and the center of the aperture was offset by 7.6° eccentrically. The same fixation cross used in the hemifield phase combination test was used again here to aid binocular fixation. The mean diameter of the dots was 0.35°. The dots' speed, the duration of the stimuli, and the percentage of the signal dots were identical to those in the dichoptic motion coherence test. See Figure 1B and Figure 1D; refer to Li et al.³³ for details.

TABLE. Summarized Clinical Details of the Three Groups

Clinical Details	Normal Group	Exotropia Group	Esotropia Group
Male sex, n (%)	7 (70.0)	10 (52.6)	7 (70.0)
Age (y)			
Range	24–30	10–39	9–25
Mean ± SD	26.30 ± 2.26	16.05 ± 6.80	13.40 ± 4.95
Spherical equivalent (diopters), mean ± SD			
Deviated/nondominant eye	−2.05 ± 2.02	−1.20 ± 2.60	4.18 ± 1.92
Fixing eye	−2.10 ± 2.10	−0.92 ± 2.78	4.06 ± 1.94
Best-corrected visual acuity, n (%)			
Deviated/nondominant eye			
20/20	10 (100)	19 (100)	9 (90.0)
20/25	0 (0)	0 (0)	1 (10.0)
Fixing eye			
20/20	10 (100)	19 (100)	9 (90.0)
20/25	0 (0)	0 (0)	1 (10.0)
Measurable stereoacuity, n (%)	10 (100)	17 (89.5)	4 (40.0)
Stereoacuity, arcsecs			
Arcsec range	20–25	20–400	63–500
Mean ± SD	21.5 ± 2.42	82 ± 99.50	215.75 ± 196.14
Degree of strabismus before treatment (prism diopters)			
Degree range	–	25–70 pd	20–55 pd
Mean ± SD	–	exotropia 37.58 ± 14.31	esotropia 38.00 ± 10.59
Degree of strabismus during test (prism diopters)			
Degree range	–	3–7 pd	2–5 pd
Mean ± SD	–	exotropia 4.26 ± 1.05	esotropia 3.80 ± 1.03
Age of onset of strabismus			
Range	–	1–26	2–8
Mean ± SD	–	7.47 ± 5.89	3.70 ± 1.90
Duration of strabismus			
Age range	–	1–20	1–19
Mean ± SD	–	6.74 ± 4.70	4.80 ± 5.02
Years after correction of strabismus			
Age range	–	0–8	1–15
Mean ± SD	–	1.84 ± 2.39	4.90 ± 3.86
Retinal correspondence test			
Bagolini test: no. of NRC, n (%)	10 (100)	19 (100)	8 (80.0)
Synoptophore test: no. of NRC, n (%)	10 (100)	15 (78.9)	5 (50.0)

NRC, normal retinal correspondence.

There was a total of 10 subjects in the normal group and esotropia group and a total of 19 in the exotropia group. Age was not matched between the groups.

Procedure

In the binocular combination paradigm, after completing a fusion task to maintain fixation, subjects aligned the line or the phase of the probe grating to indicate the center of the dark stripe of the target. The phase shift of the target grating was +22.5° in the nondominant eye and −22.5° in the fellow eye (configuration 1) or the reversed (configuration 2) (in Figs. 1A and 1C we only showed the pattern in configuration 1). Each configuration was repeated eight times for each type of stimuli (line or grating). The perceived phase was calculated based on these eight repetitions which were presented randomly.

In the dichoptic motion coherence test, after completing a fusion task to maintain fixation, subjects judged dots' motion direction (either up or down) by pressing two keys. We used a three-down, one-up staircase procedure with step sizes of 50% contrast in the first trial and 25% contrast in the others. Different staircases were randomly interleaved and terminated at the sixth reversal point.^{33,48} Both the corrected strabismic subjects and normal controls completed these tests.

Strabismic subjects were tested with base contrast fixed at the nondominant eye; normal controls were tested twice with the base contrast fixed at both eyes.

Data Fitting

We fitted the perceived phase versus the interocular contrast ratio (PvR) curves in binocular phase combination using the modified contrast gain-control model in MATLAB according to Ding and Sperling's equation.^{41,42}

$$\phi = 2 \tan^{-1} \left[\frac{\eta^{1+\gamma} - \delta^{1+\gamma}}{k + \eta^{1+\gamma} + \delta^{1+\gamma}} \tan \left(\frac{\theta}{2} \right) \right]$$

In this equation, ϕ represented the measured perceived phase difference between two configurations, θ represented the interocular phase difference which was fixed at 45°, δ represented the PvR, γ represented the transducer nonlinearity, and k represented the position uncertainty of phase perception. So we obtained the η value, which represented

