Visual search deficits in amblyopia

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Amblyopia is a neurodevelopmental disorder defined as a reduction in visual acuity that cannot be corrected by optical means. It has been associated with low-level deficits. However, research has demonstrated a link between amblyopia and visual attention deficits in counting, tracking, and identifying objects. Visual search is a useful tool for assessing visual attention but has not been well studied in amblyopia. Here, we assessed the extent of visual search deficits in amblyopia using feature and conjunction search tasks. We compared the performance of participants with amblyopia ($n = 10$) to those of controls ($n = 12$) on both feature and conjunction search tasks using Gabor patch stimuli, varying spatial bandwidth and orientation. To account for the low-level deficits inherent in amblyopia, we measured individual contrast and crowding thresholds and monitored eye movements. The display elements were then presented at suprathreshold levels to ensure that visibility was equalized across groups. There was no performance difference between groups on feature search, indicating that our experimental design controlled successfully for low-level amblyopia deficits. In contrast, during conjunction search, median reaction times and reaction time slopes were significantly larger in participants with amblyopia compared with controls. Amblyopia differentially affects performance on conjunction visual search, a more difficult task that requires feature binding and possibly the involvement of higher-level attention processes. Deficits in visual search may affect day-to-day functioning in people with amblyopia.

Introduction

Amblyopia (lazy eye) is a neurodevelopmental disorder traditionally characterized by low-level deficits including reduced visual acuity, stereoacuity, and contrast sensitivity (Hess & Howell, 1977; Levi & Harwerth, 1977; Levi, Harwerth, & Manny, 1979; McKee, Levi, & Movshon, 2003; Thomas, 1978). It arises from abnormal visual experience in early childhood, when input to the central nervous system from one eye is suppressed. Research during the past few decades has shown that the amblyopic deficit is much more extensive than originally thought. For example, it has been demonstrated that participants with amblyopia have deficits in perception of global motion (Aaen-Stockdale & Hess, 2008; Simmers, Ledgeway, Hess, & McGraw, 2003), processing of global contours (Levi, Yu, Kuai, & Rislove, 2007), and shape detection (Hess, Wang, Demanins, Wilkinson, & Wilson, 1999). Several recent studies have also shown visual attention deficits in amblyopia (Ho et al., 2006; Popple & Levi, 2008; Sharma, Levi, & Klein, 2000; Tripathy & Levi, 2008).

Amblyopia and visual attention

Attention is a high-level process that allows us to choose visual information important for the task at hand (Wolfe, 2000) while filtering out distracting information. The allocation of attention is influenced both by top-down goal-directed behaviors as well as bottom-up inputs related to the saliency of the visual targets (Bisley, 2011). Several recent studies examined the effect of amblyopia on visual attention (Ho et al., 2006; Popple & Levi, 2008; Roberts, Cymerman, Smith, Kiorpes, & Carrasco, 2016; Sharma et al., 2000; Tripathy & Levi, 2008). For example, Sharma et al. (2000) found that people with amblyopia undercounted features presented to the amblyopic eye, although the attentional cuing effects were similar for those with amblyopia and controls. Roberts et al. (2016) examined involuntary and voluntary attention in an orientation discrimination task where there were either valid, invalid, or neutral cues to the location of the target element before it appeared on the display. They found no effect of amblyopia on response accuracy. On the other hand, adults and children with amblyopia exhibited impaired multiple object tracking, both in the amblyopic and the fellow eyes (Ho et al., 2006; Tripathy & Levi, 2008). In addition, attentional blink (failure to detect a second target shown shortly after the first is presented in a rapid sequence of images) was less finely tuned temporally in the amblyopic eye than in the fellow eye in adults (Popple & Levi, 2008). These studies suggest an important connection between visual attention and amblyopia. Moreover, our recent meta-analysis of plasticity in adults with amblyopia (Tsirlin, Colpa, Goltz, & Wong, 2015) suggested that visual attention might play an important role in modulating the amblyopic deficit.

Visual search

Visual search is one of the most well-studied and relevant paradigms for understanding visual attention. While some visual search paradigms focus on accuracy as the main outcome measure (Cameron, Tai, Eckstein, & Carrasco, 2004; Eckstein, Thomas, Palmer, & Shimozaki, 2000), in other visual search paradigms, the participants are instructed to find a target among distractors as quickly as possible, while either scanning the scene or maintaining fixation (Wolfe, 1998; Wolfe, 2000). Participants' reaction time (RT) and slope of reaction time versus number of distractor items (RT/item slope) are the typical primary dependent variables in these paradigms. An increase in RT with an increase in the number of distractor items (i.e., a steeper RT/item slope) could indicate a greater attentional load (Wolfe, 1998; Wolfe, 2000). However, this could also be attributed to other factors, including retinal loci as set size increases (Carrasco & Frieder, 1997).

Feature search and conjunction search are two classic types of visual search paradigms. In feature search, the target has one distinguishing feature from the distractors (e.g., a red line among green lines). In conjunction search, the target has a combination of features that distinguish it from the distractor (e.g., a red horizontal line among red vertical lines and green horizontal and vertical lines). Higher-order processing is needed to bind conjunction features together. In older serial models of visual search, feature search had been considered preattentive (Treisman, 1985; Treisman & Gelade, 1980). It was assumed that for certain features, such as orientation or color, processing of the visual scene occurs in parallel using low-level feature maps encoded by subpopulations of highly tuned neurons (Treisman, 1985; Treisman, 1986; Treisman & Gelade, 1980). Thus, RTs in feature searches were thought to be unaffected by the number of distractors. Conjunction search (or searches for features not represented in feature maps) was said to be performed in a serial fashion, where attention was directed to one item at a time. Thus, RTs increased linearly with an increase in the number of items. Some subsequent research, especially based on measuring accuracy with timed searches, suggested that all visual search might be done in a parallel fashion with RTs increasing due to the decreasing signal-to-noise ratio or a limited capacity of the system, which yielded parallel models of visual search (Cameron et al., 2004; Eckstein et al., 2000; Verghese, 2001). The serial/parallel debate is ongoing, and the exact mechanisms of visual search are still being elucidated (Moran, Zehetleitner, Liesefeld, Müller, & Usher, 2016; Thornton & Gilden, 2007). For the purposes of the current discussion, we adopted the Guided Search 4.0 (GS4) model proposed by Wolfe et al. (2007). This is the latest version of a model that has been in development for the past 20 years. It combines both parallel and serial processes and can predict many aspects of visual search (Moran et al., 2016; Wolfe, 2007). In this model, shown in a simplified schematic in Figure 1, the parallel processing in early vision provides input to the object recognition process via a selective bottleneck governed by the allocation of visual attention. Preattentive processing in this model reflects any visual processing that occurs prior to the deployment of attention. The "guidance" system uses preattentive processing to signal potential areas of interest and to essentially rank items in terms of attentional priority. In simple feature search, which has a strong bottom-up component, this guidance is very effective, requiring almost no serial processing, so adding distractors does not increase RTs significantly. In a difficult conjunction search, the guidance is not as effective, and a more serial deployment of attention is
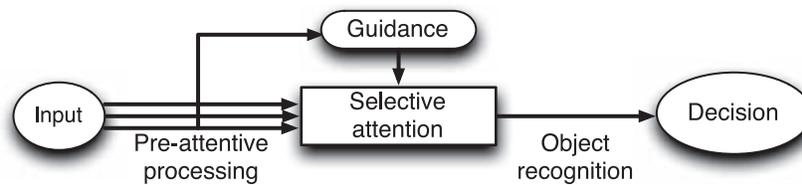
Figure 1. Simplified version of the Guided search 4.0 model, adapted from Wolfe (2007).

required, generating increases in RTs per added distractor. Once items are selected for processing, information starts accumulating on all items in parallel. A target or a distractor determination is made when information reaches a threshold.

