The Effect of Bangerter Filters on Binocular Function in Observers With Amblyopia

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Submitted: July 14, 2014
Accepted: October 13, 2014

Citation: Chen Z, Li J, Thompson B, et al. The effect of Bangerter filters on binocular function in observers with amblyopia. *Invest Ophthalmol Vis Sci*. 2015;56:139–149. DOI:10.1167/iovs.14-15224

Purpose. We assessed whether partial occlusion of the nonamblyopic eye with Bangerter filters can immediately reduce suppression and promote binocular summation of contrast in observers with amblyopia.

Methods. In Experiment 1, suppression was measured for 22 observers (mean age, 20 years; range, 14–32 years; 10 females) with strabismic or anisometropic amblyopia and 10 controls using our previously established "balance point" protocol. Measurements were made at baseline and with 0.6-, 0.4-, and 0.2-strength Bangerter filters placed over the nonamblyopic/dominant eye. In Experiment 2, psychophysical measurements of contrast sensitivity were made under binocular and monocular viewing conditions for 25 observers with anisometropic amblyopia (mean age, 17 years; range, 11–28 years; 14 females) and 22 controls (mean age, 24 years; range, 22–27; 12 female). Measurements were made at baseline, and with 0.4- and 0.2-strength Bangerter filters placed over the nonamblyopic/dominant eye. Binocular summation ratios (BSRs) were calculated at baseline and with Bangerter filters in place.

Results. Experiment 1: Bangerter filters reduced suppression in observers with amblyopia and induced suppression in controls ($P = 0.025$). The 0.2-strength filter eliminated suppression in observers with amblyopia and this was not a visual acuity effect. Experiment 2: Bangerter filters were able to induce normal levels of binocular contrast summation in the group of observers with anisometropic amblyopia for a stimulus with a spatial frequency of 3 cycles per degree (cpd, $P = 0.006$). The filters reduced binocular summation in controls.

Conclusions. Bangerter filters can immediately reduce suppression and promote binocular summation for mid/low spatial frequencies in observers with amblyopia.

Keywords: binocular vision, amblyopia, contrast sensitivity, psychophysics

Disrupted binocular vision in early childhood can lead to amblyopia, a neurodevelopmental disorder of vision.[1,2] The effects of amblyopia on visual function can be broadly segregated into monocular and binocular deficits.[3–5] The definitive monocular deficit is impaired best-corrected visual acuity in an otherwise healthy eye. However, the monocular effects of amblyopia also extend to a wide range of visual functions, including contrast sensitivity[6,7] and global processing of form and motion.[8–10] Global processing deficits also are present when patients view through their nonamblyopic eye,[11] presumably due to the larger numbers of binocular cells in the extrastriate visual brain areas thought to be responsible for these higher level visual functions.[12]

Visual deficits evident under binocular viewing are characterized by a suppression of information from the amblyopic eye[13,14] and include impaired or absent stereoscopic depth perception[15] and a lack of binocular summation,[16–19] which represents a binocular advantage for detecting stimuli presented close to threshold. In observers with normal binocular vision, binocular viewing confers a sensitivity improvement of approximately 1.4 over monocular viewing.[20–22]

The gold-standard treatment for amblyopia is occlusion of the nonamblyopic eye, which directly targets the monocular loss of visual acuity.[1] However, it is becoming increasingly clear that binocular mechanisms also have an important role in the amblyopia syndrome. For example, suppression of the amblyopic eye (defined as the reduced contribution of the amblyopic eye to the binocular percept) is not only related to binocular deficits, but stronger suppression also is associated with poorer monocular vision in the amblyopic eye.[23] Furthermore, it has been demonstrated that patients with strabismic and/or anisometropic amblyopia retain the capacity for normal binocular combination[24] and even normal binocular summation[25] if suppression is overcome. Reducing suppression also has been found to improve binocular and monocular visual function in adults with amblyopia.[26–29] Therefore, there is a renewed interest in promoting binocular function as part of amblyopia therapy.

www.iovs.org | ISSN: 1552-5783

It is possible that partial, rather than full, occlusion of the nonamblyopic eye may allow for amblyopia therapy to target monocular and binocular visual deficits. One technique for partial occlusion is to adhere a Bangerter filter to the spectacle lens in front of the nonamblyopic eye.[30,31] These filters are made up of microelements that produce localized image distortions. The distortions reduce optotype acuity, vernier acuity, and contrast sensitivity to mid-high spatial frequencies in the filtered eye.[32,33] The nominal strength of Bangerter filters is intended to reflect the decimal acuity that occurs when viewing through the filter. For example, the 0.4 filter is intended to reduce visual acuity to 20/50 or 0.4 logMAR and the 0.2 filter is intended to reduce acuity to 20/100 or 0.7 logMAR. Therefore, smaller filter strength values indicate a greater reduction in acuity. However, considerable variability in the effect of Bangerter filters on acuity has been reported in a number of studies.[34]

Partial occlusion of the nonamblyopic eye with Bangerter filters has been compared to full occlusion of the nonamblyopic eye in a recent randomized clinical trial.[35] The improvement in visual acuity was similar for the two treatments and, unexpectedly, Bangerter filters did not lead to greater improvements in stereopsis than full occlusion. We investigated this result by measuring the effect of Bangerter filters on visual function in observers with normal vision.[34] We found that partial occlusion of one eye with a Bangerter filter had a profoundly detrimental effect on stereopsis that was over and above that expected from the reduced visual acuity. Therefore, it would appear that Bangerter filters do not promote stereopsis. The reason suggested is that the randomly placed microelements, while being good at only minimally interfering with acuity, had the unfortunate effect of decorrelating the information between the eyes and as a consequence destroyed stereopsis. However, stereopsis is not the only form of binocular visual function. In our previous study we also found that Bangerter filters reduced contrast sensitivity, particularly for high spatial frequencies. As mentioned above, it has been demonstrated that reducing the contrast of images in the nonamblyopic eye of amblyopes can overcome suppression and allow for binocular combination (simultaneous perception) of suprathreshold stimuli.[24] Furthermore, presenting higher contrast images to the amblyopic eye than the fellow eye can allow for normal levels of binocular summation for threshold contrast detection tasks in adults with strabismic amblyopia.[25] Therefore, it is possible that by reducing contrast sensitivity in the fellow eye, Bangerter filters could allow for a more rudimentary form of binocularity, namely simultaneous perception and binocular summation in observers with amblyopia. This was the question we set out to answer in the present study.

In Experiment 1 we assessed whether placing a Bangerter filter over the nonamblyopic eye allowed for binocular combination using an established psychophysical measure of interocular suppression. In Experiment 2 we investigated whether placing a Bangerter filter over the nonamblyopic eye would allow for binocular summation on a contrast detection task.

Methods

Participants

A total of 22 observers with anisometropic ($n = 16$) or strabismic ($n = 6$) amblyopia took part in Experiment 1 (mean age, 20 years; range, 14–32 years; 10 female). Three participants (S11, S20, and S22) were categorized as having strabismic amblyopia, although their eyes were aligned at the time of testing, all had a history of strabismus surgery. A separate group of 25 observers with anisometropic amblyopia took part in Experiment 2 (mean age, 17 years; range, 11–28 years; 14 female). Clinical details are provided in Table 1. Only observers with anisometropic amblyopia were included in Experiment 2 to ensure bifoveal fixation of the contrast targets. Amblyopia was defined according to the Preferred Practice Pattern for amblyopia provided by the American Academy of Ophthalmology (AAO),[36] at least 0.2 logMAR interocular acuity difference with a history of anisometropia (at least −2.00 diopters [D] difference for myopia, +1.50 D difference for hyperopia, and 2.00 D difference for astimagtism), strabismus or both.