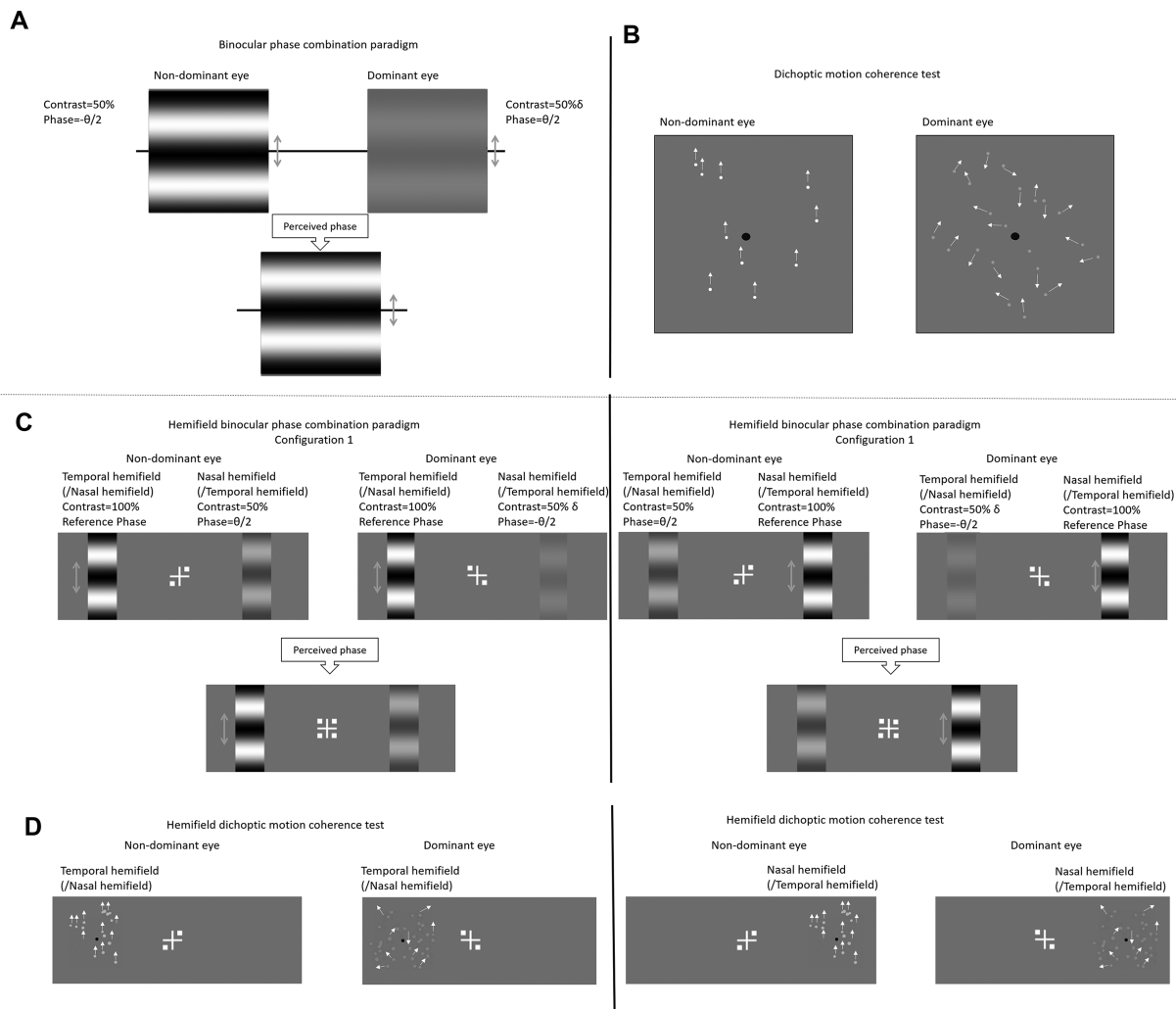


FIGURE 1. An illustration of the stimuli used in the four paradigms for measuring suppression. **(A)** Binocular phase combination test. **(B)** Dichoptic motion coherence test. **(C)** Hemifield binocular phase combination test. **(D)** Hemifield dichoptic motion coherence test. For **(A)** and **(C)**, $\theta = 45^\circ$, $\delta = 0, 0.1, 0.4, 1.0, 1.5$, and 2.0 . For **(B)** and **(D)**, the signal dots were presented in the nondominant eye with constant and high contrast, while the contrast of the noise dots in the dominant eye was varied.

the effective contrast ratio of the nondominant eye from the best-fitted function.

According to a previous study,⁴⁸ a two-step measurement for dichoptic motion coherence yielded comparable results as curve fitting procedure. Therefore, we applied this method in hemifield dichoptic motion coherence test, as already widely used in other studies.^{34,48,49}

RESULTS

Central and Hemifield Patterns of Interocular Suppression in Normal Subjects

The groups of previous exotropia, previous esotropia and normal control subjects had different mean ages ($F = 15.922$; $P < 0.001$). Because we administered ample practice trials, all subjects should understand the tasks and age should not have confounded the results.

The PvR curves of binocular phase combination in foveal and two hemifields for 10 normal subjects with base contrast selected in different eyes are shown in [Figure 2](#), and the

average PvRs curves of binocular phase combination are shown in [Figure 5A](#). As the contrast ratio increased from 0 to 2.0, the perceived phase decreased from around $+45$ to -45 . Using a two-way mixed-design ANOVA, we tested the effects of eccentricity (a within-subjects factor with three levels: foveal, nasal, and temporal visual fields) and of eye (a between-subject factor with two levels: dominant and nondominant) on the interocular suppression. The effective contrast ratios at balanced point of phase perception predicted by these PvR curves were similar in all the conditions ([Fig. 3A](#)). The effective contrast ratios were neither affected by eccentricity ($F = 0.539$; $P = 0.466$) nor by eye ($F = 0.393$; $P = 0.677$). However, the effective contrast ratios measure by dichoptic motion coherence test were significantly affected by eccentricity ($F = 7.262$; $P = 0.002$), but not affected by eye ($F = 0.810$; $P = 0.372$, [Fig. 3B](#)). A post hoc analysis showed that the difference was attributed to the foveal and nonfoveal comparison (foveal versus nasal hemifield: $t = 0.080$ [$P = 0.002$]; foveal versus temporal hemifield: $t = 0.083$ [$P = 0.001$]), but not to the nasal and temporal hemifield comparisons ($t = 0.003$; $P = 0.893$).