Wolfe and colleagues (2007) liken the selective attention bottleneck to a carwash: Although only one car can enter a carwash at a given time, several cars can be inside the carwash simultaneously. Similarly, during visual search, only one item (or a group of items) can be selected for processing at a time, but several items can be in the process of being examined simultaneously (information accrual). Important variables in this process include (a) processing time (the time it takes to process individual items as reflected in an overall increase in RT; processing time can also be thought of as the time required to classify an item as a target or a distractor) and (b) processing rate (the rate at which items can be selected for processing as reflected in the RT/item slopes).

Amblyopia and visual search

To our knowledge, only a few studies have assessed visual search in amblyopia. In general, they were limited by small sample size or lack of RT measurements. For example, Sireteanu and Rettenbach (2000) assessed perceptual learning in visual search in four participants with strabismic amblyopia. They found no difference in perceptual learning rates between the amblyopia and the control groups; however, they did not report RTs or any other common measures of performance in visual search. Popple and Levi (2005) measured the accuracy of target localization in a simple feature search task in one participant with strabismic amblyopia. They found that the participant's percentage correct responses did not differ substantially from controls. Because the viewing time in this experiment was fixed, RTs were not measured. Finally, Neri and Levi (2006) used feature and conjunction search tasks with line segments of varying length to study feature binding in normal and amblyopic vision. They measured line-length thresholds for identifying a target line among distractor lines. They found that line-length thresholds for conjunction search were elevated during amblyopic eye viewing but not with the fellow eye

viewing. Again, because the stimulus presentation times were fixed, RTs were not measured.

Current experiments

Importantly, all of the studies referenced above (Neri & Levi, 2006; Popple & Levi, 2005; Sireteanu & Rettenbach, 2000) did not explicitly control for low-level sensory and visuomotor amblyopic deficits. When testing higher-level visual function in amblyopia, it is important to design the experiments carefully to ensure that the typical low-level visual and visuomotor deficits are not the underlying cause of the observed higher-level deficits. Using both feature and conjunction search tasks, we addressed these issues specifically by (a) using Gabor patches with a low central frequency as stimuli (2.5 cpd), to ensure visibility in amblyopic participants; (b) using perceptually equalized stimulus properties across participants and viewing conditions to account for crowding (Bonneh, Sagi, & Polat, 2007) and contrast deficits (Hess & Howell, 1977; Levi et al., 1979; Levi & Harwerth, 1977; Thomas, 1978) that are characteristic of amblyopia; and (c) controlling for eye movements using a central fixation target and monitoring fixation using an eye tracker (a covert attention task). This was performed because we have previously shown that saccades in people with amblyopia have longer latencies than those in normal controls, which could lead to longer RTs (Niechwiej-Szwedo, Chandrakumar, Goltz, & Wong, 2012; Niechwiej-Szwedo, Goltz, Chandrakumar, Hirji, & Wong, 2010). Importantly, however, fixation does not impede participants from performing the task because visual search can be performed without eye movements (Klein & Farrell, 1989; Zelinsky & Sheinberg, 1997).

Our experimental design included both feature and conjunction search tasks. Given that simple feature search is associated with effective guidance from preattentive processes and that we effectively controlled for low-level amblyopic deficits, we predicted that there will be no difference in feature search performance between participants with amblyopia and controls. By ensuring that the low-level deficits are not the cause for any observed differences between groups, the feature search task in effect serves as a control for the conjunction search task. Accordingly, any performance

differences in participants with amblyopia on conjunction search as reflected in significantly longer RTs (increased processing time) and/or steeper RT/item slopes (slower processing rate) would indicate a differential visual search deficit in amblyopia that could include attention.

Methods

Participants

Ten participants with anisometropic, strabismic, or mixed amblyopia completed the experiments. Clinical characteristics for the participants with amblyopia are shown in Table 1. Twelve participants with normal or corrected-to-normal vision with no history of amblyopia or strabismus formed the control group. All participants were assessed by a certified orthoptist for best-corrected visual acuity (ETDRS chart), binocular fusion (Bagolini and Worth 4 dot tests), stereoacuity (Randot and Stereo Fly), and eye alignment (cover-uncover test and alternate prism cover test). Participants also underwent a custom-designed stereopsis test with random dot stereograms on a mirror stereoscope. Eye dominance in controls was assessed using a version of the Dolman test. Amblyopia was defined as visual acuity of 0.1 logMAR (20/25) or worse in the amblyopic eye with a minimal intraocular difference of 0.2 logMAR. Anisometropia was defined as a difference of 1 diopter in either the spheric or astigmatic correction between the two eyes, strabismus as the presence of a manifest deviation (heterotropia) on cover test, and mixed amblyopia as the presence of both anisometropia and manifest strabismus with a deviation greater than 8 prism diopters.

To reflect the natural continuum of binocularity in participants with amblyopia (ranging from residual stereopsis, to binocular fusion only, to no measurable binocularity), we devised a new unified binocularity score. We assigned this score using results from standard clinical tests of binocular fusion (Bagolini and Worth 4 dots) and stereopsis (clinical and lab-based) in ascending order to reflect the hierarchy of binocularity. The scoring system is detailed in Table 2.

The study was approved by the Research Ethics Board at The Hospital for Sick Children. All protocols adhered to the guidelines of the Declaration of Helsinki. Informed consent was obtained from all participants.

Apparatus

All experiments were run using Psychtoolbox 3.0.11 with MATLAB R2011b on a Dell Alienware X51 R2

				Visual acuity (logMAR)		Refractive correction			Binocularity		
ID	Age	Sex	Type	R	L	R	L	Deviation (near; prism diopters)	Binocular Fusion (Bagolini/W4D)	Stereo acuity (Randot/RDS) (arcsecs)	Unified score
1	36	F	AN	0.00	0.40	−1.00	+1.00	LET 2	Yes	140/137	6
2	23	F	AN	−0.10	0.48	−2.25	+0.25+2.25×85	LET 2	Yes	200/366	6
3	22	F	AN	0.00	0.48	−1.50+0.50×80	+1.00+1.25×95	LET 2	Yes	200/846	5
4	24	M	AN	0.1	−0.10	+2.50	Plano	RXT 2	Yes	3,000/565	5
5	29	F	AN	0.48	−0.10	−5.00	−1.25	RET 2, ET+E 4	Yes	3,000/1,611	5
6	48	F	AN	0.70	0.00	+2.25+0.25×174	−0.75	RET 2	Yes	400/480	5
7	32	F	ST	−0.10	0.30	−1.00+0.50	−1.00+0.50	LET 8, ET+E 10	Yes	400/nil	4
8	26	F	ST	0.40	−0.10	+2.25+1.50×164	+2.25+1.50×44	RET 16, ET+E 20, RHT 3	Diplopic	nil/nil	1
9	43	F	ST	0.30	0.00	−1.25+2.25×65	−0.75+1.75×100	RET 30, RHT 5	Suppression	nil/nil	0
10	27	F	MX	0.8	−0.10	+7.00+1.00×180	+6.00	RXT 20	Suppression	nil/nil	0
Mean age: 31				Mean amblyopic acuity: 0.44						Mean unified binocularity: 3.7	

Table 1. Clinical characteristics of participants with amblyopia. *Notes:* Deviation at near is reported here for best comparison as the stimuli used for the experiments were presented at near (100 cm). For description of the unified binocularity score, please see the Methods section and Table 2. F = female; M = male; AN = anisometropic amblyopia; ST = strabismic amblyopia = MX = mixed amblyopia; L = left eye; R = right eye; E = esophoria; ET = esotropia; XT = exotropia; ET+E = total esodeviation as determined by simultaneous prism cover test (ET) and alternate prism cover test (ET+E); RDS = random dot stereograms.