Ten control observers took part in Experiment 1 (mean age, 24 years; range, 18–29 years old; 5 female). Data from 6 of these observers have been reported previously.[34] A total of 22 control observers took part in Experiment 2 (mean age, 24 years; range, 22–27; 12 female). Normal vision was defined as equal visual acuity between the eyes of at least 0.00 logMAR; the absence of any ocular, oculomotor, or binocular abnormalities; normal stereo acuity (40 seconds of arc); a spherical equivalent (SE) refractive error $\leq$ 3.00 D and a difference in refractive error between the eyes of $\leq$ 1.00 D. A covariate of age was included in each of the statistical analyses comparing observers with amblyopia and controls to account for the differences in age between the two groups.

This study followed the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of Zhongshan Ophthalmic Center. Informed, written consent was provided by all participants before data collection. For participants under the age of 18 years, informed written consent also was provided by the participant's parent or primary care giver.

Clinical Measurements

Each participant's best refractive correction was determined by cycloplegic subjective refraction and the appropriate full correction was provided for all subsequent tests. A trial frame was used where necessary. Eye alignment was assessed using a prism cover test at near distance. All test procedures were conducted in the same clinic facilities under identical lighting conditions. Visual acuity was measured using a tumbling E logMAR chart.[34] For control participants, ocular dominance was assessed using the hole-in-card test.[37] Stereopsis was measured using the Randot Preschool Test.[38]

Experiment 1 – Objective Assessment of Interocular Suppression

The aim of Experiment 1 was to assess the effect of Bangerter filters on interocular suppression in observers with amblyopia and normal controls. Interocular suppression was measured using an established psychophysical approach that involves judging the mean orientation of a group of Gabor patches (sinusoidal grating stimuli multiplied by a Gaussian luminance profile). Signal elements with a common orientation are presented to one eye and noise elements with random orientations are presented to the other eye.[39] The relative contrast of the elements presented to each eye is varied to identify the interocular contrast difference at which information from the two eyes is weighted equally by the visual system (i.e., suppression is no longer present). We previously have used this technique successfully to measure the effect of Bangerter filters on normal binocular vision.[34]

The stimuli were constructed from a population of 10×10 randomly orientated Gabor patches (1 cycle per degree [cpd], 1 octave bandwidth) and were presented for a duration of 200 ms. Signal elements, which were all oriented either horizon-

TABLE 1. Clinical Details

Subject*	Ag, y	Sex	Type	History	Ocular Deviation	BCVA, LogMAR Ambyopic	BCVA, LogMAR Nonamblyopic	Refraction Error OS	Refraction Error OD	Stereopsis, Sec Arc
1	17	F	A	NO	Ortho	0.5	0.0	+3.50/+1.25 × 85	+1.25/+0.50 × 165	Nil
2	22	F	A	Patching	Ortho	0.4	−0.1	−2.25/−0.50 × 180	+2.75	Nil
3	22	F	A	NO	Ortho	0.7	0.0	+3.75/+1.25 × 85	+1.00	Nil
4	22	M	A	Patching	ortho	0.2	−0.1	+4.50	+0.50	Nil
5	22	F	M	Surgery + patching	Exo 5 prism	0.3	0.0	−0.50	+1.25/+0.75 × 95	800
6	32	M	S	NO	Eso 14 prism	0.5	0.0	−1.00	−2.00/−0.75 × 165	Nil
7	16	F	A	NO	Ortho	0.4	0.0	−1.25	+2.25/+0.75 × 180	Nil
8	17	M	A	NO	Ortho	0.5	−0.1	+4.25/+1.00 × 65	+1.25/+0.75 × 145	Nil
9	21	F	A	NO	Ortho	0.7	0.0	+1.00	+5.50/+1.25 × 90	Nil
10	16	M	A	NO	Ortho	0.3	0.0	+3.00	−0.50/−0.50 × 180	Nil
11	22	M	S	Surgery+patching	Ortho	0.4	−0.1	−1.25	−3.00	Nil
12	14	F	A	Patching	Ortho	0.4	−0.1	+0.50	+3.50/+1.25 × 175	800
13	18	M	A	NO	Ortho	0.5	−0.1	−0.50	+4.75/+0.50 × 145	Nil
14	21	F	A	Patching	Ortho	0.2	0.0	+4.25/+2.50 × 165	+1.50	400
15	23	M	A	Patching	Ortho	0.3	−0.1	+3.50/+0.50 × 95	PL	800
16	19	M	A	Patching	Ortho	0.2	−0.1	−0.50	+3.50	800
17	21	M	A	NO	Ortho	0.3	−0.1	+1.25/+2.50 × 145	−0.25/+0.50 × 55	Nil
18	17	M	A	Patching	Ortho	0.3	0.0	+5.25	+2.25	Nil
19	14	F	A	Patching	Ortho	0.5	−0.1	+0.50	+4.50/+1.00 × 75	Nil
20	16	M	S	Surgery+patching	Orth	0.2	0.0	+2.25	+1.50	800
21	19	M	S	NO	Eso 15 prism	0.7	0.0	+0.50	−0.25/−0.50 × 175	Nil
22	21	M	S	Surgery+patching	Ortho	0.3	0.0	−0.75	−3.50/−0.50 × 165	Nil
23	13	M	A	Patching	Ortho	0.8	0.0	+7.50/+0.50 × 120	−0.25	Nil
24	19	M	A	Patching	Ortho	0.5	0.0	+4.50/+1.50 × 100	−3.25	Nil
25	11	F	A	Patching	Ortho	0.2	−0.1	+4.75	+2.75/+1.5 × 95	Nil
26	18	F	A	Patching	Ortho	0.2	0.0	−1.50	+1.50/−4.25 × 180	Nil
27	16	F	A	Patching	Ortho	0.4	−0.2	+3.25/+0.75 × 145	PL	100
28	18	F	A	Patching	Ortho	0.3	0.0	−0.50/−0.50 × 155	−1.25/−0.75 × 177	100
29	13	F	A	Patching	Ortho	0.3	0.0	+2.00/+1.25 × 95	+0.50/+0.50 × 95	Nil
30	11	M	A	Patching	Ortho	0.7	0.0	+1.25/+0.75 × 95	+5.75/+0.75 × 65	Nil
31	14	M	A	Patching	Ortho	0.8	0.0	+5.50/+3.50 × 85	PL	Nil
32	15	M	A	Patching	Ortho	1.0	−0.1	+0.25	+6.50	Nil
33	23	F	A	Patching	Ortho	0.7	0.0	+3.25/+1.5 × 135	−1.25/−0.50 × 5	200
34	13	F	A	Patching	Ortho	1.0	0.0	+5.00/+2.25 × 130	+1.00/+1.50 × 80	Nil
35	12	M	A	Patching	Ortho	0.5	0.0	−0.75 × 165	+4.50/+2.00 × 75	Nil
36	20	F	A	Patching	Ortho	0.3	0.0	+4.50/+1.25 × 130	−2.00	Nil
37	14	M	A	Patching	Ortho	0.8	0.0	+2.75/+2.5 × 75	+1.00 × 80	Nil
38	19	M	A	Patching	Ortho	0.8	−0.1	+0.50	+6.00/+1.00 × 40	Nil
39	14	F	A	Patching	Ortho	0.7	0.0	+1.25	−2.50/−0.25 × 135	Nil
40	27	M	A	No	Ortho	0.7	0.0	+4.25/+3.00 × 95	+0.50/−1.00 × 165	Nil
41	24	M	A	Patching	Ortho	0.4	0.0	+4.00	−0.75/−0.5 × 166	Nil
42	25	F	A	Patching	Ortho	0.4	0.0	+3.50	−0.75	Nil
43	11	F	A	Patching	Ortho	0.3	0.0	+1.00/+0.50 × 25	+3.75/+0.75 × 70	Nil
44	24	M	A	Patching	Ortho	0.3	0.0	+5.50/0.75 × 115	+1.75/+0.50 × 175	Nil
45	16	F	A	Patching	Ortho	0.5	0.0	−1.00	+4.50/−1.50 × 150	Nil
46	18	F	A	No	Ortho	1.0	−0.1	+7.25/+1.50 × 160	PL	Nil
47	28	F	A	Patching	Ortho	0.7	0.0	+4.00	−0.75/−0.50 × 100	Nil

