Does Partial Occlusion Promote Normal Binocular Function?

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Purpose. There is growing evidence that abnormal binocular interactions play a key role in the amblyopia syndrome and represent a viable target for treatment interventions. In this context the use of partial occlusion using optical devices such as Bangerter filters as an alternative to complete occlusion is of particular interest. The aims of this study were to understand why Bangerter filters do not result in improved binocular outcomes compared to complete occlusion, and to compare the effects of Bangerter filters, optical blur and neutral density (ND) filters on normal binocular function.

Methods. The effects of four strengths of Bangerter filters (0.8, 0.6, 0.4, 0.2) on letter and vernier acuity, contrast sensitivity, stereoacuity, and interocular suppression were measured in 21 observers with normal vision. In a subset of 14 observers, the partial occlusion effects of Bangerter filters, ND filters and plus lenses on stereopsis and interocular suppression were compared.

Results. Bangerter filters did not have graded effect on vision and induced significant disruption to binocular function. This disruption was greater than that of monocular defocus but weaker than that of ND filters. The effect of the Bangerter filters on stereopsis was more pronounced than their effect on monocular acuity, and the induced monocular acuity deficits did not predict the induced deficits in stereopsis.

Conclusions. Bangerter filters appear to be particularly disruptive to binocular function. Other interventions, such as optical defocus and those employing computer generated dichoptic stimulus presentation, may be more appropriate than partial occlusion for targeting binocular function during amblyopia treatment. (*Invest Ophthalmol Vis Sci.* 2012; 53:6818–6827) DOI:10.1167/iovs.12-10390

It was once thought that humans with strabismic amblyopia had a complete loss of binocularity and that there was no possibility for recovery of binocular function, let alone stereopsis.[1–3] This led to an emphasis on monocular treatment approaches and, in particular, complete occlusion of the fixing eye for all or part of each day. There is now evidence indicating that patients with strabismic amblyopia possess a structurally intact binocular visual system that has been rendered functionally monocular due to inhibitory interactions prior to the point at which binocular combination occurs. For example, it has been shown that observers with strabismic amblyopia exhibit normal binocular combination both at[4] and above[5,6] threshold once suppression has been overcome by varying the relative contrast of images presented to each eye. The idea that strabismic amblyopia does not preclude binocular function represents a significant change in our understanding of the disorder and has significant implications for treatment. Animal studies have shown that restoration of vision in kittens who experienced 6 days of monocular deprivation between 5 to 9 weeks of age is enhanced by a period of binocular stimulation that can be as short as 2 hours a day.[7] Consistent with this is recent data from a binocular training approach[8–13] which uses dichoptic presentation of stimuli, whereby the stimulus presented to the amblyopic eye has a higher contrast than the stimulus presented to the fellow eye in order to overcome interocular suppression. The training is based on a task that requires combination of information between the two eyes, and repeated task performance has been shown to result in improved monocular and binocular function in a significant proportion of patients. This includes both adults and children who had reached an asymptote in their monocular response to patching therapy. The technique can be implemented using a mirror haploscope,[8,9] a head-mounted video display,[12] or a handheld media player (iPod).[13] In comparison, the standard treatment approach is based on complete occlusion of the fixing eye in an attempt to improve the function of the amblyopic eye. Keeping the patient under strictly monocular viewing conditions, even if it is for only part of the day, is not ideal in terms of this new binocular perspective.

The use of partial occlusion techniques is of particular interest within the context of promoting binocularity in the treatment of amblyopia. This is because these techniques may allow for binocular combination while still penalizing the vision of the fixing eye.[14–16] In principle, therefore, partial occlusion methods could provide a simple, cheap alternate approach to the computer-based binocular training method

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that has been proposed, with the proviso that the computer based technique requires active binocular combination whereas partial occlusion can, at best, provide conditions that are permissive for binocular cooperation.

One example of fellow eye penalization that could potentially allow for some degree of binocularity is the use of atropine to blur the vision of the fixing eye.[17] For this particular technique, however, the amount of blur will depend on a number of factors such as individual sensitivity, refractive error, viewing distance, and time, rendering it a less than ideal method for promoting stable binocular function. In fact, there is some evidence to suggest that binocular outcomes may be slightly better after patching than atropine penalization in patients with anisometropic amblyopia.[18] A more consistent level of optical blur during fellow eye penalization can be induced using spectacle lenses,[16,19] although this too will depend on the ammetropia and viewing distance. An alternative, possibly more stable, approach is the use of Bangerter filters to degrade vision in the fellow eye.[14,20] These filters provide penalization that differs from that of blurred lenses and opaque occluders in that they are composed of microelements that produce localized image distortions[21] and influence visual acuity, contrast sensitivity, vernier acuity, and stereopsis.[21–24] Bangerter filters have been widely used to simulate a number of visual conditions such as cataracts[25,26] and vitreous haze in uveitis.[27] They come in a range of strengths and, in principle, could be ideal for providing the combination of controlled, stable penalization and partial binocular vision necessary for a better binocular outcome. Although there were some initial reports supporting this possibility,[14] a more recent randomized, large scale, clinical trial has shown that Bangerter filters provide comparable binocular outcomes to 2 to 6 hours of complete monocular occlusion.[20] The first aim of this study was to understand why Bangerter filters don't produce better binocular outcomes than complete patching.

An alternative method for providing partial occlusion is the neutral density (ND) filter.[28] ND filters reduce vision not by blurring or distorting but by reducing the quantal catch available to neurons with smaller receptive fields. Thus, these filters reduce acuity without reducing contrast, meaning that contrast fidelity is maintained even at low resolution. ND filters placed over the fellow eye can lead to more normal patterns of interocular suppression in amblyopes[29] and simulate amblyopic suppression in observers with normal binocular vision.[30] The use of ND filters has also been advocated as a means of balancing the vision in the two eyes of amblyopic observers to promote better stereopsis.[31,32]

Thus, optical defocus, Bangerter distortion, or methods producing overall luminance reduction[33] could all provide potential alternatives to full occlusion and result in better binocular outcomes. The second aim of this study was to compare all three of these partial occlusion techniques in observers with normal binocular vision to determine which allows for the most robust binocular function while still reducing the acuity in one eye. To enable such a comparison, filters were matched to produce comparable monocular letter acuity deficits prior to assessment of the effects on binocular function. We chose this acuity-based metric as the strength of monocular partial occlusion for amblyopia therapy is based on the rationale that acuity in the fixing eye should be reduced below that of the fellow amblyopic eye.[20] Due to the inherent variability between Bangerter filters of the same nominal strength,[21,23,24] we first fully characterized our batch of filters in terms of their effects on monocular performance measures including acuity, contrast sensitivity, and vernier acuity prior to measuring the effects on binocular function.