Score	Test	Result
0	Bagolini and Worth 4 dot	Suppression on both tests
1	Bagolini and Worth 4 dot	Diplopic/simultaneous perception on one of the tests
2	Bagolini	Fused
3	Worth 4 dot	Fused
4	Contour stereopsis (Stereo Fly/Randot circles)	Poorer than 100 arcsec
5	Contour stereopsis (Randot)	Better than 100 arcsec
5	Stereopsis RDS	400–3,000 arcsec
6	Stereopsis RDS	Better than 400 arcsec
7	Stereopsis RDS	Better than 100 arcsec

Table 2. The unified binocularity score.

desktop computer. The stimuli were displayed on an LED monitor at a refresh rate of 120 Hz (BenQ XL2420TL 24-in. [16:9]; resolution of 1,920 × 1,080; display size 53 × 30 cm). The monitor was linearized using gamma correction. The viewing distance was 100 cm. At this distance and resolution, one pixel subtended 0.87 min of visual angle in the center of the screen. Responses were obtained using a Logitech Gamepad F310. The experiments were performed in a dark room, and participants' heads were stabilized with a chin and forehead rest.

Fixation was monitored with an EyeLink 1000 remote eye tracker (SR Research, Ottawa, Canada) mounted on the desk between the display and the participant. This eye tracker has a 500-Hz sampling rate, 0.5° average accuracy, and 0.05° RMS resolution. Before each session, the eye tracker was calibrated (binocularly or monocularly depending on the session) by recording fixations to known target positions encompassing the entire range of stimulus locations horizontally and vertically.

Procedure and stimuli

Each participant completed four experiments in the same order: Control Experiment 1 (CE1) for contrast threshold estimation, Control Experiment 2 (CE2) for target separation estimation, Experiment 3 for feature search, and Experiment 4 for conjunction search. They were done under three viewing conditions: nondominant (or amblyopic) eye, dominant (or fellow) eye, and binocular. The order of viewing conditions was randomized and counterbalanced across participants. In all experiments, Gabor patches were used with the following parameters: spatial frequency: 2.5 cycles per degree; phase: 90°; aspect ratio: 1.5; bandwidth: 1 or 1.8 octave; and orientation: vertical or horizontal. The phase was chosen such that the full amplitude of the underlying sinusoid would be visible. The background was set to the mean luminance value of the Gabor patches.

Control Experiment 1 for contrast threshold estimation (CE1)

Individual contrast thresholds were obtained using a three-down one-up staircase with a two-interval forced-choice paradigm (with the threshold defined as 79% on the psychometric function). Before the beginning of each trial, a fixation cross was presented in the center of the screen. When the participants were ready, they pressed a button to initiate a trial. The staircase terminated after 12 reversals, and the last six reversals were used to compute the mean threshold. The stimulus was a single vertical Gabor patch of variable contrast presented in the center of the screen (starting contrast was 100%). Contrast changed in steps of 10% before two reversals, in steps of 5% between two and six reversals, and in steps of 1% beyond six reversals. The Gabor patch was presented in one of the two 500-ms intervals, whereas the other interval contained just the luminance matched background. A fixation cross appeared between the intervals for 500 ms. The interval in which the Gabor patch was presented was selected at random on each trial. After the presentation of the two intervals, the participants indicated which interval contained the Gabor.

Control Experiment 2 for target separation estimation (CE2)

The minimal separation between targets at which crowding did not occur was measured using a three-down one-up staircase with a two-alternative forced-choice paradigm (with the threshold defined as 79% on the psychometric function). The staircase terminated after 12 reversals, and the last six reversals were used to compute the mean threshold. Before the beginning of each trial, a fixation cross was presented in the center of the screen. The cross remained throughout the presentation of the stimulus, and the participants were instructed to maintain fixation. When the participants were ready, they pressed a button to initiate a trial. The stimulus was presented for 500 ms. The stimulus consisted of three horizontal Gabor patches arranged in a row. The Gabor patches had the same parameters as in CE1 and were assigned a contrast 10 times the individual threshold established in CE1. The flanking Gabors always had a bandwidth of 1 octave, and the central Gabor had a bandwidth of either 1 or 1.8 octaves. After the presentation of the stimulus, the participant indicated whether the central Gabor was wide or narrow (bandwidth of 1.8 or 1). The bandwidth of the Gabor was selected at random. The Gabors were initially presented with a separation of 105 arcmin between the centers. The separation was decreased in steps of 4.35 arcmin before three reversals and in steps of 0.87 arcmin beyond three reversals. The three Gabors were presented horizontally in the top left

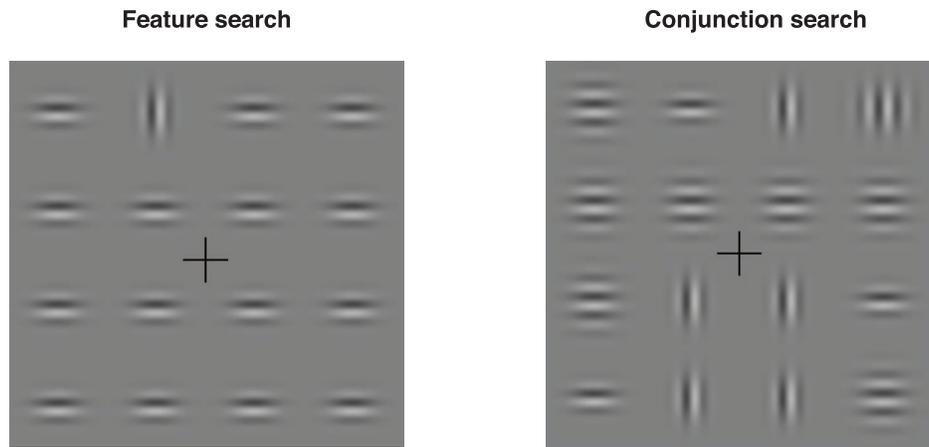**Feature search**   **Conjunction search**

Figure 2. Visual search stimuli. Both images are showing a stimulus with 16 items and target present. For the conjunction search stimulus, the target (90° and 1.8 bandwidth) is the in upper right corner of the image.

corner of a virtual positioning grid, which was used to position Gabors in the visual search experiments (see below). We placed the Gabors at this location because this was the most eccentric position used in our visual search experiments. Because crowding is known to be worse at larger eccentricities (Levi, Klein, & Aitsebaomo, 1985), our estimate of target element separation at the most eccentric location would be large enough to prevent crowding effects at the more central locations. To shift the Gabors closer (or further) at each step, the whole virtual positioning grid was recalculated and either symmetrically minified or magnified. In this manner, when the distance between the centers of Gabor patches decreased, all three Gabors also moved closer to fixation. Because most of our participants could perform the task at the smallest separations between the Gabors (with the exception of two participants in the amblyopic eye condition only), we terminated the experiment after 10 consecutive correct answers at the smallest distance (0.87 arcmin) between the Gabors.