M, male; F, female; A, anisometropic amblyopia; S, strabismic amblyopia; M, mixed amblyopia; Ortho, orthophoria, BCVA, best corrected vision acuity.

* Participants 1 through 22 took part in Experiment 1, and participants 23 to 47 took part in Experiment 2.

tally or vertically, were presented to one eye and noise elements with a random orientation (following a uniform distribution) were presented to the other eye (Fig. 1). Stimuli were presented via a pair of video goggles (eMagin Z800 3D Visor; eMagin Corporation, Bellevue, WA, USA) driven by a MacBook Pro (Apple, Inc., Cuperlino, CA, USA) laptop computer running Matlab (Mathworks Ltd, Natick, MA, USA) and the Psychophysics ToolboxVersion3.[40,41] The observer's task was to judge the mean orientation of the signal Gabors following a two alternative forced choice procedure (horizontal or vertical). Task difficulty was controlled by varying the relative number of signal and noise elements in the stimulus using a 3-down 1-up staircase procedure, and signal/noise thresholds corresponding to 79.4% correct were determined. The suppression measurement consisted of 8 staircases. Signal elements were presented to the amblyopic (or nondominant) eye and noise to the nonamblyopic fellow (or dominant) eye for 4 staircases (configuration 1). The opposite configuration was used for the remaining 4 staircases whereby signal was presented to the nonamblyopic fellow (or dominant eye) and noise was presented to the amblyopic (or nondominant) eye (configuration 2). The interocular contrast ratio also was

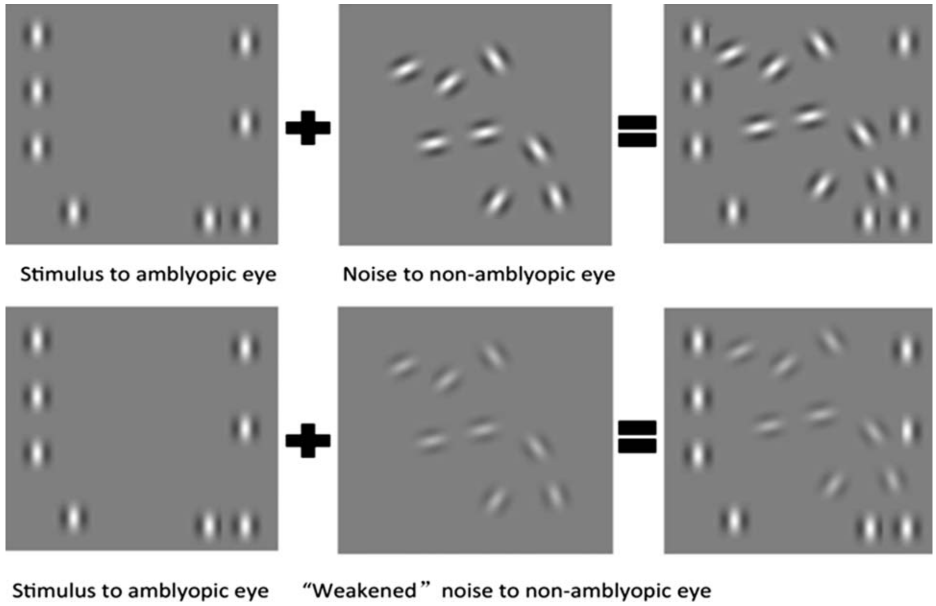

FIGURE 1. Schematic representation of the stimuli used to measure interocular suppression. The stimulus depicted on the *top row* has a contrast ratio of 1 (equal contrast to both eyes). The stimulus depicted on the *bottom row* has a contrast ratio of 0.5 (100% contrast to the amblyopic eye and 50% contrast to the fellow eye). The *left column* shows signal, the *middle column* noise, and the *right column* the binocular percept if information from both eyes is combined equally (i.e., no suppression).

varied. The amblyopic (or nondominant) eye always was presented with 100% contrast and the nonamblyopic eye was presented with 100%, 80%, 50%, and 20% contrast on individual staircases (interocular contrast ratios of 1, 0.8, 0.5, and 0.2). This resulted in 2 threshold measurements (configurations 1 and 2) for each of 4 interocular contrast ratios. Linear functions then were fitted to the threshold and contrast ratio data for each eye, and the interocular contrast ratio at which these two functions intersected was defined as the "balance point" contrast ratio at which information from both eyes was weighted equally. Higher balance point ratios corresponded to weaker suppression (greater contrast could be tolerated in the nonamblyopic fellow eye) whereas lower ratios corresponded to stronger suppression.[34,39]

Suppression measurements were made without a Bangerter filter in place, and with 0.6-, 0.4-, and 0.2-strength Bangerter filters placed over the nonamblyopic (dominant) eye. The sequence of testing was randomized across participants.

Experiment 2 – Contrast Sensitivity

The results of Experiment 1 indicated that Bangerter filters could promote binocular combination in observers with amblyopia by reducing suppression of the amblyopic eye. The aim of Experiment 2 was to assess whether this effect would allow for binocular contrast summation to occur in observers with amblyopia.

Contrast sensitivity measurements were made using sinusoidal gratings presented within a circular aperture with a diameter of 4°. The stimuli were multiplied by with a spatial envelope consisting of a 0.5° half-Gaussian ramp which blended the edges of the stimuli into the background. Contrast was defined as Michelson contrast. The stimuli were generated using Psykinematix[42] software (KyberVision, Montreal, Canada) running on a Mac Pro laptop and presented at the center of an EIZO 21-inch CRT monitor (EIZO Corporation, Ishikawa, Japan) with a resolution of 1280×1024 pixels and a refresh rate of 85 Hz placed at distance of 120 cm in a dimly lit room. Algorithms within Psykinematix that allow for 10.8 bits of monochromatic contrast resolution were used.

On each trial, participants reported the orientation of the grating following a 2-alternative forced choice procedure (vertical versus horizontal). Stimuli were presented for 200 ms and stimulus presentation was signaled with an auditory cue. Trials were separated by an interstimulus interval of 500 ms. Thresholds were measured using a 3-down 1-up interleaved staircase procedure with six reversals converging on 79.4% accuracy. The step size was 50% before the first reversal. Subsequent step sizes were 12.5% and 25.0% for incorrect responses. The mean of the last four reversals was taken as threshold. The starting contrast of each staircase was set to the corresponding threshold obtained during a familiarization session.