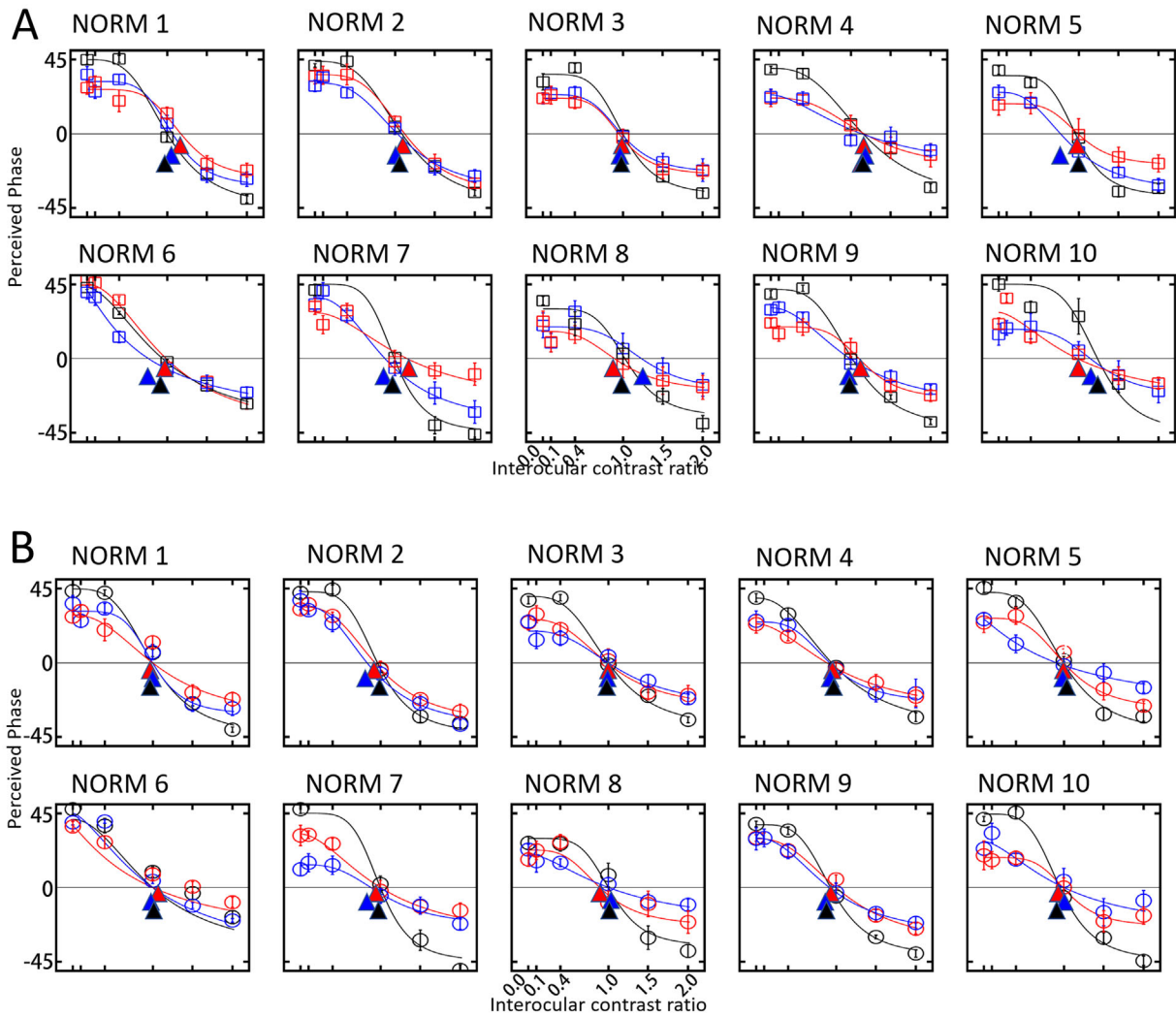


FIGURE 2. (A) The phase versus PVR curves for the normal subjects with the base contrast fixed at nondominant eye. (B) The phase versus PVR curves for the normal subjects with the base contrast fixed at dominant eye. The perceived phase is shown on the y-axis, and the PVR is shown on the x-axis. Data from different subjects are shown in separate panels. Predictions of the PVR functions in different visual fields are represented in different color: central visual field (black), nasal hemifield (red), and temporal hemifield (blue). The triangles in different colors indicate the contrast ratios where the perceived phase is zero (i.e., defined as effective contrast ratio)