Methods

Experimental Procedures

Participants. Twenty-one participants (8 female, mean age 19 years, SD 1.9 years) took part in this study. Inclusion criteria were: visual acuity of at least 20/20 in each eye, absence of any ocular, oculomotor, or binocular abnormalities, normal stereoacuity ($\leq$40 seconds of arc), and a spherical equivalent refractive error between +1.00 dioptric sphere (DS) and −2.50 DS with a dioptric difference of less than 0.50 diopters (D) between eyes. This study followed the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of Zhongshan Ophthalmic Center. Informed consent was obtained from all participants prior to data collection. All participants took part in the assessment of Bangerter filters on monocular function, the Worth-4-dot test, and stereopsis. A subgroup of 14 participants took part in the measurements involving monocular defocus and luminance reduction.

Measurements of Visual Function. Each participant's best refractive correction was determined using subjective refraction, and the appropriate correction was provided using a trial frame during testing if required. All test procedures were conducted in the same clinic room under identical lighting conditions. As the aim of these measurements was to characterize the effects of Bangerter filters, optical defocus, and ND filters in the context of partial occlusion, we did not fix pupil size, and observers completed the measurements with natural pupils.

Visual Acuity. Visual acuity was measured using a visual acuity chart (tumbling E logMAR) viewed from a distance of 4 m at a luminance of 500 cd/m^2. The chart followed the Early Treatment Diabetic Retinopathy Study (EDTRS) standards in terms of optotype spacing and consisted of 5 optoypes per line for a total of 12 lines decreasing from 1.0 logMAR to −0.3 logMAR in steps of 0.1 logMAR. A forced-choice testing method was employed, and visual acuity was scored using the standard technique of subtracting 0.02 logMAR units for each correctly identified optotype.

Vernier Acuity. Vernier acuity was measured using test chart software (Test Chart Xpert; Thomson Vision Solutions, Harfield, Herts, UK) running on a PC computer, and stimuli were displayed on a 17" CRT monitor (107S61; Philips, Amsterdam, The Netherlands) (85 Hz refresh rate, 1024 $\times$ 768 resolution) viewed from a distance of 2.4 m. The vernier acuity target consisted of a pair of black bars each subtending 60 minutes of arc presented on a white background at 100% contrast. The horizontal separation of the bars was controlled by the experimenter, and participants reported whether the top bar was offset to the left or the right of the bottom bar. The acuity threshold was estimated using the average of a descending and ascending method of limits.

Contrast Sensitivity. Contrast sensitivity was measured for Gabor patches (sinusoidal grating stimuli convolved with a Gaussian luminance profile) with a spatial sigma of 2° and a temporal sigma of 500 ms with spatial frequencies of 0.5, 1, 2, 5, and 10 cycles per degree (cpd). Stimuli were generated using visual psychophysics software (Psykinematix; KyberVision, Montreal, Canada) running on a laptop computer (MacBook Pro; Apple, Inc., Cupertino, CA) and were displayed on a 17" CRT monitor (107S61; Philips) (85 Hz refresh rate, 1024 $\times$ 768 resolution, mean luminance of 200 cd/m^2) viewed from 60 cm with the aid of a chin rest. Participants judged whether the stimulus was oriented horizontally or vertically on each trial following a two-alternative forced-choice procedure. Following a familiarization procedure, participants completed five threshold measurements for each spatial frequency in a random sequence. Seventy-five percent correct thresholds were estimated using a Baysian adaptive staircase run over a maximum of 100 trials which generated data that were fit by a Weibull function.

Stereopsis. Stereoscopic depth perception was measured using the Randot Preschool Test viewed from a distance of 40 cm.

Table. The Relationship between Bangerter Filter Strength, Visual Acuity, Defocus Induced by Plus Lenses, and ND Filter Strength

Bangerter Filter Strength	Visual Acuity in LogMAR (SD)	Corresponding Defocus, (SD) and [Predicted Defocus*] in D	Corresponding ND Filter Strength (SD) in Log Units
0.8	0.29 (0.1)	0.61 (0.3) [0.68]	1.86 (0.3)
0.6	0.32 (0.09)	0.73 (0.2) [0.72]	1.93 (0.3)
0.4	0.35 (0.1)	0.79 (0.2) [0.76]	2.10 (0.4)
0.2	0.55 (0.1)	1.16 (0.3) [1.12]	2.81 (0.2)†

* The predicted defocus was calculated from a logistic fit to the summary data reported by Holladay et al.[39] in their Table 1 assuming a 7 mm pupil.

† For this data point three participants required an ND filter stronger than 3 log units to reduce their acuity to the levels measured for the 0.2 Bangerter filter. As 3 log units was the strongest filter available for testing, the values for these participants were set to 3 meaning that this value is an underestimation.

Clinical Measurement of Suppression. Interocular suppression was measured using the Worth-4-dot test. A Worth-4-dot source (Worth 4-dot Attachment; Richmond Products, Albuquerque, NM) was fitted to a scleral transilluminator (Finoff Transilluminator; HEINE Optotechnik GmbH & Co., Herrsching, Germany) which allowed for the presentation of four circular dots (circumference 19 mm, 2 green, 1 white, 1 red) with equal luminance. Participants wore red/green anaglyph glasses (Original Bernell Model Red/Green Goggles; Bernell VTP, Mishawaka, IN) over their best refractive correction with the red filter over the right eye. Suppression was tested at near (33 cm) and distance (6 m), and results were recorded as no suppression (all four dots seen and the white dot was seen as white or alternating between red and green due to retinal rivalry) or partial suppression (all four dots seen with the white dot consistently perceived as either red or green with no retinal rivalry). Partial suppression on the Worth-4-dot test is not typically used clinically, however it is included here as we have previously found that the distinction between full and partial suppression on this test can be informative in a research context.[34,35] Full suppression (less than four dots seen) did not occur under any of the testing conditions used in this study.