Contrast sensitivity measurement sessions began by familiarizing the participants with the task. This involved a single monocular threshold measurement for the 3 cpd stimulus. The task was repeated until a stable threshold was achieved. Measurements then were made for five spatial frequencies; 0.5, 1, 3, 9, and 16 cpd under binocular and monocular (amblyopic/nondominant eye and nonamblyopic/dominant eye) viewing conditions. For monocular measurements, the nonviewing eye was occluded with an opaque eye patch. The order of spatial frequencies was randomized across participants, as was the sequence of binocular and monocular testing.

After a short break, measurements of monocular and binocular contrast sensitivity were made with a 0.4- and a 0.2-strength Bangerter filter placed over the nonamblyopic/dominant eye. Measurements were made for 3 and 9 cpd stimuli only because pilot measurements indicated that contrast sensitivity did not differ reliably between the nonamblyopic eyes of patients and the dominant eyes of controls for these spatial frequencies. This meant that binocular summation ratios (BSRs) could be compared fairly between the groups. The testing order was randomized across participants.

The BSRs were calculated according to the following equation: BSRs = CS_{bin}/CS_{best}, in which CS_{bin} refers to the contrast sensitivity under binocular viewing, and CS_{best} refers to the contrast sensitivity of the better eye under monocular viewing. This equation was applied separately to the baseline data and the data collected with a Bangerter filter partially occluding the nonamblyopic/dominant eye. For the Bangerter filter measurements, the best monocular contrast sensitivity was determined by comparing the sensitivity for the amblyopic/nondominant eye without a filter to the sensitivity for the nonamblyopic/dominant eye occluded with the appropriate strength of Bangerter filter.

Results

Experiment 1

Baseline measurements of suppression using the Gabor stimulus revealed significantly stronger suppression for observers with amblyopia (mean contrast ratio = 0.67, SD = 0.10) than controls (mean contrast ratio = 0.84, SD = 0.2), in agreement with previous studies.[24,39] A univariate ANOVA with a fixed factor of group (amblyopes versus controls) and a covariate of age conducted on the contrast ratio data revealed a significant difference between the groups ($F_{1,29} = 5.6$, $P = 0.025$) and no effect of age ($F_{1,29} = 0.006$, $P = 0.9$). Importantly, psychophysical task performance did not differ significantly between observers with amblyopia and controls at the balance point contrast (mean % signal = 17.1, SD = 3.3 for amblyopes and mean % signal = 21.3, SD = 9.0 for controls; $F_{1,29} = 1.7$, $P = 0.2$) indicating that any differences between the groups were not due to difficulties in performing the signal/noise segregation task per se. Within the amblyopia group, there was no significant difference in suppression between observers with strabismic versus anisometropic amblyopia (mean contrast ratio = 0.65, SD = 0.9 for anisometropes and mean contrast ratio = 0.74, SD = 0.12 for strabismics; $F_{1,19} = 2.8$, $P = 0.1$).

A mixed subjects ANOVA with factors of group (amblyopes versus controls) and Bangerter filter strength (baseline, 0.6, 0.4, and 0.2) and a covariate of age conducted on the contrast ratio values revealed a significant interaction between group and Bangerter filter strength, whereby Bangerter filters tended to reduce suppression in patients with amblyopia and induce suppression in control observers, ($F_{1,42} = 12.6$, $P < 0.0001$, corrected for sphericity; Fig. 2). In other words, Bangerter filters had completely opposite effects for amblyopes and controls. This interaction still was present if the baseline data were excluded from the analysis ($F_{1,36} = 10.7$, $P = 0.001$).

A within subjects ANOVA conducted on the contrast ratio values for observers with amblyopia revealed a significant main effect of Bangerter filter strength ($F_{1,23} = 16.1$, $P < 0.001$). Paired sample t-tests (Bonferroni corrected) conducted on consecutive pairs of filter strengths revealed significant differences between baseline (no filter) and the 0.6 filter strength ($t_{21} = 3.8$, $P = 0.001$), and the 0.4 and 0.2 filter strengths ($t_{21} = 3.5$, $P = 0.002$). There was no significant difference between the 0.6 and 0.4 filter strengths ($t_{21} = 0.9$, $P = 0.4$). Notably, for the 0.2-strength Bangerter filter condition, the balance point contrast ratios for the group were not significantly different from 1 ($t_{21} = 1.0$, $P = 0.3$), indicating that, on average, suppression was no longer present for this test. To assess whether this effect was due to a "balancing" of acuity between the eyes we measured nonamblyopic eye visual acuity for a subset of 11 observers with 0.6-, 0.4-, and 0.2-strength Bangerter filters in place. The results are shown in Table 2. Of the 7 patients who achieved a balance point close to 1 with Bangerter filters in place, 4 required a 0.2-strength filter, 2 a 0.4-strength filter, and 1 a 0.6-strength filter. With these filters in place, visual acuity in the nonamblyopic eye was reduced below the visual acuity of the amblyopic eye in 4/7 patients. Therefore, it seems that overcoming suppression with Bangerter filters does not necessarily require nonamblyopic eye visual acuity to be reduced below that of the amblyopic eye.

The same within subject ANOVA model applied to the data for control observers also revealed a significant main effect of Bangerter filter strength ($F_{3,27} = 10.2$, $P < 0.001$); however, paired t-tests conducted on consecutive pairs of filter strengths only revealed a significant difference between the 0.4- and 0.2-strength filters ($t_9 = 4.5$, $P = 0.001$). The baseline and 0.6-strength filter measurements did not significantly differ ($t_9 = 0.68$, $P = 0.51$), nor did the 0.6- and 0.4-strength filters ($t_9 = 2.1$, $P = 0.07$).

Experiment 2

Average contrast sensitivity functions measured without Bangerter filters are shown in Figure 3. A within subjects ANOVA with factors of viewing condition (binocular, dominant eye, nondominant eye) and spatial frequency (0.5, 1, 3, 9, and 16 cpd) conducted on the log contrast sensitivity data for controls revealed the expected significant main effects of viewing condition ($F_{2,42} = 83.6$, $P < 0.0001$) and spatial frequency ($F_{2,40} = 344.8$, $P < 0.0001$), and a significant interaction ($F_{3,54} = 5.8$, $P < 0.003$). Subsequent analyses revealed that dominant eyes exhibited a significantly higher contrast sensitivity than nondominant eyes ($F_{1,21} = 6.3$, $P = 0.02$), that did not vary with spatial frequency ($F_{2,32} = 1.1$, $P = 0.3$). In addition, binocular viewing resulted in significantly higher contrast sensitivity than dominant ($F_{1,21} = 101.6$, $P < 0.0001$) and nondominant ($F_{1,21} = 205.7$, $P < 0.0001$) eye viewing. This effect was more pronounced for low than high spatial frequencies (significant interaction between viewing condition and spatial frequency; dominant eyes versus binocular viewing, $F_{2,49} = 8.8$, $P < 0.0001$; nondominant eyes versus binocular viewing, $P < 0.0001$, $F_{2,34} = 9.6$, $P = 0.001$).

The same analysis conducted for observers with amblyopia revealed significant main effects of spatial frequency ($F_{2,50} = 561.7$, $P < 0.0001$) and viewing condition ($F_{1,27} = 148.6$, $P < 0.0001$), and an interaction between the these two factors ($F_{3,78} = 64.1$, $P < 0.0001$). Nonamblyopic eye viewing and binocular viewing exhibited significantly higher contrast sensitivity than amblyopic eye viewing (nonamblyopic versus amblyopic, $F_{1,24} = 123.9$, $P < 0.0001$; binocular versus amblyopic, $F_{1,24} = 188.4$, $P < 0.0001$). This effect was more pronounced for high spatial frequencies than low spatial frequencies (nonamblyopic versus amblyopic, $F_{2,56} = 74.8$, $P < 0.0001$; binocular versus amblyopic, $F_{1,24} = 202.1$, $P < 0.0001$). A comparison between contrast sensitivities for the nonamblyopic eye and binocular viewing conditions demonstrated that contrast sensitivity was significantly higher under binocular viewing conditions ($F_{1,24} = 9.8$, $P = 0.004$) and that this effect was more pronounced for low spatial frequencies ($F_{2,42} = 5.5$, $P = 0.01$).