Experiments 3 and 4 for visual search

For both feature and conjunction searches, participants were instructed to find a target element in an array of distractor elements as the number of distractor elements was varied. On each trial, the target was either present or absent. We measured RT as the time it took the participants to determine whether the target was present in the display. Before the beginning of each trial, a fixation cross was presented in the center of the screen. When the participant was ready, they pressed a button to initiate a trial. The stimuli were several Gabor patches randomly positioned within the available slots of a grid such that the (horizontal and vertical) separation between the adjacent patches was equal to the participant's target separation threshold

measured in CE2. The average and standard deviation of the Gabor eccentricities for all stimuli in one session were 2.2° ± 0.73°. The Gabor patches were assigned a contrast value 10 times the participant's individual threshold measured in CE1. The number of Gabors in the array could be 4, 10, or 16. In feature search, the target had an orientation of 90° whereas all the distractors had an orientation of 0°, and all Gabors had a bandwidth of 1 octave (see Figure 2). In conjunction search, the target had an orientation of 90° and a bandwidth of 1.8 octaves, whereas the distractors had orientations of either 0° or 90° and a bandwidth of either 1 or 1.8 octaves (see Figure 2). In both cases, a fixation cross was presented in the center of the screen, and the participant was instructed to maintain fixation throughout the trial. Once the participant detected the presence (or absence) of the target, they reported whether the target was present or not by a button press. Each stimulus configuration (4, 10, or 16 Gabors) was presented 60 times (30 target present, 30 target absent) for a total of 180 trials per task. Eye movements were recorded during these tasks to ensure participants maintained fixation.

Data analysis

Because of saccadic deficits in participants with amblyopia (Niechwiej-Szwedo et al., 2010; Niechwiej-Szwedo et al., 2012), trials with saccadic eye movements were excluded. As is customary in visual search analyses (Wolfe, 1998), trials with incorrect responses were excluded as well. Median RTs (to control for nonnormal distributions of RT) and RT/item slopes for each viewing condition (binocular, dominant/fellow, nondominant/amblyopic) were analyzed using separate analyses of variance (ANOVAs). Each ANOVA had Group (controls vs. amblyopia) as a between-subjects

variable and Target (present vs. absent) and Number of Distractors (3 vs. 9 vs. 15) as within-subjects variables. Post hoc analyses were conducted using the Welch test. We used an alpha of 0.05. RT/item slopes were computed using a regression on raw data for each observer and each condition (target and viewing condition).

We also examined the relation between performance on visual search and two clinical measures: amblyopic visual acuity and binocularity (McKee et al., 2003). We computed correlations between the visual acuity of the amblyopic eye (in logMAR) and the unified binocularity score with median RT, as well as with RT/item slopes in the conjunction search task during amblyopic eye viewing. Because there were two Target levels and three Distractor levels, we combined the data across these conditions before correlating with each clinical measure. To combine the data, we first ranked the RTs for each condition (Target × Distractors) across participants in descending order (lower ranks for greater RTs). Subsequently, we took the six resulting ranks for the six conditions for each observer and averaged them to obtain one mean rank per observer. We did the same for RT/item slopes across the two Target levels (present/absent). We then computed Pearson correlation coefficients between the mean RT ranks or mean RT/item slope ranks and visual acuity, as well as between the mean RT ranks or mean RT/item slope ranks and binocularity.

Results

Control experiments

The average contrast in the amblyopic/nondominant eye viewing condition was 2.5 times larger for amblyopes than for controls (contrast ratio of 0.094 vs. 0.038). The gap size was slightly larger on average for the amblyopic/nondominant eye condition for the amblyopic group than the controls (separation of 3.13 arcmin vs. 0 arcmin). The gap was larger than 0 only for 2 of the amblyopes. For other viewing conditions, both contrast and gap differences were small.

Feature search

Group means of the individual median RTs, RT/item slopes, and percentage correct for the feature search are shown in Figure 3. For RTs (Figure 3A), Group had no effect—there were no significant differences between participants with amblyopia and controls in either the main effects: binocular, $F(1, 20) = 0.03$, $p = 0.86$; dominant, $F(1, 20) = 0.2$, $p = 0.66$;

nondominant/amblyopic, $F(1, 20) = 0.99$, $p = 0.33$, or any interactions.

The interaction between Target and Number of Distractors was significant for the dominant, $F(2, 40) = 4.6$, $p = 0.016$, and nondominant/amblyopic, $F(2, 40) = 6.1$, $p = 0.005$, viewing conditions but not in the binocular viewing condition, with Target having a significant effect in stimuli with four and 10 distractors but not with 16 distractors as shown by post hoc analysis. Target had no significant main effect on RTs during the dominant eye viewing condition but had a significant effect in the binocular viewing condition, $F(1, 20) = 5.5$, $p = 0.03$, and nondominant/amblyopic eye viewing, $F(1, 20) = 6.6$, $p = 0.018$, with mean RTs being 26 and 40 ms longer (respectively) when the target was absent as compared with target present. We also found a significant main effect of Number of Distractors in all three viewing conditions but with an opposite directionality to that observed in high-attention load tasks: RTs *decreased* as the number of distractors increased: binocular, $F(2, 40) = 16$, $p < 0.001$; dominant, $F(2, 40) = 29.1$, $p < 0.001$; nondominant, $F(2, 40) = 17.7$, $p < 0.001$. The RT differences between four items and 16 items were small: 52 ms on average. A decrease in RT with an increase in distractors has been documented previously in the visual search literature (Bacon & Egeth, 1991).

For RT/item slopes (Figure 3B), there were no significant main or interaction effects of Group or Target in any of the viewing conditions. As shown in Figure 3C, all observers were able to perform this task with high accuracy. Taken together, these findings suggest that our feature search did indeed have a low attentional load (Wolfe, 1998) and that low-level deficits in amblyopia were unlikely to be the cause for the observed differences between groups in conjunction search described below.