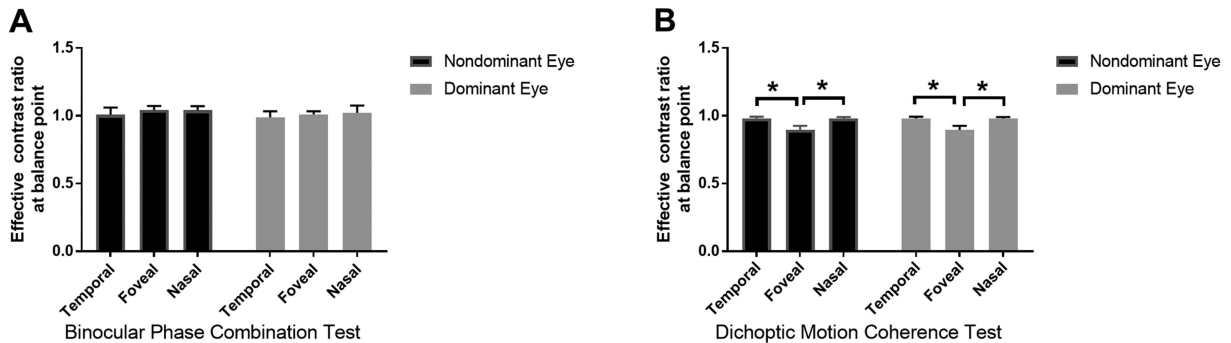


FIGURE 3. Comparisons of effective contrast ratios in different hemifields and different eyes of normal controls. Lower values on the y-axes with signify stronger suppression. (A) Comparisons of the effective contrast ratios tested by the binocular phase combination test and the hemifield binocular phase combination test. (B) Comparisons of the effective contrast ratios tested by the dichoptic motion coherence test and the hemifield dichoptic motion coherence test. *Statistically significant difference ($P < 0.05$). Error bars are ± 1 SEM.

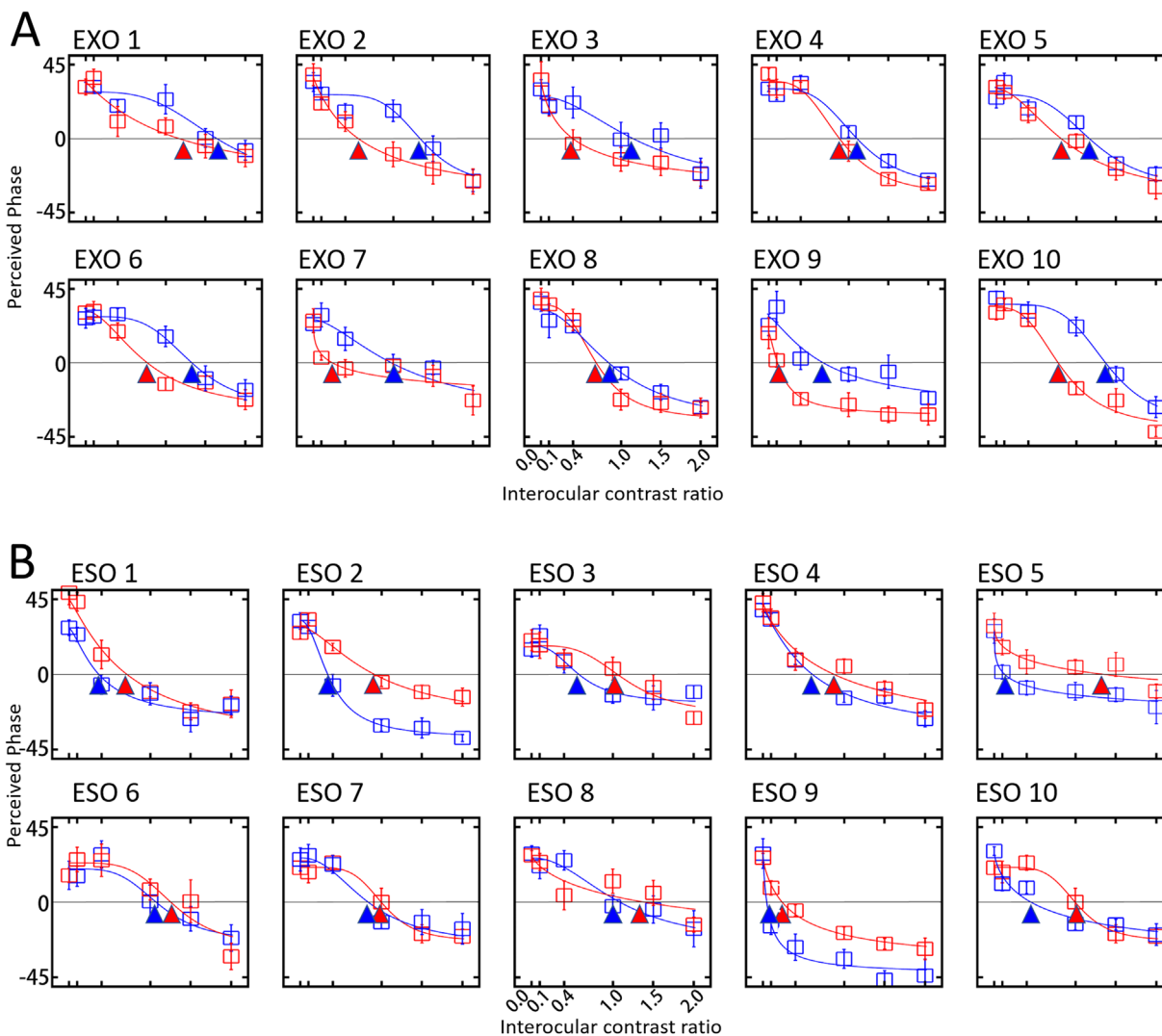


FIGURE 4. (SEM) The phase versus PvR curves for the subjects with a history of exotropia (EXO). Results from 10 subjects are randomly selected. (B) The phase versus PvR curves for the subjects with a history of esotropia (ESO). The perceived phase is shown on the y -axis, and the PvR is shown on the x -axis. Data from different subjects are shown in separate panels. Predictions of the PvR functions in different visual fields are represented in different color: nasal hemifield (red), temporal hemifield (blue). The triangles in different colors indicates the contrast ratios where the perceived phase is zero (i.e., defined as the effective contrast ratio).