It has been reported previously that the nonamblyopic eyes of nonbinocular amblyopes can exhibit monocular contrast sensitivity in the nonamblyopic eye that is superior to the monocular contrast sensitivity of controls.[3] A mixed ANOVA conducted on the log sensitivity data for the nonamblyopic eye of amblyopes and the dominant eye of controls with a covariate of age revealed no significant interaction between Group (amblyopes versus controls) and Spatial Frequency ($F_{2,70} = 2.6$, $P = 0.09$). However, there was a tendency for the nonamblyopic eye contrast sensitivities to be higher than control eyes for the low spatial frequencies with the opposite effect occurring at higher spatial frequencies (Fig. 3c). An

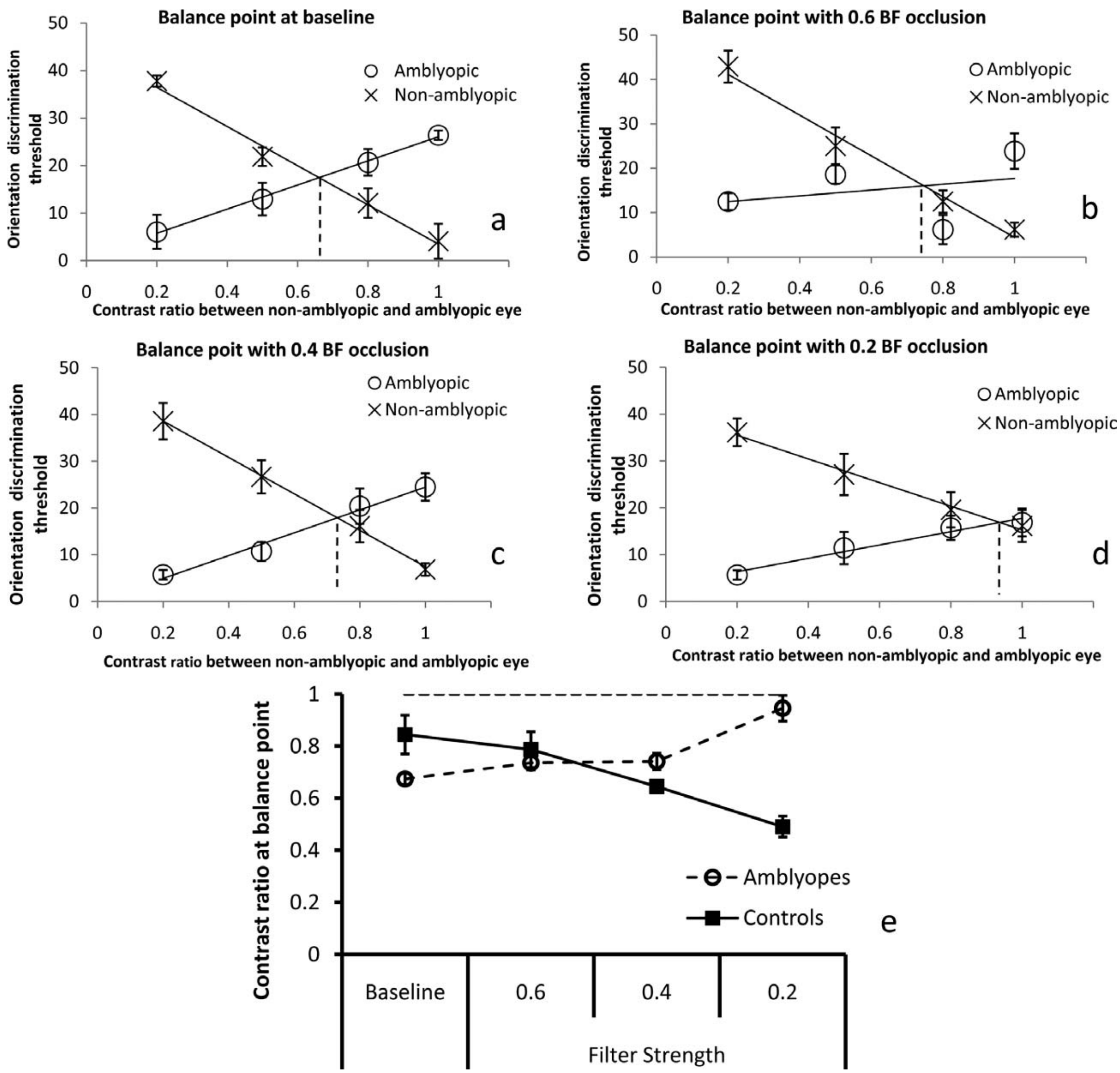

FIGURE 2. The effect of Bangerter filters on interocular suppression in observers with amblyopia. The *top four panels* show group average orientation discrimination thresholds for each combination of eye (*circle* and *cross symbols*) and contrast ratio. Thresholds are in units of number of signal Gabors and larger threshold values value indicate poorer performance. Contrast ratios of 1 indicate no contrast difference between the eyes. The *solid lines* show the best linear fits to each eye's thresholds. The *point at which these lines intersect* is the balance point and the *dashed lines* indicate the corresponding interocular contrast ratio. (**a**) Shows average baseline data. (**b–d**) Show data for the 0.6-, 0.4-, and 0.2 Bangerter filter strengths, respectively. As the strength of Bangerter filter placed over the nonamblyopic eye increased, the balance point contrast ratio moved closer to 1. (**e**) Shows the contrast ratio at balance point for controls (*solid line*) and amblyopes (*dashed line*) as a function of Bangerter filter strength. The *horizontal dashed line* shows a contrast ratio of 1 indicative of no suppression. Stronger Bangerter filters induced suppression in controls and binocular combination in amblyopes. *Error bars*: ±1 SEM.

ANOVA comparing binocular contrast sensitivity for amblyopes and controls with a covariate of age demonstrated that controls had significantly greater binocular contrast sensitivity ($F_{1,44} = 14.1$, $P < 0.001$). As shown in Figure 3d, the difference in binocular contrast sensitivity between controls and amblyopes became larger with increasing spatial frequency, (significant interaction between group and spatial frequency, $F_{2,78} = 16.1$, $P = 0.001$).

The BSRs were calculated for each participant for each spatial frequency. Controls exhibited significantly higher levels of binocular summation than amblyopes, ($F_{1,44} = 10.6$, $P < 0.002$), and this effect did not interact with spatial frequency ($F_{2,97} = 2.3$, $P = 0.1$, Fig. 4). Both groups exhibited BSRs that were significantly different from 1 for all spatial frequencies (1 sample *t*-test, $P < 0.05$) with the exception of the 16 cpd spatial frequency for the amblyopic group ($P = 0.4$). Controls exhibited higher levels of binocular summation than amblyopes for every spatial frequency (independent samples *t*-test, $P < 0.05$).