Psychophysical Measurement of Suppression. Initial attempts were made to assess interocular suppression using an established approach based on dichoptic viewing of random dot kinematograms.[6,35,36] However, the microelements present within the Bangerter filters distorted the perceived motion direction and rendered these measurements inaccurate. We, therefore, adopted a version of the task that is based on the same principle but uses static form perception as a psychophysical measure. The task is described in detail elsewhere.[6] Briefly, a population of 10 × 10 randomly oriented Gabor patches (1 cpd; 1 octave bandwidth) were presented for a duration of 200 ms. Signal elements which were oriented either horizontally or vertically were presented to one eye, and noise elements with a random orientation (following a uniform distribution) were presented to the other eye via a pair of video goggles (eMagin Z800 3D Visor; eMagin Corporation, Bellevue, WA) driven by a laptop computer (MacBook Pro; Apple, Inc.) running technical computing software (Matlab; Mathworks, Natick, MA) and vision research software (Psychophysics Toolbox Version 3; Open Source SW available at http://psychtoolbox.org).[37,38] The observer's task was to judge the orientation of the signal Gabors. 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. Thresholds were measured for signal elements presented to the dominant eye and noise elements to the nondominant eye as well as signal elements presented to the nondominant eye and noise elements to the dominant eye. In addition, thresholds were measured for a fixed element contrast of 100% in the nondominant eye and element contrasts of 100, 80, 50, and 20% in the dominant eye. Staircase measurements were randomly interleaved across these eight conditions (2 eyes × 4 contrast offsets). When the test was combined with monocular penalization, the penalization was applied to the nondominant eye.

Monocular Penalization

Measurements of Monocular Visual Function through Bangerter Filters. All monocular measurements were made for dominant eyes only as defined using the hole-in-card test. Measurements were made for letter acuity, vernier acuity, and contrast sensitivity with participants viewing through Bangerter filters with densities of 0.8, 0.6, 0.4, and 0.2. These filter strengths were chosen as the nominal strength increased in equal steps of 0.2, and they provided a representative sample of the range filter of strengths available. In accordance with the manufacturer's instructions, the new Bangerter filters were moistened and applied to plano ophthalmic lenses. The nonviewing eye was occluded with an opaque eye patch. The sequence in which each filter was tested was randomized across participants. Each measurement was repeated twice to account for any learning effects.

Measurements of Binocular Function. Clinical (Worth-4-dot) and psychophysical measurements of suppression as well as measurements of stereopsis were assessed under partial occlusion conditions induced by a Bangerter filter, optical defocus, or an ND filter. Because the effect of Bangerter filters on visual acuity does not vary reliably with increasing filter density,[23] we selected levels of optical blur and ND filter strength by matching their effects on monocular acuity to those of the Bangerter filters. Specifically, for each participant, we measured monocular acuity for each strength of Bangerter filter. We then removed the Bangerter filter and gradually increased the amount of plus lens defocus (in steps of 0.25 D) or ND filter strength (in steps of 0.3 log units) until the same acuity was recorded. Defocus or ND filter strength was then increased past this point and gradually decreased to ensure that the match between acuity level and the amount of defocus/luminance reduction was reliable. By following this procedure, we were able to estimate the level optical defocus and strength of ND filter that induced a level of acuity loss that matched the loss induced by each strength of Bangerter filter. To ensure that our results were not contaminated by learning of the chart, we compared our measured acuities for optical defocus to predicted values gained from fitting a logistic function to previously published data assessing the effect of optical blur on acuity.[39] Further details are provided in the table notes.

Plus lenses were mounted in a trial frame in addition to the participant's optimal correction where necessary, and ND filters were mounted in a filter bar that was held in front of the viewing eye. The ND filter strengths varied from 0.3 (50% light transmission) to 3 (0.1% light transmission).

Results

The Effect of Bangerter Filters on Visual Function

All Bangerter filter strengths significantly reduced letter acuity relative to the no-filter baseline (0.8, $t_{20} = 13.6$, $P < 0.0001$; 0.6, $t_{20} = 11.8$, $P < 0.0001$; 0.4, $t_{20} = 13.9$, $P < 0.0001$; 0.2, $t_{20} = 25.1$, $P < 0.0001$). In addition, when the baseline measurements were excluded from the analysis, letter acuity

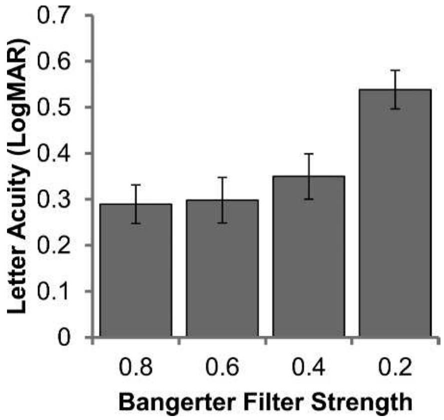

FIGURE 1. Letter acuity assessed through Bangerter filters. The baseline acuity with no filter in place was 0 logMAR for all participants. *Error bars* show 95% confidence intervals (CIs).

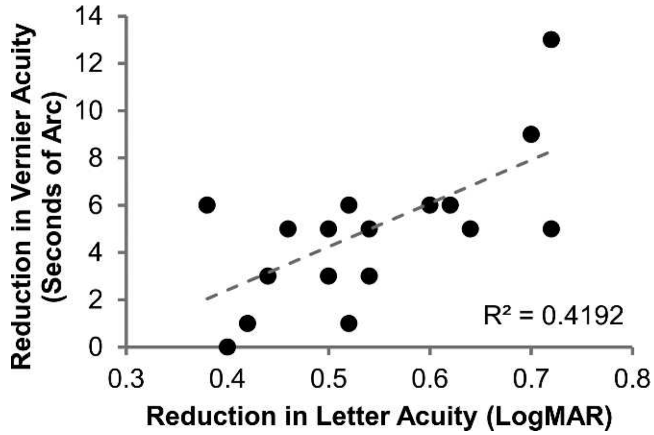

FIGURE 3. The relationship between the deficits in vernier acuity and letter acuity induced by the 0.2 strength Bangerter filter.

decreased significantly with increasing Bangerter filter strength ($F_{3,60} = 44.1$, $P < 0.001$). However, the amount of visual acuity reduction was not consistent across the different filter strengths (Fig. 1). Post hoc paired *t*-tests (assessed at the Bonferroni corrected critical P value of 0.008) demonstrated that visual acuity for viewing through the 0.2 filter strength was significantly worse than acuity when viewing through any of the other three filter strengths (0.2 vs. 0.4, $t_{20} = 8.1$, $P < 0.001$; 0.2 vs. 0.6, $t_{20} = 9.5$, $P < 0.001$; 0.2 vs. 0.8, $t_{20} = 11.8$, $P < 0.001$). Interestingly, the effects of the 0.4, 0.6, and 0.8 strength filters on letter acuity were not reliably different from one another ($P > 0.008$).