Interocular Suppression Between Nasal and Temporal Hemifields in Subjects With Previous Exotropia

The PvR curves of binocular phase combination for 10 randomly selected subjects with previous exotropia were shown in Figure 4A and the group average PvR curves were shown in Figure 5B. The effective contrast ratios predicted by these PvR curves were significantly lower in the nasal hemifields than in the temporal hemifields ($t = 3.635$; $P = 0.002$) (Fig. 5B). Averaged across all the subjects with previous exotropia, the effective contrast ratio was significantly lower than that of normal controls in the nasal hemifield ($t = 4.572$; $P < 0.001$), but not significantly different from that of normal controls in the temporal hemifield ($t = 1.191$; $P = 0.244$) (Fig. 6A). The effective contrast ratios obtained from the dichoptic motion coherence test were lower in both hemifields (nasal: $t = 14.543$ [$P < 0.001$];

temporal: $t = 7.752$ [$P < 0.001$]; Fig. 6B), which suggested a stronger interocular suppression in motion-based binocular visual function. Similarly, a nasotemporal asymmetry with deeper suppression in the nasal hemifield was also observed ($t = 4.574$; $P < 0.001$; Fig. 6B).

Interocular Suppression Between Nasal and Temporal Hemifields in Subjects With Previous Esotropia

Figure 4B showed the PvR curves for 10 subjects with previous esotropia in different hemifields and Figure 5C showed the group average PvR curves. The effective contrast ratios predicted by these PvR curves were significantly lower in the temporal hemifields, compared with that in the nasal hemifields ($t = 4.217$; $P = 0.002$; Fig. 5C). Averaged across all the subjects with previous

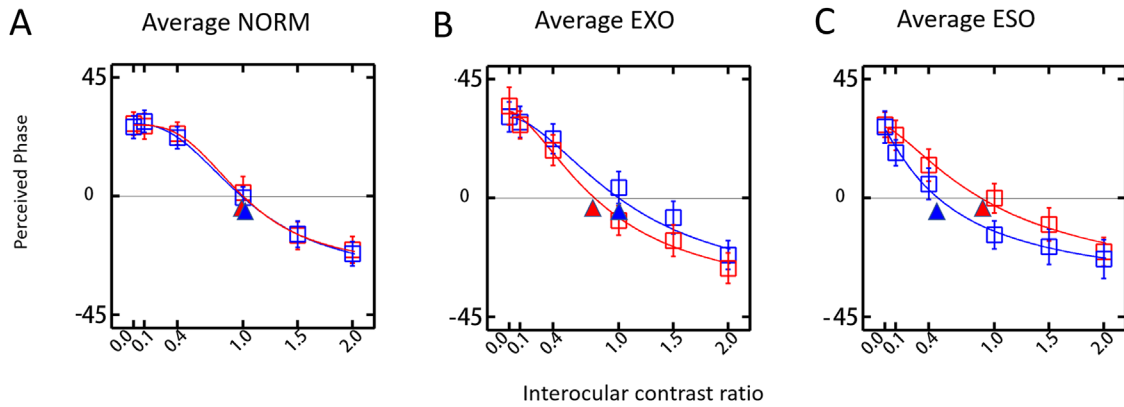


FIGURE 5. (A) The average perceived phase versus interocular contrast (PvR) curves for the normal subjects (NORM). (B) The average perceived phase versus interocular contrast (PvR) curves for the subjects with a history of exotropia (EXO). (C) The average perceived phase versus interocular contrast (PvR) curves for the subjects with a history of esotropia (ESO). The perceived phase is shown on the *y*-axis, and the PvR is shown on the *x*-axis. Predictions of the PvR functions in different visual fields are represented in different color: nasal hemifield (red), temporal hemifield (blue). The triangles in different colors indicates the contrast ratios where the perceived phase is zero (i.e., defined as the effective contrast ratio)