The effect of 0.2- and 0.4-strength Bangerter filters on BSRs was measured for the 3 and 9 cpd stimuli. Measurements were not available for one control participant and two participants

Table 2. Visual Acuity and Contrast Ratios at Baseline and With 0.6-, 0.4-, and 0.2-Strength Bangerter Filters (BF) in Place for 11 Participants With Amblyopia

ID	Visual Acuity (LogMAR)					Contrast Ratio at Balance Point, Nonamblyopic/Amblyopic			
	AME Baseline	NME Baseline	NME BF 0.6	NME BF 0.4	NME BF 0.2	Baseline	BF 0.6	BF 0.4	BF 0.2
1	0.52	0.02	0.36	0.38	0.72	0.59	0.62	0.65	2.00
2	0.42	−0.12	0.32	0.38	0.68	0.60	0.64	0.63	1.10*
3	0.78	0.04	0.24	0.32	0.64	0.64	0.65	0.69	1.28*
4	0.24	−0.12	0.2	0.28	0.54	0.75	0.84	0.83	1.10*
5	0.36	0.04	0.24	0.3	0.58	0.86	0.89	1.01*	0.49
6	0.56	0.06	0.3	0.4	0.7	0.68	0.67	0.70	0.81
7	0.42	0.02	0.36	0.38	0.68	0.56	0.60	0.68	0.91
8	0.52	−0.14	0.24	0.34	0.66	0.59	0.70	0.63	1.00*
9	0.72	0.02	0.34	0.38	0.76	0.51	0.62	0.63	0.66
10	0.32	0.04	0.32	0.4	0.66	0.82	0.65	1.05*	1.11
11	0.44	−0.12	0.24	0.28	0.58	0.92	1.10*	1.06	2.26
Mean (± SD)	0.48 (± 0.16)	−0.02 (± 0.08)	0.29 (± 0.06)	0.35 (± 0.05)	0.65 (± 0.07)	0.68 (± 0.13)	0.72 (± 0.16)	0.78 (± 0.18)	1.16 (± 0.53)

Visual acuity data are shown for the amblyopic eye (AME) and nonamblyopic eye (NME) at baseline, and for the nonamblyopic eye with Bangerter filters in place to the left of the Table. Contrast ratios are shown to the right of the Table.

* Contrast ratios close to 1 were achieved by 7 participants. Participant 1 moved from a contrast ratio of 0.65 with the 0.4 filter to 2.00 with the 0.2 filter. This indicates a switch in dominance from the nonamblyopic to the amblyopic eye and not normal binocular combination. Participant 5 changed from a contrast ratio of 1.01 for the 0.4 filter to a ratio of 0.49 with the 0.2 filter. This was due to an outlying data point in the 0.2 filter measurements.

with amblyopia completed measurements for the 0.4-strength Bangerter filter only.

Before analyzing the BSRs, the effect of Bangerter filters on monocular contrast sensitivity was examined. A mixed ANOVA with factors of filter strength (baseline versus 0.4 strength filter versus 0.2 strength filter), spatial frequency (3 vs. 9 cpd) and group (nonamblyopic eyes versus dominant eyes) was conducted on the log contrast sensitivity values. As shown in Figure 5, there was a monotonic reduction in contrast sensitivity with increasing filter strength for the nonamblyopic eyes of patients and dominant eyes of controls ($F_{2,67} = 43.8$, $P < 0.0001$). This effect was more pronounced for the 9-cpd stimulus than the 3-cpd stimulus ($F_{2,78} = 9.6$, $P < 0.001$) and was not significantly different between the two groups ($F_{1,39} = 1.9$, $P = 0.2$). For the group of amblyopic observers, the 0.4-strength Bangerter filter tended to reduce the difference in contrast sensitivity between the amblyopic and nonamblyopic eyes for the 3- and 9-cpd stimuli.

A mixed ANOVA with factors of filter strength (baseline versus 0.4-strength filter versus 0.2-strength filter), spatial frequency (3 vs. 9 cpd) and group (nonamblyopic eyes versus dominant eyes) and a covariate of age was conducted on the BSRs to assess the effect of Bangerter filters on binocular summation. As shown in Figure 6, Bangerter filters reduced binocular summation for controls and increased binocular summation for amblyopic observers (significant interaction between Bangerter filter strength and group, $F_{2,78} = 4.1$, $P = 0.02$). The 0.4-strength Bangerter filter significantly increased the BSRs for the amblyopic observers for the 3-cpd stimulus ($t_{24} = 3.0$, $P = 0.006$). The 0.2-strength Bangerter filter had no significant effect for either spatial frequency. For controls, the 0.2-strength filter significantly reduced BSRs relative to baseline for the 3-cpd ($t_{20} = 2.4$, $P = 0.03$), but not the 9-cpd stimulus ($t_{20} = 2.2$, $P = 0.06$). The 0.4-strength filter had no significant effect (3 cpd, $t_{20} = 2.0$, $P = 0.06$; 9 cpd, $t_{20} = 1.5$, $P = 0.13$). Importantly, the BSRs measured for observers with amblyopia with the 0.4 filter in place did not differ significantly from those of controls with no filter in place (amblyopia 3 cpd mean binocular summation ratio = 1.3, SD = 0.4; 9 cpd = 1.2, SD = 0.7; controls 3 cpd = 1.1, SD = 0.1; 9 cpd = 1.3, SD = 0.3). This demonstrates that with the Bangerter filter in place, observers with amblyopia exhibited more normal BSRs.

Discussion

The aim of this study was to test the hypothesis that partial occlusion of the nonamblyopic eye with a Bangerter filter could reduce suppression and allow for binocular summation in observers with amblyopia. The hypothesis was supported. Partial occlusion allowed for more normal binocular combination on a task designed to measure interocular suppression as well as more normal BSRs for contrast sensitivity in observers with amblyopia. It has been shown previously that normal binocular combination and binocular summation for contrast can be measured in adults with amblyopia if the contrast of stimuli shown to the nonamblyopic eye is reduced to overcome suppression.[24,25,43] It is likely that the effect of Bangerter filters on binocular function in amblyopia is mediated by the same mechanism because the results reported here, and previously, demonstrated that contrast sensitivity is reduced in the filtered eye.[32,35] Overall, the results are consistent with the idea that observers with amblyopia possess the capacity for binocular vision, but that this capacity is blocked under normal viewing conditions.[44] Notably, Bangerter filters had opposite effects on binocular function in observers with amblyopia and controls. While the filters promoted binocular function in the amblyopic visual system,