A similar pattern of results was observed for vernier acuity (Fig. 2). All filters significantly reduced vernier acuity relative to baseline (0.8, $t_{20} = 4.7$, $P < 0.001$; 0.6, $t_{20} = 5.6$, $P < 0.001$; 0.4, $t_{20} = 7.0$, $P < 0.001$; 0.2, $t_{20} = 8.2$, $P < 0.001$), and vernier acuity decreased with increasing Bangerter filter strength when baseline data were excluded from the analysis ($F_{2,4} = 23.7$, $P < 0.0001$). Again, the effect of filter strength was not consistent. The 0.2 filter differed from all other filter strengths (0.2 vs. 0.4, $t_{20} = 4.7$, $P < 0.001$; 0.2 vs. 0.6, $t_{20} = 5.3$, $P < 0.001$; 0.2 vs. 0.8, $t_{20} = 6.7$, $P < 0.001$), whereas vernier acuity did not vary significantly across the 0.4, 0.6, and 0.8 filter strengths ($P > 0.008$). The magnitude of the letter acuity deficit induced by the 0.2 strength Bangerter filter was reliably correlated with the corresponding vernier acuity deficit (Fig. 3; Pearson's $r = 0.65$, $P = 0.002$).

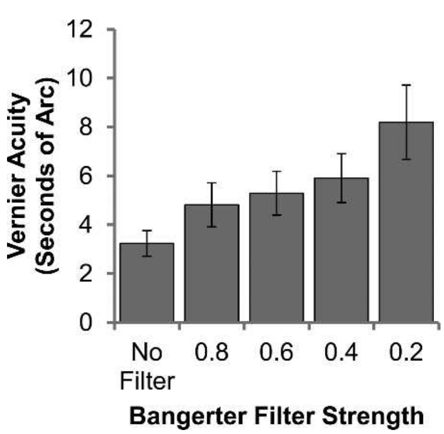

FIGURE 2. Vernier acuity with and without Bangerter filters. *Error bars* show 95% CIs.

Bangerter filters significantly reduced contrast sensitivity across all spatial frequencies measured (Fig. 4; $F_{4,80} = 74.4$, $P = < 0.001$), although the magnitude of the filter effect differed with spatial frequency (significant filter × spatial frequency interaction, $F_{13,266} = 15.16$, $P < 0.001$). This pattern of results remained when the no-filter baseline measurements were excluded from the analysis (main effect of filter strength, $F_{2,46} = 44.9$, $P < 0.001$ and filter strength × spatial frequency interaction, $F_{11,218} = 4.2$, $P = 0.01$). As can be seen from Figure 4, the 0.2 strength filter had the most pronounced effect on contrast sensitivity whereas the other three filter strengths had similar effects to one another. Furthermore, Figure 4 shows that the filters had a greater effect on contrast sensitivity for higher spatial frequencies (the last three data points in Fig. 4 representing spatial frequencies of 2, 5, and 10 cpd).

Penalization of the dominant eye with a Bangerter filter reliably decreased stereoscopic depth perception for all filter strengths (Fig. 5; 0.8, $t_{20} = 16.0$, $P < 0.0001$; 0.6, $t_{20} = 28.9$, $P < 0.0001$; 0.4, $t_{20} = 26.0$, $P < 0.0001$; 0.2, $t_{20} = 25.8$, $P < 0.0001$). In addition, the four filter strengths differed reliably from one another in the extent to which they reduced stereopsis ($F_{2,47} = 69.9$, $P < 0.0001$; 0.8 vs. 0.6, $t_{20} = 6.0$, $P < 0.0001$; 0.8 vs. 0.4, $t_{20} = 9.3$, $P < 0.0001$; 0.8 vs. 0.2, $t_{20} = 10.8$, $P < 0.0001$; 0.6 vs. 0.4, $t_{20} = 5.4$, $P < 0.0001$; 0.6 vs. 0.2, $t_{20} = 7.7$, $P < 0.0001$; 0.4 vs. 0.2, $t_{20} = 4.6$, $P = 0.001$). It is worth noting that even the weakest Bangerter filter had a pronounced effect on stereopsis, reducing the threshold by a factor of 2.6 (SD = 0.88) or 0.36 logMAR. When the no-filter baseline data was removed from the analysis to account for this pronounced decrease, the reduction in stereo sensitivity with increasing Bangerter filter strength was well fit with a linear function ($R^2 = 0.98$, $P = 0.009$). To assess whether the effect of Bangerter filters on stereo acuity was related to their effect on monocular visual acuity, we conducted a linear regression with a dependent variable of stereo sensitivity and independent variables of Bangerter filter strength (four levels), monocular acuity at each Bangerter filter strength (four measurements), and observer (21 observers). We did not include baseline (no-filter) data in the model as there was very little variation in monocular acuity or stereo sensitivity for this condition across observers. Stereo sensitivity was reliably predicted by Bangerter filter strength (beta = –0.7, $t = –5.3$, $P < 0.001$) but not by the effect of the Bangerter filters on monocular acuity (beta = 0.12, $t = 0.9$, $P = 0.4$) indicating that the effect of Bangerter filters on stereopsis is not reliably related to their effects on monocular acuity. This is illustrated in Figure 6 where the individual participant data for stereo sensitivity and monocular acuity are shown for each