Conjunction search

The conjunction search results were quite different from the feature search (Figure 4; individual graphs for the amblyopia group are shown in the Appendix). For RTs, a significant difference between controls and participants with amblyopia (main effect of Group) was found in the amblyopic/nondominant eye, $F(1, 20) = 11.1$, $p = 0.003$, and fellow/dominant eye, $F(1, 20) = 4.4$, $p = 0.049$, viewing conditions. The amblyopia group exhibited longer processing times, with RTs being 399 ms greater on average than those of controls (range = 271–537 ms in the six conditions). There was also a significant interaction between Group and Number of Distractors for the dominant eye viewing condition, $F(1, 20) = 11.2$, $p < 0.001$, with a greater increase in RTs with increase in distractors for the amblyopia group (this
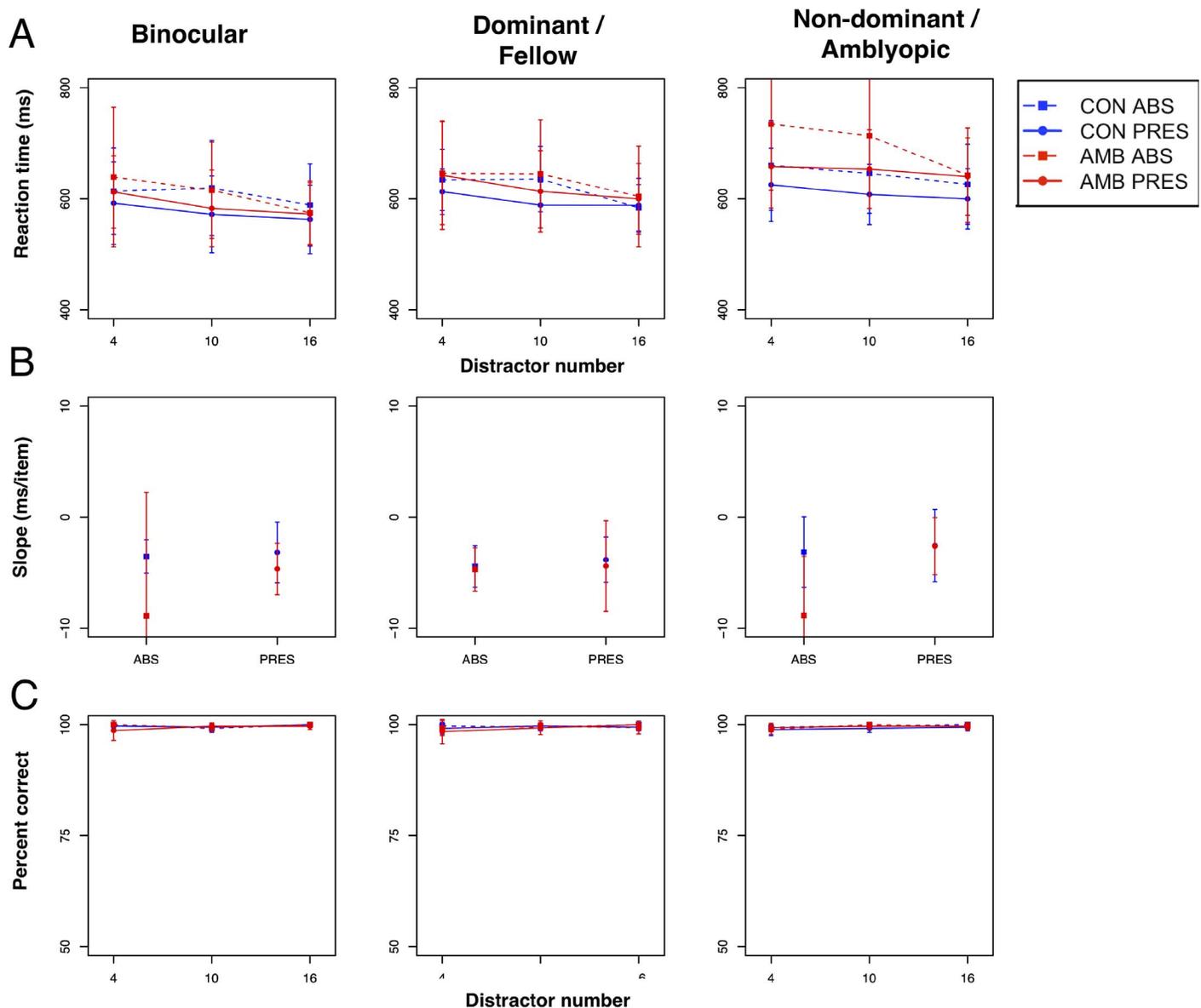
Figure 3. Feature search results. On all plots, red symbols and lines show the amblyopia group mean data and blue symbols and lines the control group mean data. Square symbols with dashed lines show data for target absent stimuli and round symbols with solid lines show target present stimuli. (A) Mean RTs with correct trials without eye movements only. (B) Mean RT/distractors slopes for correct trials without eye movements. (C) Percentage correct responses. Error bars show ±1 confidence intervals. CON ABS indicates control, target absent; CON PRES, control, target present; AMB ABS, amblyopic participants, target absent; AMB PRES, amblyopic participants, target present.

result is also reflected in the RT/item data below). Otherwise, the RTs for both groups exhibited typical conjunction search behavior for all viewing conditions, that is, significant interactions[1] between Target and Number of Distractors, binocular, $F(2, 40) = 23.7$, $p < 0.001$; dominant, $F(2, 40) = 9.8$, $p < 0.001$; nondominant, $F(2, 40) = 10.2$, $p < 0.001$), with (a) the differences in RTs for both target absent trials and target present trials increasing with an increase in the number of distractors and (b) higher overall RTs for target absent trials than those for target present trials.

For RT/item slopes, there was a significant main effect of Target for all viewing conditions (binocular, $F[1, 20] = 31.1$, $p < 0.001$; dominant, $F[1, 20] = 7.9$, $p = 0.01$; nondominant, $F[1, 20] = 18.7$, $p < 0.001$), with target absent trials showing steeper slopes than target present trials, as expected for a high-attentional load task. Importantly, there was a significant effect of Group on RT/item slopes in dominant eye viewing, $F(1, 20) = 8.5$, $p = 0.008$: Participants with amblyopia had steeper slopes (i.e., slower processing rate) than controls (mean target
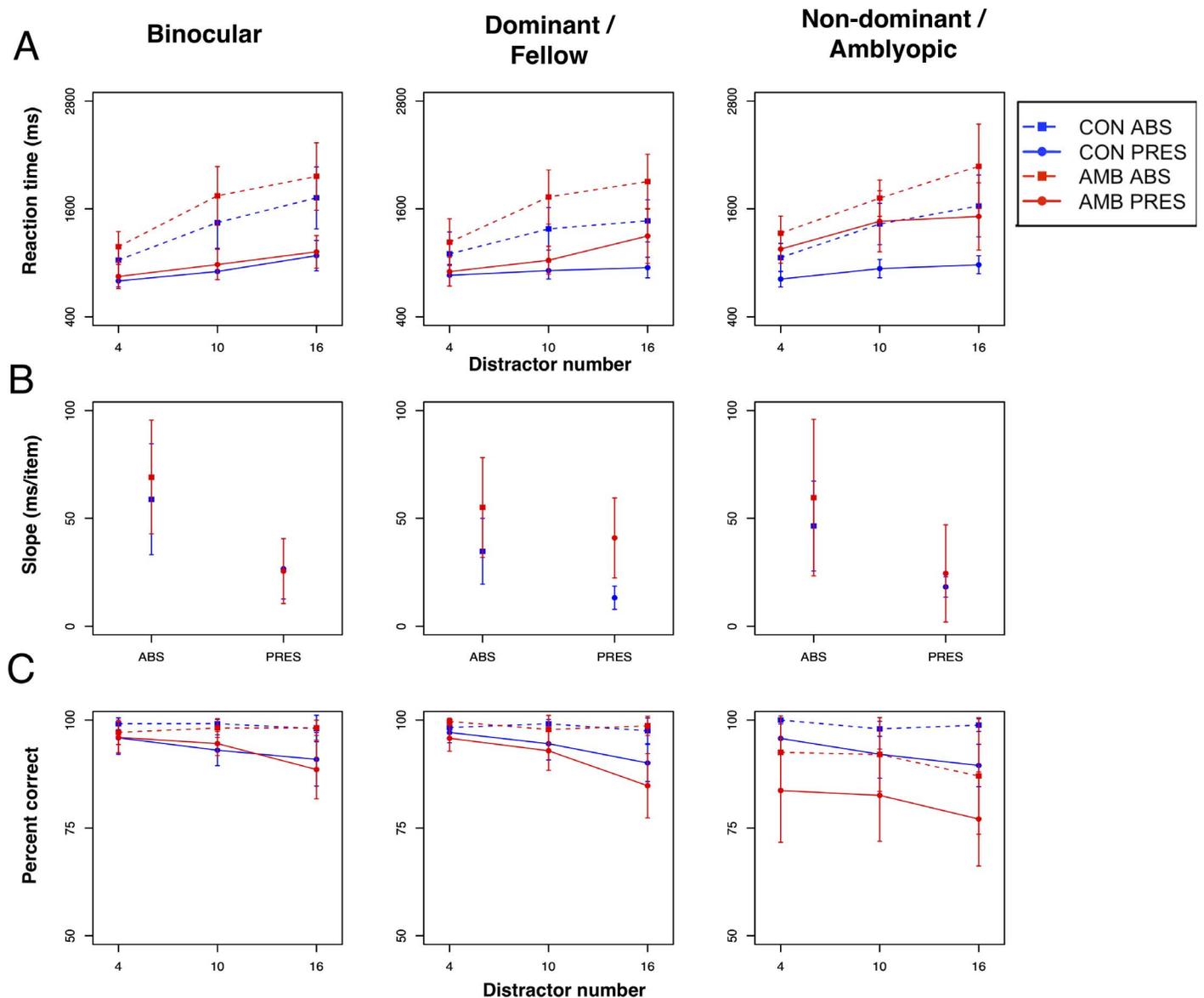
Figure 4. Conjunction search results. All conventions are as in Figure 3. (A) RTs with correct trials without eye movements. (B) Mean slopes (RT/item). (C) Percentage correct responses.