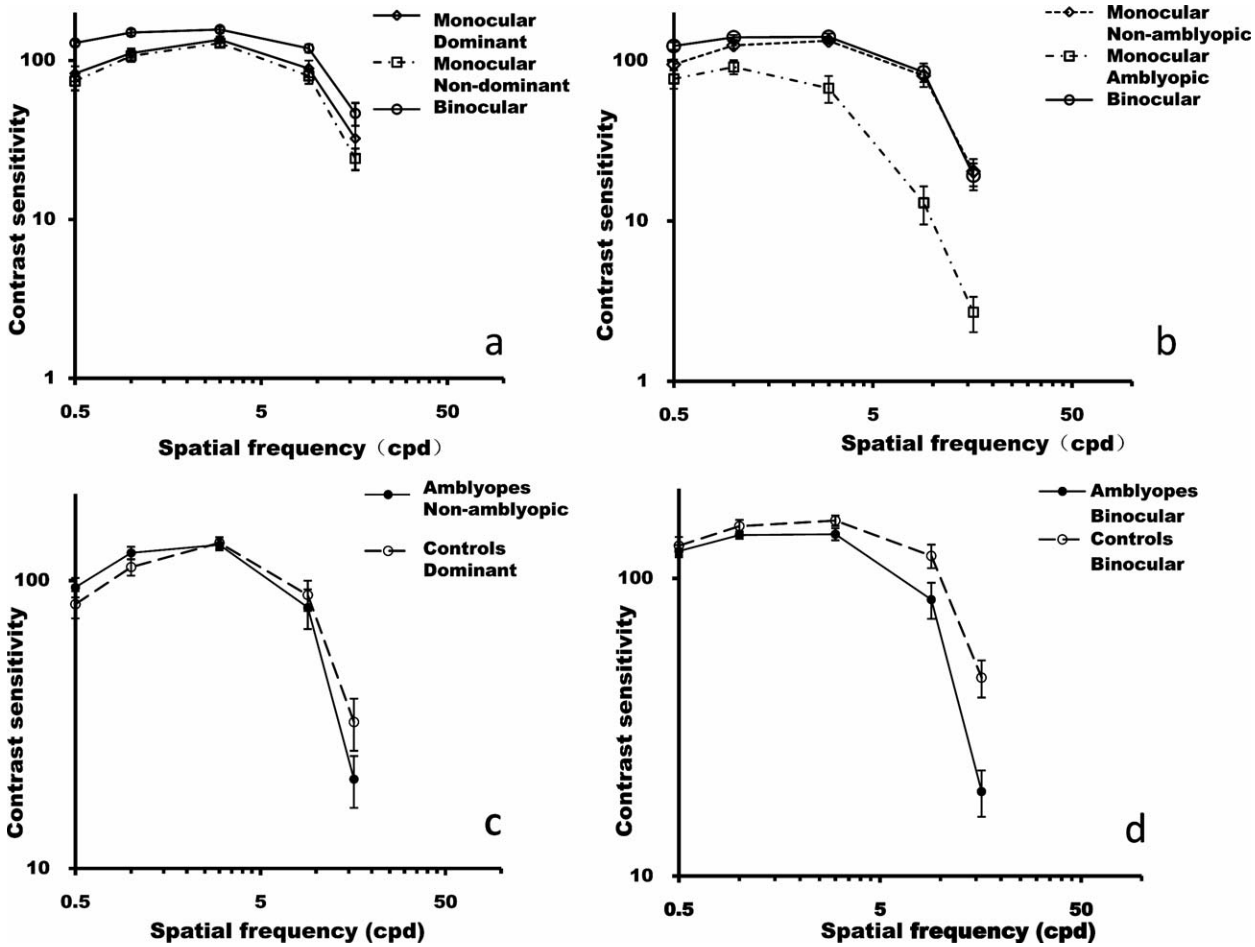

Figure 3. Baseline contrast sensitivity functions for controls (**a**) and observers with amblyopia (**b**) under binocular and monocular viewing conditions. (**c**) Shows a comparison of monocular contrast sensitivity between nonamblyopic eyes of patients and dominant eyes of controls. (**d**) Shows binocular contrast sensitivities for patients and controls. Note that the *y*-axis is truncated in (**c**) and (**d**) to allow for the differences between the groups to be seen. *Error bars*: ±1 SEM.

they degraded binocularity in controls. This is consistent with recent models of binocular vision and highlights the importance of balanced excitatory and inhibitory interactions between the two eyes for normal binocular function.[45,46]

If Bangerter filters promote binocular function then why are the binocular outcomes equivalent for amblyopic patients who are treated using these filters and those treated with full occlusion of the nonamblyopic eye?[34] One possibility is the use of Randot Stereo as an outcome measure. It has been found previously that Bangerter filters significantly degrade Randot stereopsis, due almost certainly to the local distortions (which result in reduced interocular correlation) induced in the retinal image of one eye.[35,47] Therefore, other more rudimentary measures of binocular function that occur before disparity encoding, such as binocular summation of contrast or global measures of suppression, still may reflect an advantage of Bangerter filters. The finding that partial occlusion with Bangerter filters can improve motor fusion in patients with strabismic amblyopia is consistent with the idea that the filters can promote a rudimentary degree of binocular function[48] (however, comments from Agervi[49]). This effect also may underlie the accelerated improvement in visual acuity that occurs when Bangerter filters are combined with spectacle correction relative to spectacle correction alone.[31] However, it is important to note that no differences were found for the Lang stereo or Bagolini lenses tests in this particular clinical trial. Alternatively, the acute effects of Bangerter filters described here may not translate to long-term treatment outcomes especially if stereopsis is selectively degraded by these filters. The incorporation of a wider range of binocular function tests into future clinical trials should shed further light on the question of binocular outcomes following treatment of amblyopia.

One notable characteristic of our results was that the strength of Bangerter filter that tended to improve binocular function was not consistent between the two experiments. Specifically, the average filter strength allowing for normal performance on the suppression task was 0.2 compared to 0.4 for the binocular summation task. This may have been due to the use of different participants in the two studies. Another possibility is that the filters interacted differently with the spatial properties of the stimuli used in the two experiments. For example, the spatial frequency of the stimulus elements used in Experiment 2 was 1 cpd compared to 3 and 9 cpd in Experiment 2. Therefore, the need for stronger filters to "balance" the eyes in Experiment 1 may have reflected the fact that stronger Bangerter filters are required to reduce sensitivity to low spatial frequencies.[32–34]

The contrast sensitivity data collected in Experiment 2 without Bangerter filters in place demonstrated the expected

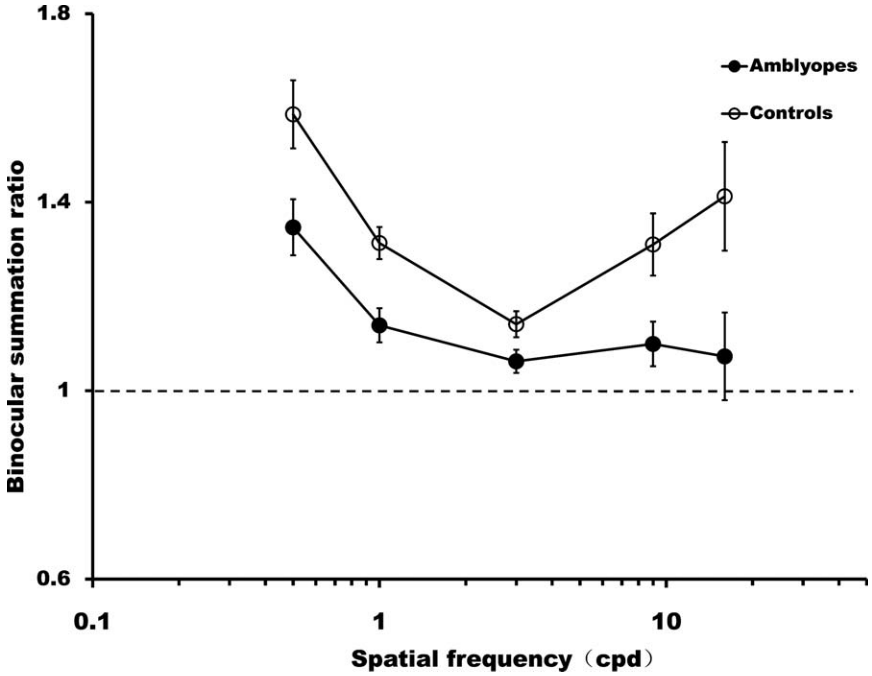

FIGURE 4. BSRs at baseline for controls (*open circles*) and observers with amblyopia (*closed circles*) as a function of spatial frequency. The *dashed horizontal line* shows a binocular summation ratio of 1 (i.e., no summation). Controls showed greater binocular summation than patients and patients showed greater summation for low spatial frequencies. *Error bars*: ±1 SEM.

effect of binocular summation for controls and a significant reduction in binocular summation for participants with amblyopia. However, there was an unexpected result. Participants with amblyopia did show measureable binocular summation, particularly for low spatial frequency targets where the monocular sensitivity of the amblyopic eye was highest. This suggests that suppression may vary with spatial frequency and/or the relative contrast sensitivity of the amblyopic eye. In addition, there was a nonsignificant tendency for nonamblyopic fellow eyes to have a greater sensitivity to low spatial frequencies than dominant eyes. "Supernormal" contrast sensitivity for nonamblyopic fellow eyes was first described by Hess and Howell,[50] and may be a consequence of the added temporal effects of unstable fixation rather than a real change in contrast gain.