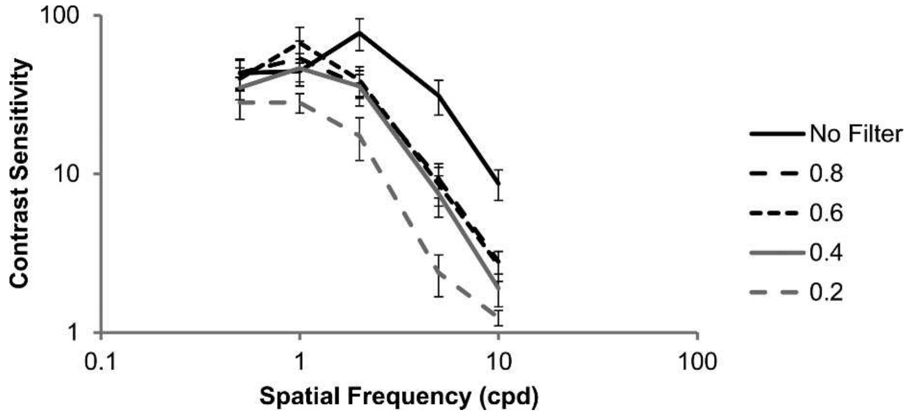

FIGURE 4. The effect of Bangerter filters on contrast sensitivity. Bangerter filters tended to reduce sensitivity for the higher spatial frequencies, and the effects of the 0.8, 0.6, and 0.4 filters were similar to one another. *Error bars* show 95% CIs.

strength of Bangerter filter. The reduction in stereo sensitivity with increasing Bangerter filter strength is not matched by an orderly reduction in monocular visual acuity, and there are no reliable relationships between monocular visual acuity and stereo sensitivity within the data corresponding to each separate filter.

Bangerter filters induced partial suppression on the Worth-4-dot test at both distance and near (Fig. 7). No participants experienced full suppression. The 95% confidence intervals (CIs) assigned to the proportions shown in Figure 7 were calculated using the Wilson score interval[40] and indicate that the extent of partial suppression did not vary with Bangerter filter strength or test distance (the CIs overlap).

The Effect of Bangerter Filters, Optical Defocus, and ND Filters on Binocular Function

For each participant, each strength of Bangerter filter was matched with a level of optical defocus and a strength of ND filter that produced a corresponding deficit in monocular acuity (see Methods for details). The group means for these comparisons are shown in the table.

Measurements of stereopsis with the dominant eye penalized with a Bangerter filter, a corresponding level of defocus, or a corresponding strength of ND filter are shown in Figure 8. The effect of Bangerter filters was characterized by a sharp reduction in stereopsis for the weakest filter and then a gradual reduction for subsequent filters. There was very little effect of defocus on stereopsis with modest but reliable reductions occurring only for the highest level of defocus used. ND filters had the opposite effect, with even the weakest ND filter essentially eliminating stereopsis.

Measurements of suppression using the Worth-4-dot test are shown in Figure 9 for the near-viewing distance and Figure 10 for the far-viewing distance. Both Bangerter filters and ND filters induced partial suppression in the majority of participants for both viewing distances, whereas defocus did not tend to induce partial suppression.

In order to provide a quantitative measurement of the suppression induced by the 0.6, 0.4, and 0.2 strength of Bangerter filters and matched ND filters, we assessed the effect of each filter type placed over the nondominant eye on performance of a dichoptic signal/noise orientation discrimination task.[6] Within this task signal elements were presented to one eye, and noise elements were presented to the other eye, and the relative contrast of elements between the two eyes was varied (see Methods section for further details). The

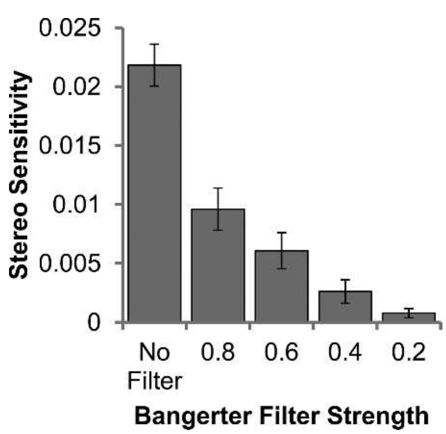

FIGURE 5. The effect of Bangerter filters on stereoscopic depth perception measured using the Randot Preschool Stereoacuity Test. Data are shown in units of stereo sensitivity (1/threshold in seconds of arc). *Error bars* show 95% CIs.

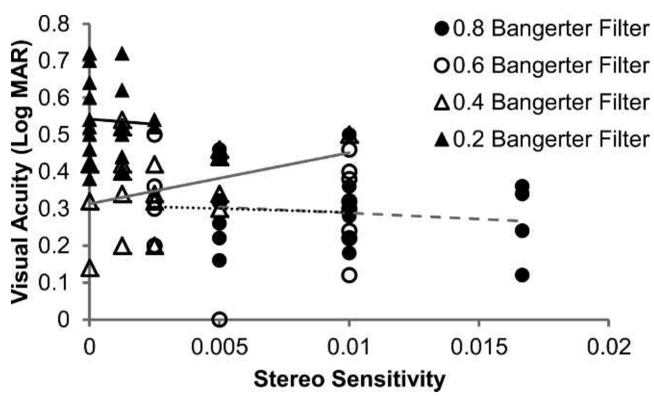

FIGURE 6. The effect of Bangerter filters on stereo sensitivity (1/stereo threshold in seconds of arc) and visual acuity (logMAR). Each data point represents an individual participant. Measurements made using the 0.8 strength filter are shown with *filled circles*, the 0.6 filter with *open circles*, the 0.4 filter with *open triangles*, and the 0.2 filter with *closed triangles*. The linear functions represent the best linear fit to the data for each strength of Bangerter filter. The *grey dashed line* represents the fit to the data for the 0.8 strength Bangerter filter, the *black dashed line* represents the 0.4 filter data, the *solid grey line* the 0.6 filter data, and the *solid black line* the 0.2 filter data. The 0.2 strength filter reduced both acuity and stereopsis relative to the other filters, but there was no evidence for a consistent relationship between the effects of each filter on both stereopsis and monocular acuity.