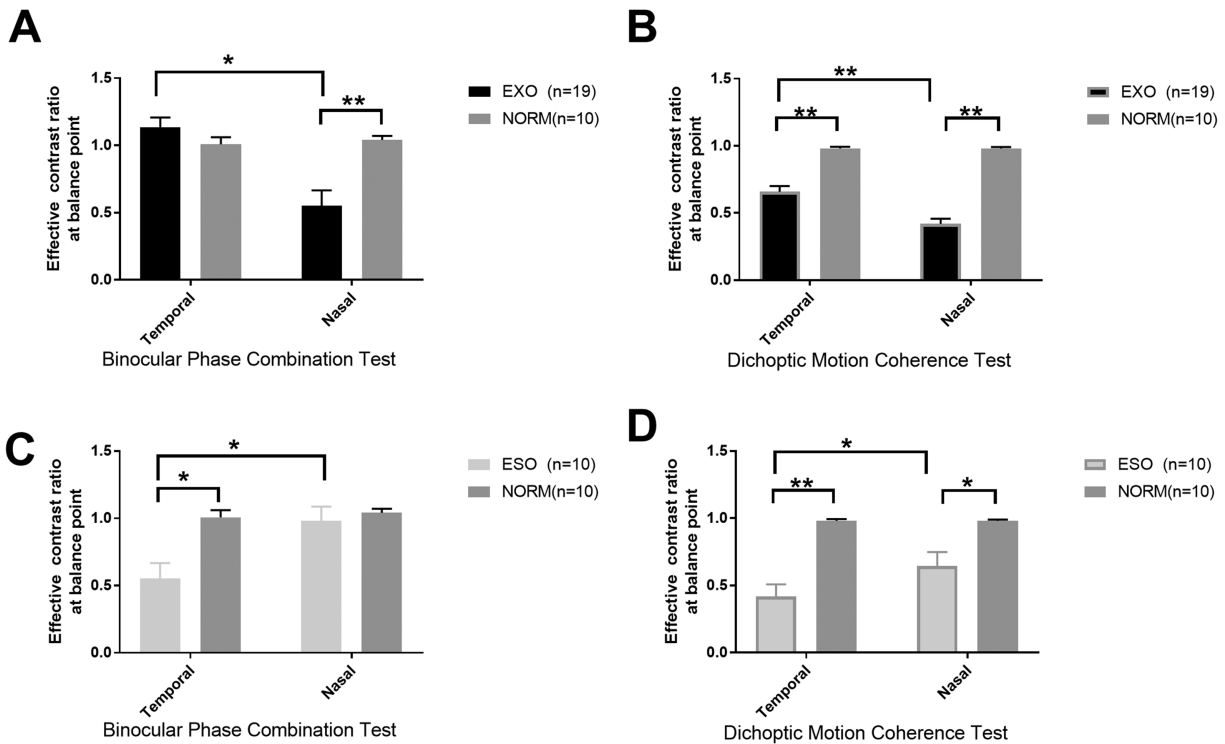


FIGURE 6. Comparisons of the effective contrast ratios in different hemifields between subjects with previous strabismus and normal controls. Lower values on the *y*-axes indicate stronger suppression. (A) Comparison of the effective contrast ratios measured by the hemifield binocular phase combination test between subjects with previous exotropia and normal controls. (B) Comparison of the effective contrast ratios measured by the hemifield dichoptic motion coherence test between subjects with previous exotropia and normal controls. (C) Comparison of the effective contrast ratios measured by the hemifield binocular phase combination test between subjects with previous esotropia and normal controls. (D) Comparison of the effective contrast ratios measured by the hemifield dichoptic motion coherence test between subjects with previous esotropia and normal controls. *Statistically significant difference ($P < 0.05$). **Statistically significant difference ($P < 0.001$). Error bars are ± 1 SEM.

esotropia, the effective contrast ratio was significantly lower than that of normal controls in the temporal hemifield ($t = 3.632$; $P = 0.003$), but not significantly different from that of normal controls in the nasal hemifield ($t = 0.545$; $P = 0.593$) (Fig. 6C). The effective contrast ratios obtained from the dichoptic motion coherence test were lower in both

hemifields (nasal: $t = 3.207$ [$P = 0.010$]; temporal: $t = 6.078$ [$P < 0.001$]; Fig. 6D), which suggested a stronger interocular suppression in motion-based visual function. Similarly, nasotemporal asymmetry with deeper suppression in the temporal hemifield was observed ($t = 2.396$; $P = 0.040$) (Fig. 6D).

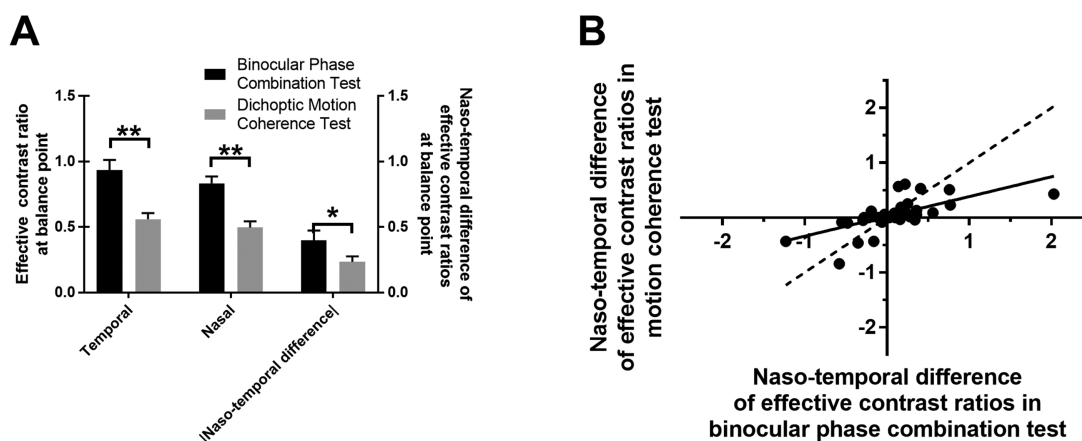


FIGURE 7. (A) Comparisons of the effective contrast ratios measured by two tests in different hemifields. Nasotemporal difference: the absolute value of nasotemporal difference of interocular suppression. (B) The relationship between the absolute value of nasotemporal difference of interocular suppression measured by two tests. The *solid line* is the best fitted line of a linear correlation; the *dashed line* is the line that indicates equivalency between the two tests. *Statistically significant difference ($P < 0.05$); **Statistically significant difference ($P < 0.01$). Error bars are ± 1 SEM.