absent: 55 vs. 34 ms/item; mean target present 41 vs. 13 ms/item). For the other viewing conditions, Group had no significant effect.

In terms of percentage correct responses as shown in Figure 4C, accuracy dropped with an increase in distractor number for all observers but more so for the amblyopia group, especially in the amblyopic/non-dominant eye viewing condition. This shows that there were no confounding speed-accuracy tradeoffs, as the percentage correct data followed the RT data for the two groups. Accordingly, the differences in RT or RT/item slopes between the groups cannot be attributed to a more strict decision criterion adopted by the amblyopia group.

Correlations with amblyopia characteristics

For RT, during conjunction search in the amblyopic/nondominant eye, the correlation between visual acuity and mean ranks (see the Methods section for details on the analysis) was not significant, but the correlation between binocularity and mean ranks was significant ($r = 0.64$, $p = 0.048$; Figure 5). As shown in Figure 5A, deficits in binocularity (poor binocularity scores) were associated with higher RTs (lower mean ranks). To ascertain which specific conditions yielded this result, we correlated mean RTs for each condition with the unified binocularity score. There were significant correlations between the performance on target absent conditions with 10 ($r = 0.7$, $p = 0.02$) and 16 ($r = 0.7$, $p =$
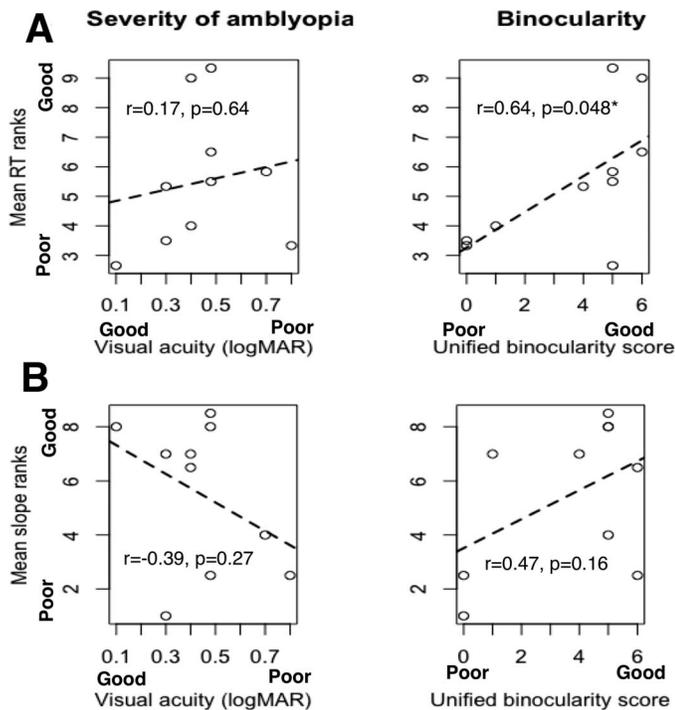
Figure 5. (A) Mean RT ranks and (B) mean RT/item slopes as a function of the unified binocularity score (see Table 1). Dashed line shows the fitted regression lines. Lower mean ranks reflect poorer performance on search.

0.02) distractors. Correlations for other conditions were not significant ($p > 0.2$). To explore this relation further, we divided participants with amblyopia into high- and low-binocularity groups using the unified binocularity score (cutoff score of 3). The Welch test on mean RT ranks showed a significant difference between the groups ($t = 3.03$, $p = 0.02$) with mean ranks of 6.3 for high-binocularity and 3.6 for low-binocularity groups, indicating that poorer binocularity was associated with longer processing time.

The correlations between visual acuity in the amblyopic eye and the mean RT/item slope ranks ($r = 0.4$, $p = 0.2$), as well as the correlation between binocularity and the mean RT/item slope ranks ($r = 0.47$, $p = 0.16$) were not statistically significant. The directions of the correlation slopes showed higher RT/item slopes for worse acuity and binocularity.

Discussion

We demonstrated here that amblyopia affects the ability to perform visual search. We controlled for low-level visual deficits typical of amblyopia, including elevated contrast thresholds, crowding, and slower eye movements. We found no performance difference between amblyopia and control groups for our feature search task. In contrast, during conjunction search, a more difficult task that requires feature binding and possibly has a higher attentional load, we found that (a) RTs were significantly longer during amblyopic and dominant eye viewing in the amblyopia group in comparison with the control group, (b) RT/item slopes were significantly greater for the fellow/dominant eye in the amblyopic group than the control group, and (c) longer RTs during the conjunction search correlated with decreased binocularity in participants with amblyopia.

Before using the GS4 model to discuss our results, we will consider alternative explanations outside of our chosen theoretical framework. Given that there are low-level deficits in amblyopia, differences in RT, RT/item slopes and accuracy could have resulted from the amblyopic group simply failing to perceive the elements in the display as well as controls. However, having controlled for major low-level deficits in our experimental design, including contrast sensitivity, crowding, and visuomotor deficits, and having demonstrated no performance differences in feature search, this explanation is unlikely.