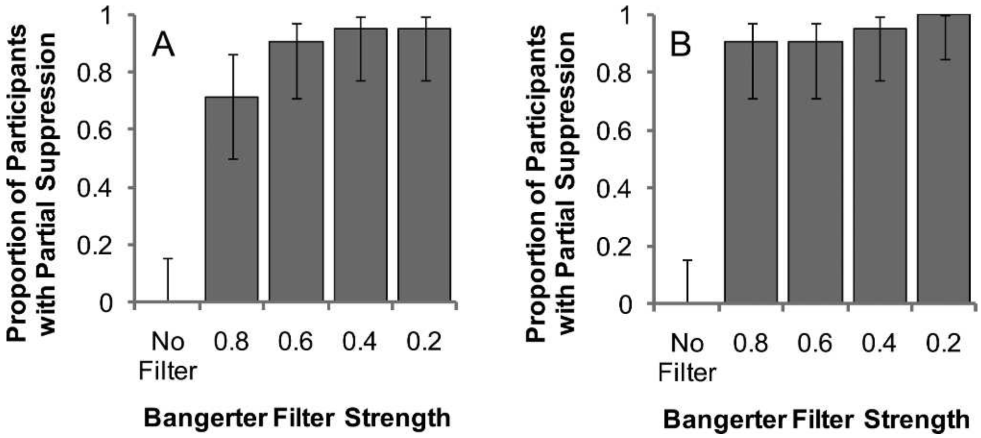

Figure 7. The effect of Bangerter filters on perception of the Worth-4-dot at near (**A**) and far (**B**) viewing distances. All filters induced partial suppression. Data are shown as the proportion of participants ($n = 21$) that reported partial suppression for each filter strength. No participants experienced partial suppression for the no-filter condition. *Error bars* show 95% CIs for binomial proportions.

group results are shown in Figure 11. For each of the panels, the threshold percentage of signal elements required for 75% correct performance is shown on the y-axis, and the contrast of the elements presented to the eye without the filter is shown on the x-axis. The contrast of the elements presented to the eye with the filter was always 100%. The thresholds measured when signal elements were presented to the eye with the filter are shown with open symbols, and the thresholds measured when signal elements were presented to the eye without the filter are shown with closed symbols. The solid and dashed lines show fits to these two data sets, respectively. The solid arrows indicate the intersection of these fits which represents the amount of suppression.[6,13,36] When the intersection coincides with a large value on the x-axis, this indicates that the two eyes are combining information approximately equally and that there is little or no suppression. However, if the intersection coincides with a small value on the x-axis, this indicates strong suppression as a large contrast offset is required for information to be combined equally between the two eyes.

The top panel in Figure 11 shows the baseline data with no filter in place. There was a small amount of suppression within the range to be expected based on normal eye dominance.[30,35] Below this panel, data for progressively stronger Bangerter filters are shown in the left column, and data for corresponding ND filters are shown in the right column. The 0.6 Bangerter filter had no effect on suppression relative to baseline measurements, whereas the 0.4 Bangerter filter induced a small increase in suppression. The 0.2 Bangerter filter, however, induced strong suppression to the extent that the two linear fits no longer intersect within the range of contrast offsets measured. The results for the corresponding ND filters (right column of Fig. 11) differ markedly from the Bangerter filter results. Even the weakest ND filter, corresponding (in terms of its effect on acuity) to the 0.6 strength Bangerter filter, induced very strong suppression and required the intersection point to be extrapolated from the range of contrasts measured. These data are consistent with the stereo acuity data in that ND filters induce a significantly greater disruption of binocular function than Bangerter filters even when the effects on monocular visual acuity were matched.

Discussion

This study had two main aims. The first was to investigate why partial occlusion with Bangerter filters does not result in improved binocular outcomes relative to full occlusion for patients with amblyopia.[20] The second was to compare the effects of

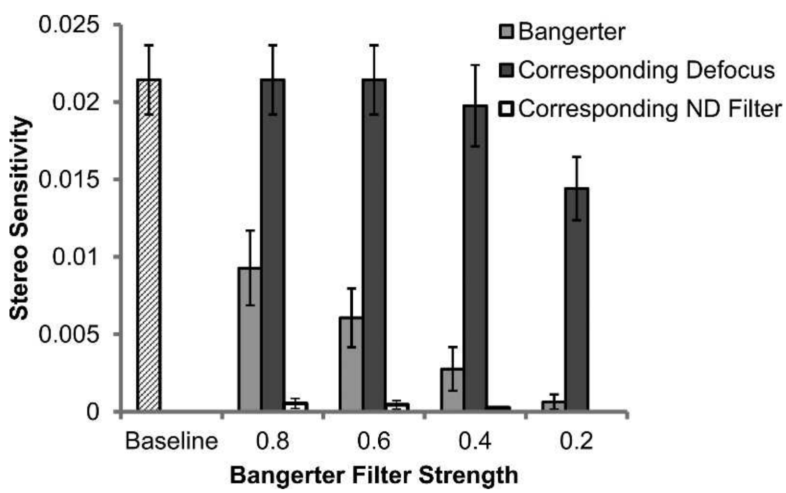

Figure 8. The effect of Bangerter filters (*light grey bars*) and corresponding levels of optical defocus (*dark grey bars*) and ND filter strength (*open bars*) on stereopsis. *Error bars* show 95% CIs.

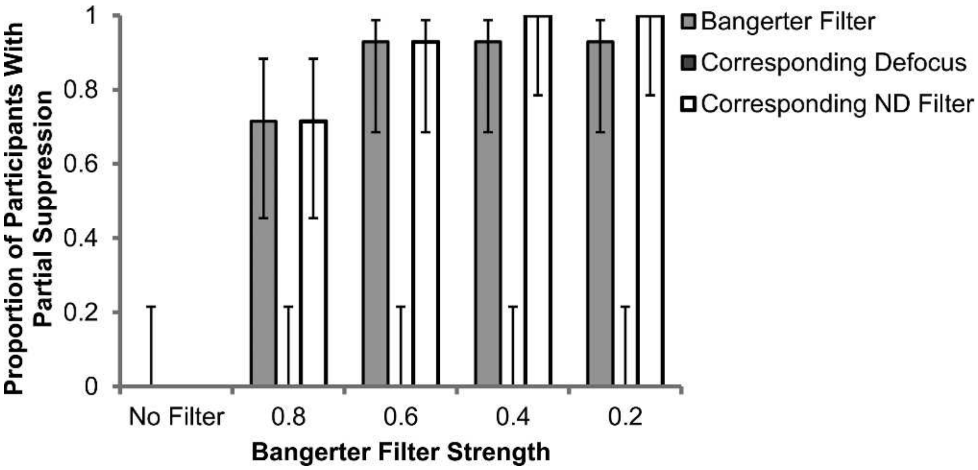

FIGURE 9. The proportion of participants experiencing partial suppression on the Worth-4-dot test for each strength of Bangerter filter and corresponding levels of defocus and ND filter strength. Both Bangerter and ND filters tended to induce partial suppression, even for the weakest filter strength, whereas defocus did not induce any suppression on this test (only *error bars* are visible). *Error bars* represent 95% CIs (Wilson score interval).

monocular partial occlusion using Bangerter filters, optical defocus, and ND filters on normal binocular visual function.