In conclusion, although Bangerter filters degrade Randot stereopsis, they were able to reduce suppression and promote a more rudimentary binocular summation in observers with

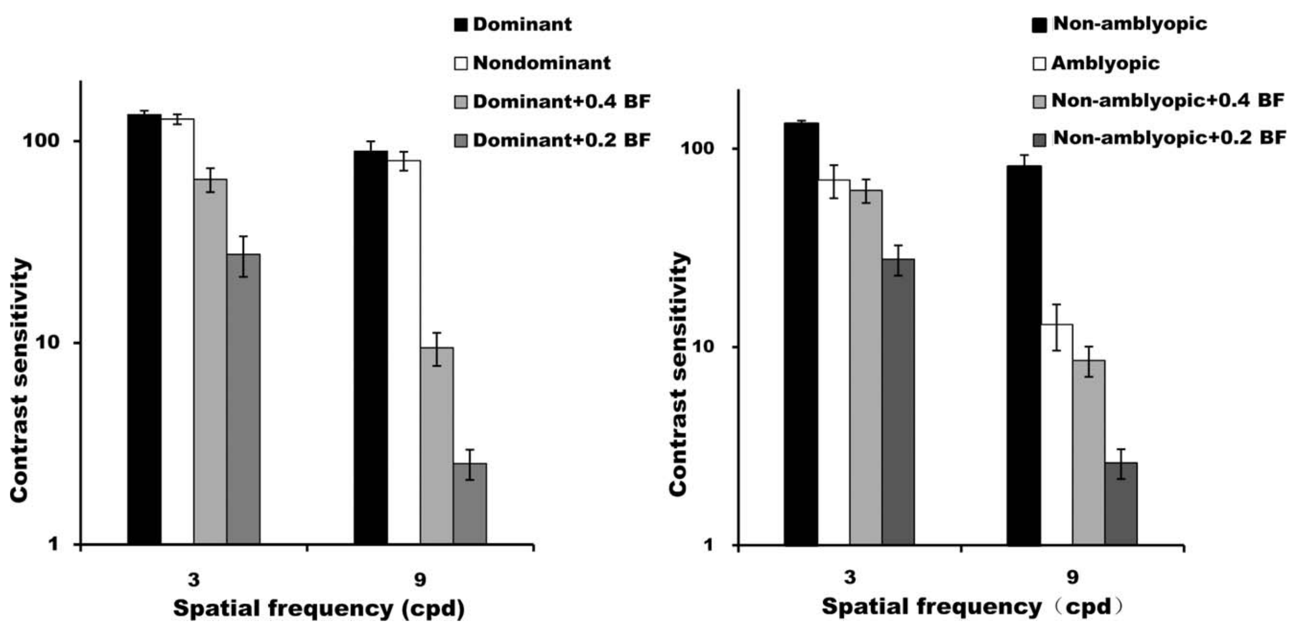

FIGURE 5. The effect of Bangerter filters on monocular contrast sensitivity for controls (*left*) and observers with amblyopia (*right*). Two spatial frequencies were tested, 3 cpd and 9 cpd. *Error bars*: ±1 SEM.

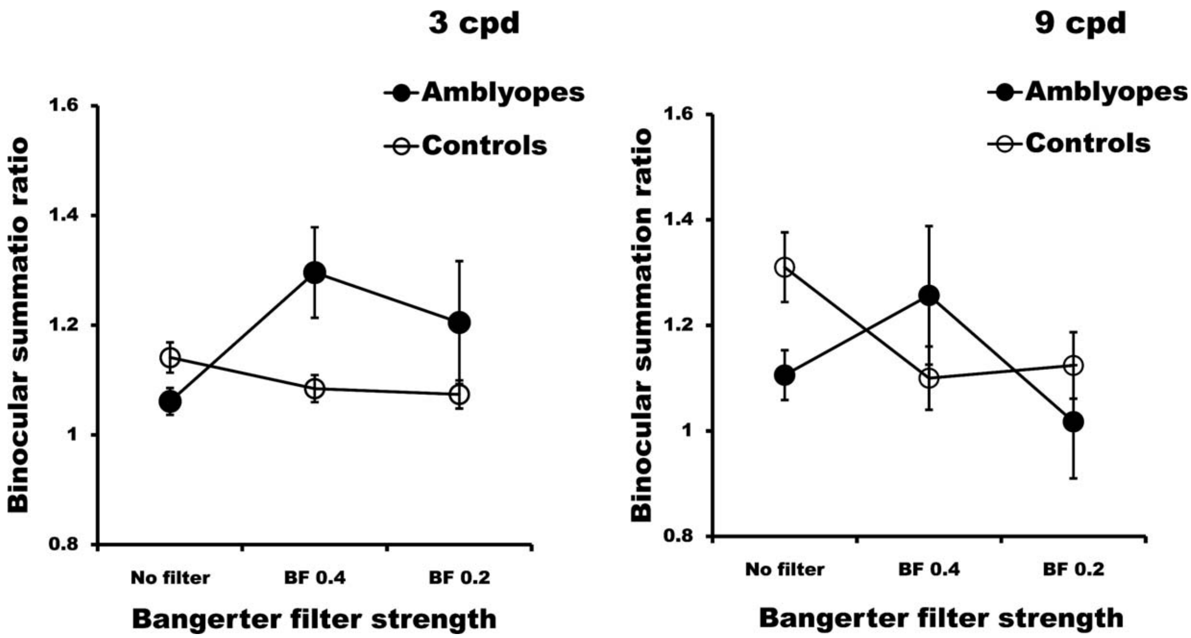

FIGURE 6. The effect of Bangerter filters on BSRs for controls and observers with amblyopia. Results are shown for the 3 cpd stimulus (*left*) and 9 cpd (*right*). The 0.4-strength filter increased BSRs for patients. The 0.2-strength filter had variable effects, possibly because contrast sensitivity in the nonamblyopic eye was reduced to such an extent that it could not contribute to summation, particularly for the 9-cpd stimulus. The 0.2 filters tended to reduce binocular summation in controls. *Error bars*: ±1 SEM.

amblyopia. Future studies may want to consider the use of Bangerter filters that promote the first stage of binocular integration in conjunction with a more active binocular training regime that targets stereoscopic function.

Acknowledgments

Supported by a National Natural Science Foundation of China Grant (81200715) and Fundamental Research Funds of State Key Laboratory of Ophthalmology (JL), a grant from the Health Research Council of New Zealand (BT), and CIHR Grant 5334 (RFH). The authors alone are responsible for the content and writing of the paper.

Disclosure: **Z. Chen**, None; **J. Li**, None; **B. Thompso**n, None; **D. Deng**, None; **J. Yuan**, None; **L. Chan**, None; **R.F. Hess**, None; **M. Yu**, None

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