Parallel models of visual attention, based on signal detection theory, postulate that the differential effect of set size in simple feature and complex conjunction searches is not based on the attentional bottleneck but could be explained by the discriminability of the target from the distractors (Eckstein et al., 2000; Verghese, 2001). According to this theory, lower discriminability leads to a noisier signal for the presence of the target in a set and thus reduces detection accuracy in timed visual search and increases RT in searches with unlimited time per trial (Eckstein et al., 2000; Verghese, 2001). Based on this theory, the difference in performance between the controls and the amblyopia group in our study could have resulted from a lower discriminability of the conjunction stimuli in participants with amblyopia. The discriminability of conjunction stimuli has been modeled as a combination of the discriminabilities of the single features in which the target is different from the distractors (Eckstein et al., 2000). In our stimuli, these features are the orientation and the bandwidth of the Gabor patches. Thus, the overall discriminability of the stimulus in the conjunction search task would be a combination the discriminabilities of these two features. For the combined discriminability of a conjunction stimulus to be impaired in amblyopia, one of two things needs to be true: either the discriminability of one of the single features is lower than that in controls or the process of combining the features is impaired. Because the two groups performed similarly on the feature search task in which orientation was the single distinguishing feature, the discriminability of Gabor orientation must be the same for both. Similarly, in our Control Experiment 2, we used Gabor bandwidth as a distinguishing feature in a detection

task to make sure stimuli are equally visible to both groups. Thus, Gabor bandwidth discriminability was equated for the two groups. The remaining explanation for the discriminability hypothesis is an impairment in the process in which the features are combined, namely, feature binding. Previous research found greater positional uncertainty and poorer stimulus localization in amblyopia (Hess & Holliday, 1992; Levi, Klein, & Yap, 1987; Wang, Levi, & Klein, 1998) that could potentially affect feature binding. However, these deficits were found primarily in strabismic amblyopia (Hess & Holliday, 1992; Levi et al., 1987; Wang et al., 1998), whereas in our sample, 60% of the observers had anisometropic amblyopia, and those observers were the ones showing the largest RT increases in the amblyopic eye in comparison with mean control data (see Appendix). It is possible that feature binding is impaired in amblyopia because of other factors and that our results are reflective of this impairment. However, it does not necessarily restrict the deficit to low-level function, as there is evidence that feature binding is an integral part of the higher-level visual attention process (Botly & De Rosa, 2012; Treisman, 1998).

We next examine our results within the framework of the GS4 (Wolfe, 2007) model. According to the model, the first obvious point of failure in amblyopia could be the preattentive processing stage and the guidance it provides to the selective attention process. However, having excluded low-level deficits in our experimental design and having demonstrated no performance deficits in feature search, we must look higher up in the visual hierarchy. Differences in RT/item slopes suggest a slower processing rate in the attentional bottleneck. In addition, elevated RTs in the amblyopic group during amblyopic and dominant eye viewing also suggest greater processing time per item. Both of these differences point to a "narrower" attentional bottleneck associated with amblyopia. This is supported by prior findings that participants with amblyopia undercount briefly presented items (Sharma et al., 2000) and track a smaller number of moving items than controls (Tripathy & Levi, 2008), suggesting a reduction in the capacity of the attentional bottleneck.

The attentional bottleneck is likely monocular in amblyopia, which would explain the lack of an overall increase in RT during binocular viewing in our experiments and those of others (Popple & Levi, 2008; Sharma et al., 2000). A separation of inputs by eye is beneficial when the visual system is forced to favor one eye over the other in the presence of binocular discordance, as in strabismus or anisometropia. This is also supported by our finding that worse performance on the conjunction search in the amblyopic eye correlated with worse binocularity.

Contrary to current findings and previous research on attention and amblyopia (Ho et al., 2006; Popple &

Levi, 2008; Tripathy & Levi, 2008), Roberts et al. (2016) found no effect of amblyopia on accuracy in a cued orientation discrimination task. In our experiments, the accuracy data, similarly to the RT data, showed impairment for the amblyopia group in comparison with controls for conjunction search. The difference in the accuracy findings between the two studies could be due to the differences in task (search vs. cued discrimination) and consequently a difference in the type of attentional processes involved. It could also be due to the differences in sample composition: 64% (9/14) of the amblyopia group in Roberts et al. (2016) had very mild amblyopia (intraocular difference <0.2 logMAR), which does not meet the generally accepted clinical definition of amblyopia (≥0.2 log-MAR difference; Christmann, Drost, & Mandelbaum, 2007), suggesting that their participants were either previously treated successfully or that they only had very mild amblyopia; in contrast, all of our observers had an intraocular difference equal to or larger than 0.2 logMAR, with 80% having moderate to severe amblyopia (>0.3 logMAR).

We have suggested previously that attention may be a modulator of low-level deficits in amblyopia (Tsirlin et al., 2015). In a meta-analysis of behavioral methods used to rehabilitate adult amblyopia, we found no significant differences between treatment types, even though the methods included different monocular and binocular tasks. Based on these findings, we suggested that the common mechanism uniting these methods could be the redirection of attention to the input from the amblyopic eye. Huang and colleagues (2014) support this suggestion. They hypothesized that shifting attention to the amblyopic eye during a detection task under binocular viewing conditions may improve visual acuity and stereopsis. They trained people with anisometropic amblyopia to attend to a repeatable and calibrated target shown to their amblyopic eye during dichoptic stimulus presentation and likened this to creating a state of binocular competition capable of recalibrating excitatory-inhibitory interactions. Although improvements in visual acuity were modest (0.08 logMAR), improvements in stereopsis were clinically significant (>two octaves). Their study supports the idea that there can be differential impacts on the attentional bottleneck under monocular versus binocular conditions in amblyopia.

We proposed further that attention might be the gateway to suppression of the input from the amblyopic eye. Based on electrophysiological data from kittens reared with varying degrees of visual deprivation, Singer (1982) proposed a similar hypothesis whereby strabismic suppression occurs as a consequence of visual attention being directed away from the deviated eye, which subsequently results in

amblyopia. It is possible that reallocated attention is the precursor to functional suppression and occurs in response to the amblyogenic trigger (anisometropia, strabismus, or deprivation). This change in attentional behavior as a result of a trigger event can ultimately lead to chronic suppression and hence neuronal changes. Another line of evidence comes from Van Balen and Henkes (1962), who measured EEG responses over the occipital lobe of human participants with strabismic amblyopia during either attentive or nonattentive viewing. They found that the waveforms during attentive viewing by the amblyopic eye were similar to those during nonattentive viewing by controls. Based on these findings, they suggested that strabismic amblyopia is comparable to a state of vision "without attention" (Van Balen and Henkes, 1962). Our current results demonstrate that feature search is intact in amblyopia whereas conjunction search is impaired. Whether training using conjunction search will enhance attentional engagement as well as reduce low-level deficits remains to be elucidated empirically.

Keywords: amblyopia, visual search, visual attention, stereopsis, visual acuity, feature search, conjunction search

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Footnote

[1] Significant main effects were also found for Target: binocular, $F(1, 20) = 73.0$, $p < 0.001$; dominant, $F(1, 20) = 63.6$, $p = 0.01$; nondominant, $F(1, 20) = 51.8$, $p <$ 0.001, and Number of Distractors: binocular, $F(1, 20) = 41.9$, $p < 0.001$; dominant, $F(1, 20) = 70.1$, $p < 0.001$; nondominant, $F(1, 20) = 25.6$, $p < 0.001$.