In order to address the first aim, we measured a range of monocular and binocular visual functions with different strengths of Bangerter filter placed over one eye. We found that Bangerter filters of different densities or "strength" did not produce a graded change in visual function. In terms of visual acuity, the 0.8, 0.6, and 0.4 strength filters produced very similar decrements to one another. These decrements were on the order of 0.3 logMAR with the 0.2 filter producing a greater deficit of approximately 0.55 logMAR. These results are consistent with previous reports indicating that the midrange filters have very similar[23] and, in some cases, nonmonotonic[21] effects on visual acuity. We found a very similar pattern of results for vernier acuity and, in agreement with previous work,[22,23] the decrement in acuity was correlated with the decrement in vernier acuity suggesting a common action of the microelements within the filters on these two visual functions. Importantly, our results for the effect of the 0.2 strength filter on visual acuity are in direct agreement with those found by Rutstein et al.[24] who also reported an average visual acuity of 0.55 logMAR (equivalent to 20/71) when children with amblyopia viewed through a 0.2 filter using their nonamblyopic eye. This indicates that the effect of these filters on acuity is similar for adults with normal vision and children with amblyopia.

The observation that the 0.8, 0.6, and 0.4 filters had very similar effects to one another also applied to contrast sensitivity. The greatest contrast sensitivity impairments occurred for the highest spatial frequencies tested with the low frequencies being relatively unaffected, even for the strongest 0.2 filter. This is in direct agreement with the measured modulation transfer functions of Bangerter filters, which demonstrate a preferential reduction of contrast in the middle-range spatial frequencies to high-range spatial frequencies.[21] In terms of binocular visual function, all Bangerter filters tended to induce partial suppression on the Worth-4-dot, and there was a precipitous drop in stereo sensitivity (0.36 logMAR) even with the weakest 0.8 strength filter we tested. This progressed with increasing filter strength until the 0.2 strength filter which essentially precluded any stereoscopic depth perception. We found that this effect of Bangerter filters on stereopsis was not reliably predicted by their effects on monocular acuity, and that the effect on stereopsis was much more pronounced than the effect on acuity. For example, the 0.4 filter reduced acuity by an average of 0.35 logMAR but reduced stereo sensitivity by an average of 0.9 logMAR. This is

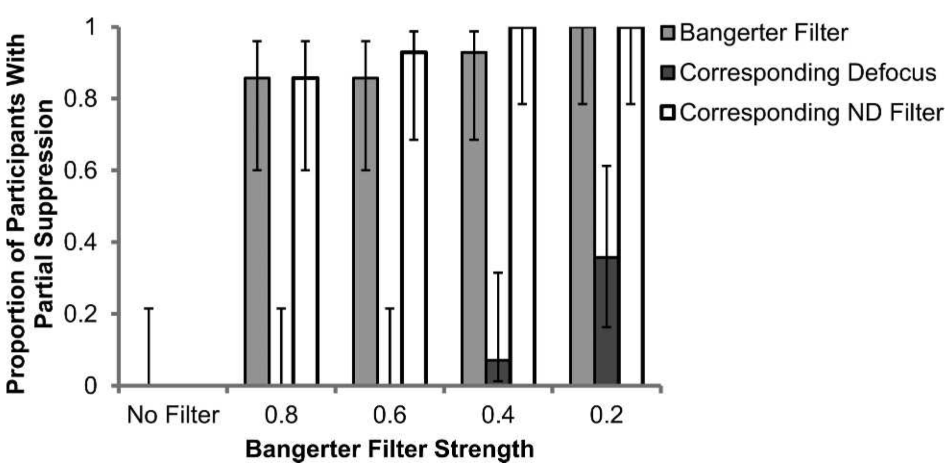

FIGURE 10. All measurements are identical to those displayed in Figure 9; however, Figure 10's results are from the far viewing distance while the results presented in Figure 9 are from the near viewing distance.