Comparing Hemifield Asymmetry of Interocular Suppression Measured by Different Paradigms

Comparisons of the effective contrast ratios at the balance point between the dichoptic motion coherence test and the binocular phase combination test are shown in Figure 7A. Data from subjects with previous exotropia and esotropia were combined for analysis. In both temporal and nasal hemifields, the effective contrast ratios measured by binocular phase combination test were higher than those found in the dichoptic motion coherence test (nasal: $t = 4.439$ [$P < 0.001$]; temporal: $t = 5.004$ [$P < 0.001$]); and the absolute value of difference between hemifields of the two tasks also reach significance ($t = 2.256$; $P = 0.032$) (Fig. 7A). The correlation between the hemifield suppression difference measured by the dichoptic motion coherence test and that measured by the phase combination test was significant and positive ($r = 0.659$; $P < 0.001$ Fig. 7B). Taken together, the results indicated that both paradigms were sensitive and efficient in detecting hemifield asymmetry of interocular suppression. The suppression measured by the dichoptic motion coherence test was stronger, but the nasotemporal difference measured by it was weaker.

Comparing Hemifield Asymmetry of Interocular Suppression and Clinical Information

We analyzed the correlation between the hemifield asymmetry of interocular suppression and clinical information, and found no significant correlation between the hemifield asymmetry of interocular suppression and subjects' age, spherical equivalent difference, ocular deviations, age of onset, duration of strabismus, years of correlation and clinical binocular tests (Bagolini striated lens and Synoptophore tests) (all $P > 0.05$). However, in subjects with previous exotropia and measurable stereopsis, we found significant correlations between near stereopsis and the hemifield suppression asymmetry (using the binocular phase combination test: $r = -0.671$ [$P = 0.003$]; using the dichoptic motion coherence test: $r = -0.559$ [$P = 0.020$]) (Figs. 8A and 8B). However, there was no significant correlation between near stereop-

sis and the average hemifield suppression (both $P > 0.05$, as measured by both tests, Figs. 8C and 8D). These results suggested that subjects with profound nasotemporal asymmetry of interocular suppression might have poorer stereopsis. Because only four subjects with previous esotropia had measurable stereopsis in this study, we were unable to conduct a similar analysis for esotropia.

DISCUSSION

In the current study, we modified the binocular phase combination test and the dichoptic motion coherence test, which were originally designed for testing the central visual field, to quantify interocular suppression in the nasal and temporal hemifield in the subjects with history of strabismus. We found excitatory binocular interaction in the nonfoveal regions when contrast between the two eyes was balanced. Consistent with previous findings,^{11,16,17} suppression in both previous exotropia and previous esotropia showed hemifield specificity. In other words, nasotemporal asymmetry persisted in subjects with a history of ocular deviation even though they had already been successfully treated.

The patterns of interocular suppression in strabismus under the condition of ocular deviation has been investigated thoroughly.^{7,16,17} Typically, exotropia exhibited nasal field suppression and esotropia exhibited temporal field suppression. This condition might be caused by the correspondence between the fovea in the fixating eye and the nonfoveal region in the deviated eye. Beyond this, little is known about interocular suppression in strabismus after patients' eyes have been realigned. Serrano-Pedraza et al.⁵⁰ found that, in some subjects with intermittent exotropia, even after the eyes had been aligned, suppression persisted in the nasal hemifield to avoid diplopia. This finding was corroborated later, with a possible linkage between the suppression during binocular alignment and the phoria maintenance in intermittent exotropia.⁵¹ In the current study, we quantified the suppression that was unevenly distributed in the hemifields and yielded behavioral results that were consistent with previous findings.