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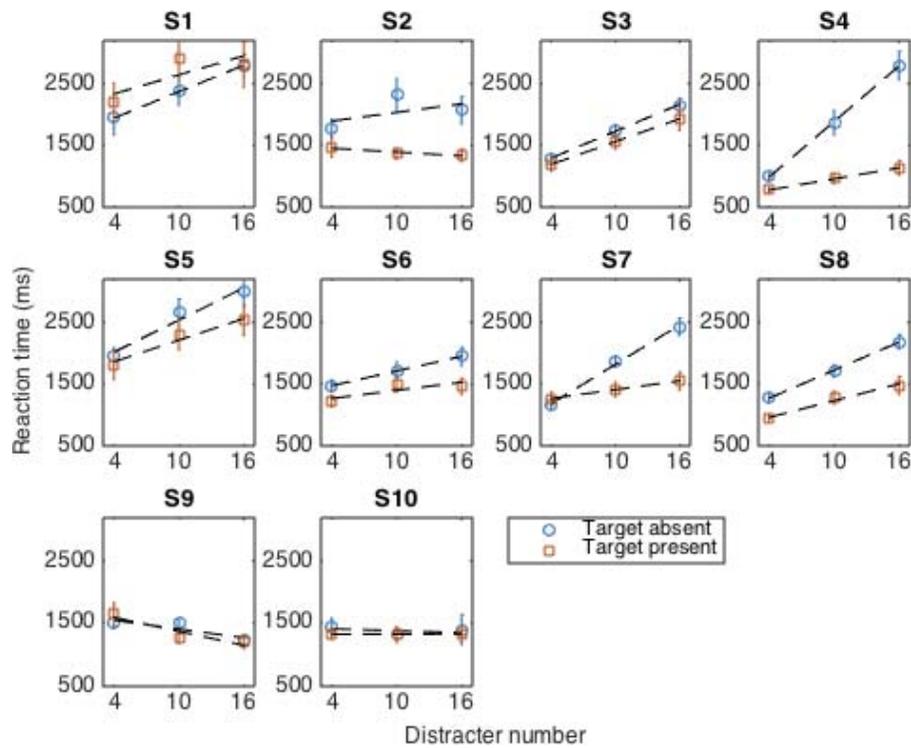
Appendix

Figure A1. Individual feature search results for amblyopic eye viewing condition for the amblyopia group. Square orange symbols show data for target present stimuli, and round blue symbols show target absent stimuli. Error bars show ±1 confidence intervals.
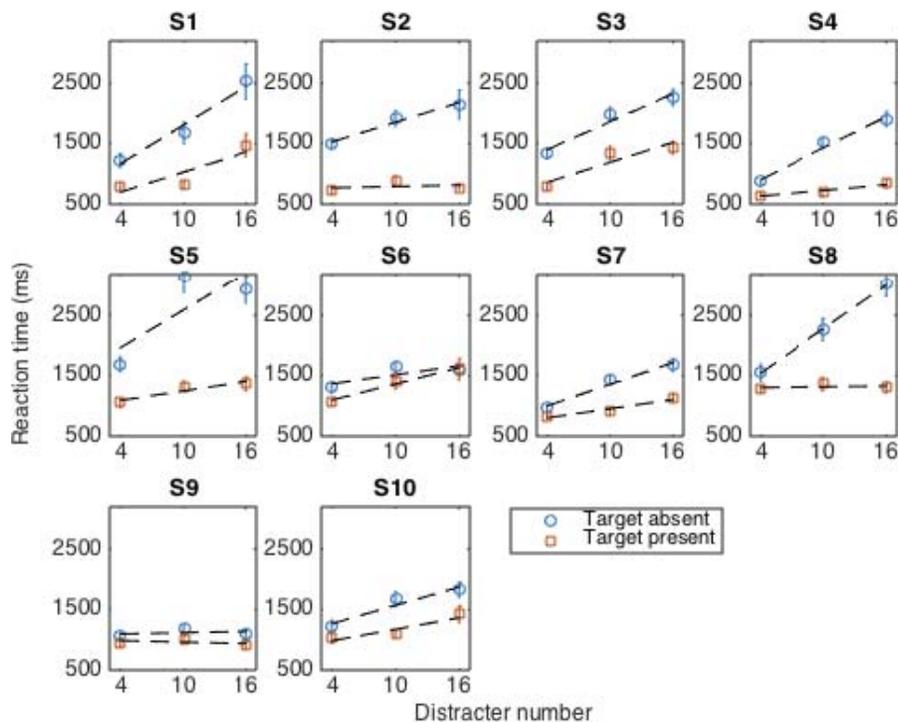

Figure A2. Individual feature search results for the binocular viewing condition for the amblyopia group. Symbols as in Figure A1.
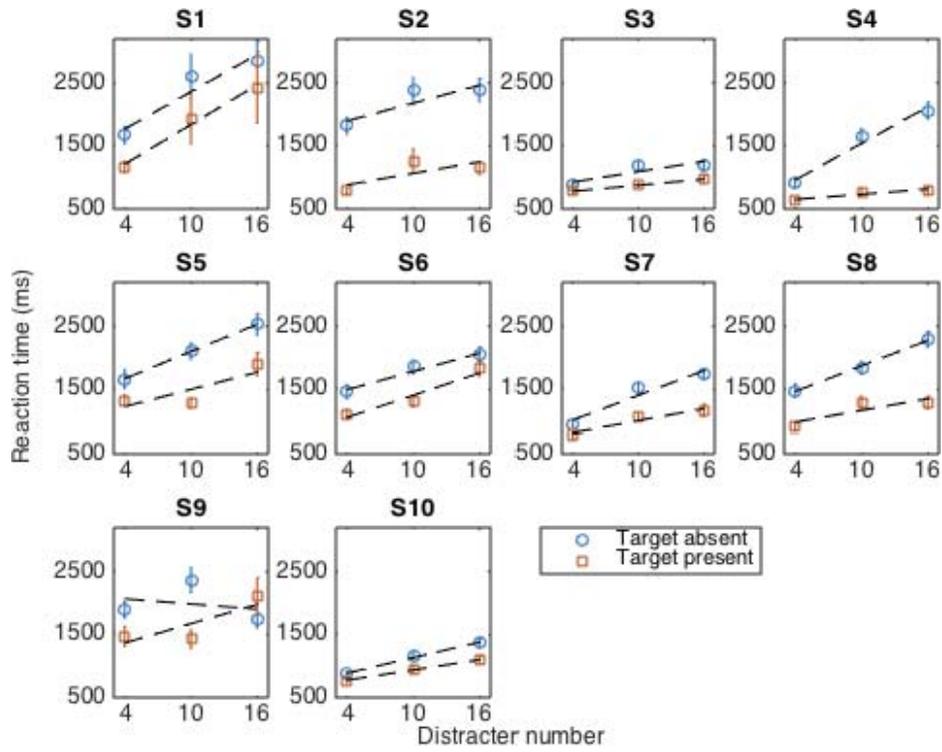
Figure A3. Individual feature search results for the dominant eye viewing condition for the amblyopia group. Symbols as in Figure A1.