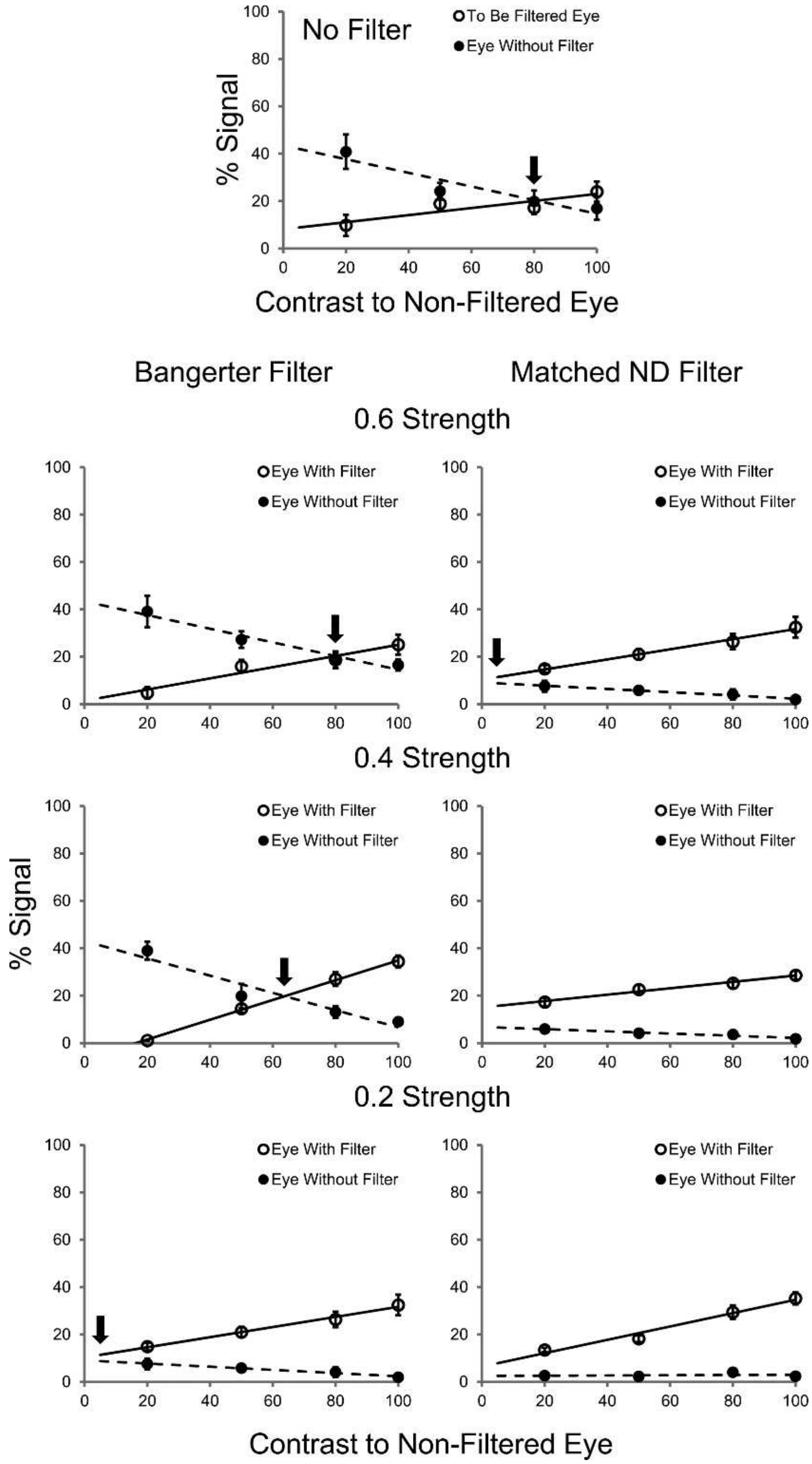

Figure 11. The effect of monocular Bangerter and ND filters on suppression measured using a dichoptic orientation discrimination task. The *top panel* shows baseline measurements with no filter in place. Below the *top panel*, the *left column* shows data for progressively stronger Bangerter filters. The *right column* shows the data for matched ND filters. Please see article text for further details.

consistent with a previous investigation which reported that Bangerter filters had a pronounced effect on stereopsis when measured using Randot Tests and that this effect was not well correlated with the effect of the filters on monocular acuity[22]; see also Larson and Bolduc.[41]

As a whole, our results and those of previous studies[21–23] indicate that the effects of Bangerter filters on visual function are not graded according to the manufacturer's reported strength, that the effects on contrast sensitivity are more pronounced for middle-range spatial frequencies to high-range spatial frequencies, and that the effects on stereopsis are disproportionately high relative to the effects on monocular acuity. The lack of a graded effect has significant implications for the practice of tapering off the strength of Bangerter filters at the end of amblyopia therapy.[14] In addition, these characteristics speak directly to the finding that the use of Bangerter filters to treat amblyopia does not result in improved binocular outcomes relative to full occlusion.[20] The 0.2 and 0.3 filters used in this previous study would not only have reduced acuity in the fellow eye but also would have significantly disrupted binocular function rather than promoting binocular recovery. Notably, the fact that Bangerter filters have such profound detrimental effects on binocular vision has been exploited for the treatment of diplopia[42–44] and the induction of deprivation amblyopia in primates.[45] This is not to say that these filters are inappropriate for amblyopia therapy, in fact they are as effective as full occlusion and are more cosmetically acceptable[20]; however, they should not be considered as a reliable method of promoting binocular function. We feel the reason for this is due to the spatial distortions introduced by Bangerter filters. We were unable to use our documented motion coherence task[6] to gauge the degree of suppression produced by Bangerter filters because these filters severely distort the motion direction of individual elements used in the coherence task. Such a distortion would be expected to affect stereopsis much more severely than equivalent optical defocus because it decorrelates the spatial information between the eyes[46] that is fundamental to stereoscopic processes.

Our comparison between the effects of Bangerter filters, optical defocus, and ND filters on binocular function began with matching the monocular acuity deficits induced by the three types of partial occlusion. With the acuity measured for each Bangerter filter as the point of comparison, relatively low amounts of optical blur (from 0.61–1.12 D) and relatively high amounts of luminance reduction (from 1.86 to >2.8 log units) were required to reduce acuity to comparable levels. The amount of blur required for each level of visual acuity was in good agreement with a previous investigation into the effects of blur on acuity.[39]

The results from the Worth-4-dots test, the Preschool Randot Test, and the psychophysical measurements of interocular suppression indicated that although the effects on monocular acuity were the same for each type of filter, both Bangerter and ND filters degraded binocular function whereas optical defocus did not. In addition, ND filters had a much more pronounced effect on binocularity than Bangerter filters. This was notable as monocular acuity was particularly resilient to luminance reduction using ND filters. One intriguing possible explanation for the pronounced effects of ND filters on binocular function is the activation of suppressive mechanisms involving the lateral geniculate nucleus (LGN), where cells are sensitive to changes in luminance (see Reference 30 for a discussion of this possibility). Both contrast and luminance have been implicated in the suppressive interactions that take place in amblyopia[4,6,47] suggesting that both the LGN and cortex may be involved. Presumably, any suppressive interactions sensitive to spatial distortion or blur would not occur until at least the level of the primary visual cortex where cells are sensitive to spatial frequency and orientation.

The results of this study indicate that the three methods of partial occlusion we tested do not have comparable effects on binocular function and that the binocular effects are not predictable from the monocular effects. Of the three types of partial occlusion, optical defocus was the most permissive for binocular function and may, therefore, allow for better binocular outcomes if used for amblyopia therapy. Optical defocus tends to reduce stereoacuity (i.e., sensitivity for fine disparities) but does allow stereopsis to occur at lower spatial scales that support coarse disparities. On the basis of our results, it seems that partial occlusion with Bangerter filters or ND filters cannot replicate the binocular stimulation that can be achieved using the combination of dichoptic computer displays, stimuli calibrated to each participant's level of suppression, and games or psychophysical tasks that require combination of information between the eyes.[6,13,36] This more recent approach has the advantage of allowing binocular vision to function at all spatial scales, unlike optical defocus where only coarse spatial scales are able to be combined.

Acknowledgments

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