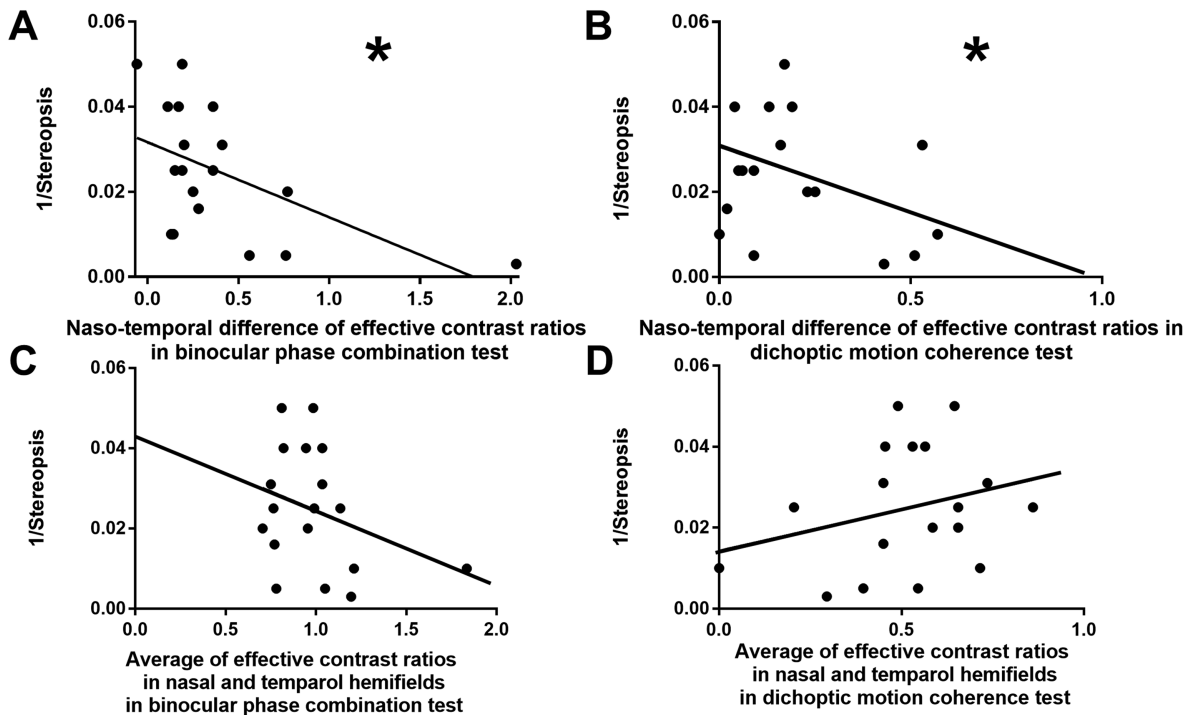


FIGURE 8. (A) The relationship between the reciprocal of near stereopsis and the absolute value of nasotemporal difference of effective contrast ratios measured by the hemifield binocular phase combination test. (B) The relationship between the reciprocal of near stereopsis and the absolute value of nasotemporal difference of effective ratios measured by the hemifield dichoptic motion coherence test. (C) The relationship between the reciprocal of near stereopsis and the average of effective contrast ratios in nasal and temporal hemifields measured by the hemifield binocular phase combination test. (D) The relationship between the reciprocal of near stereopsis and the average of effective contrast ratios in nasal and temporal hemifields measured by the hemifield dichoptic motion coherence test. Lower values on the *x*-axis indicate less imbalance of hemifield asymmetry of suppression (A and B) or stronger suppression (C and D), and lower values on the *y*-axis indicate poorer stereopsis. * Indicate statistically significant linear correlation ($P < 0.05$).

There exists excitatory binocular interaction in central vision in amblyopia and strabismus.^{36,52} The current study extended this finding in the nonfoveal region. Our results were fundamentally different from the predictions of previous suppression theories, which claimed complete suppression in corresponding regions,^{11,16} but were consistent with the current model of binocular combination.^{31,32} The results based on the paradigms using two types of suprathreshold stimuli were similar to what was found in studies using contrast matching paradigm, whereby partial interocular suppression (around 0.2–0.6) was also identified at the eccentricity of 5° in strabismus.^{26,40} The existence of residual excitatory binocular interaction in the nonfoveal region in strabismus, and the hemifield suppression patterns are similar between the current study and those from Chima et al.⁴⁰ On this basis, our study extends the findings from Chima et al.,⁴⁰ because we used two tests that should reflect functioning of different cortical areas.

Our finding demonstrated stronger but more symmetric suppression in the hemifield global motion-based task. It might be caused by the differences in neural processing, as neurons of higher cortical area (such as MT) involved in dichoptic motion coherence test tends to have larger receptive fields and more vulnerable to developmental abnormalities.⁵³ However, we could not exclude the possibility that presenting images to both hemifields in the binocular phase combination test might have interfered with measuring suppression, because identical images presented to two

eyes of intermittent exotropes at different eccentricities have been shown to elicit suppression. Future studies may follow up on this idea.

Given that interocular suppression persisted in subjects with treated intermittent exotropia whose stereopsis were tested normal,⁵ it is quite interesting that, in this study, we found a correlation between stereopsis and hemifield asymmetry of suppression. As shown in a study on stereopsis of patients with optic chiasmal lesions, who suffered from extreme nasotemporal asymmetry, the loss of functional overlapping visual fields might be an important factor leading to deficient stereopsis.⁵⁴ We think that the conventional measurement of suppression in the central visual field may be confounded by the contribution from both nasal and temporal parts,⁵⁵ and we speculate that the hemifield asymmetry of suppression may serve to better indicate how well the two eyes work together in the overlapping visual fields.

There are some limitations of the current study. First, the two tests were not stemmed from the same model. Whereas the hemifield binocular phase combination test was predicted by the binocular contrast gain-control model,⁴² the hemifield dichoptic motion coherence test was not a model-based method. Second, we did not monitor fixation during the experiment; thus, eye movements could have occurred and biased the results. Third, the current study was not designed to uncover the causal relationship between interocular suppression and stereopsis, which would require longitudinal data. Finally, our study used a cross-sectional design.

Ideally, it should be followed up by a longitudinal study so that suppression before and after strabismus correction could be compared.

CONCLUSIONS

Suppression persisted in strabismus subjects after surgical and refractive correction. The suppression was unevenly distributed in different hemifields in both previous exotropia and esotropia. Subjects with a larger imbalance of nasotemporal asymmetry showed poorer stereopsis. Therefore, the evaluation of binocular vision in strabismus should focus not only on the magnitude, but also on the asymmetric pattern of interocular suppression.

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