Attention in visually typical and amblyopic children

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Amblyopia is a cortical visual disorder caused by unequal visual input to the brain from the two eyes during development. Amblyopes show reduced visual acuity and contrast sensitivity and abnormal binocularity, as well as more "global" perceptual losses, such as figure-ground segregation and global form integration. Currently, there is no consensus on the neural basis for these higher-order perceptual losses. One contributing factor could be that amblyopes have deficiencies in attention, such that the attentional processes that control the selection of information favor the better eye. Previous studies in amblyopic adults are conflicting as to whether attentional deficits exist. However, studies where intact attentional ability has been shown to exist were conducted in adults; it is possible that it was acquired through experience. To test this hypothesis, we studied attentional processing in amblyopic children. We examined covert endogenous attention using a classical spatial cueing paradigm in amblyopic and visually typical 5- to 10-year old children. We found that all children, like adults, independently of visual condition, benefited from attentional cueing: They performed significantly better on trials with an informative (valid) cue than with the uninformative (neutral) cue. Response latencies were also significantly shorter for the valid cue condition. No statistically significant difference was found between the performance of the amblyopic and the visually typical children or between dominant and nondominant eyes of all children. The results showed that covert spatial attention is intact in amblyopic and visually typical children and is therefore not likely to account for higher-order perceptual losses in amblyopic children.

Introduction

Amblyopia is a developmental disorder of spatial vision and the most common cause of monocular vision loss in children. Amblyopia is associated with unequal visual input to the brain from the two eyes during development. Most often, it is due to either strabismus (misaligned eyes) or anisometropia (unequal refractive errors between the eyes). Amblyopic individuals experience deficits in visual acuity, contrast sensitivity (particularly at higher spatial frequencies), abnormal binocular interactions, and depth perception (e.g., McKee et al., 2003; for reviews, see Birch, 2013; Kiorpes, 2006; Levi, 2006, 2013; Levi et al., 2015; Wong, 2012). Amblyopes also experience other monocular and binocular abnormalities such as distorted visual space perception (Barrett et al., 2003; Lagrèze & Sireteanu, 1991; Mansouri et al., 2009; Popple & Levi, 2000), weakened perception of second-order form (Mansouri et al., 2005; Wong et al., 2001), crowding (see Bonneh et al. 2007; Greenwood et al., 2012; Levi, 2008), and interocular suppression (see Harrad & Hess, 1992; Hess et al., 2010; Huang et al., 2012; Mansouri et al., 2008; Narasimhan et al., 2012; Zhou et al., 2018). Beyond these losses, amblyopes also show deficits in higher-order perception that impact their ability to parse a visual scene. For example, figure-ground segregation, shape discrimination, global form and motion integration, object and face discrimination, and natural scene perception are all disrupted in amblyopia (see Grant & Moseley, 2011; Hamm et al., 2014; Kiorpes, 2006; Kiorpes et al., 2016; Kozma & Kiorpes, 2003; Levi, 2013; Wong, 2012). Therefore, amblyopia is a complex visual disorder that not only results in basic visual losses but also affects various domains of higher-order perception differentially.

The neural basis of amblyopia is less well known, and the problem is made more challenging by the diversity of these various deficits. In particular, the "higher-level" deficits, such as those involved in global form perception, cannot be explained by the losses in contrast sensitivity and acuity or neural losses that have been identified in the primary visual cortex (V1) (see Kiorpes, 2016; Levi, 2013; Shooner et al., 2015). Currently, there is also no consensus on the

Citation: Ramesh, P. V., Steele, M. A., & Kiorpes, L. (2020). Attention in visually typical and amblyopic children. *Journal of Vision*, *20*(3):11, 1–15, https://doi.org/10.1167/jov.20.3.11.

https://doi.org/10.1167/jov.20.3.11 Received August 27, 2019; published March 30, 2020 ISSN 1534-7362

general hypotheses that seek to explain the link between various perceptual deficits. Numerous, long-standing hypotheses have been proposed to explain the pattern of deficits in amblyopia and their neural correlates (see Levi, 2013). One such idea is "undersampling," which states that the loss of neurons in the cortex that are driven by the amblyopic eye leads to the behavioral deficits associated with amblyopia. In other words, there is a reduced neural representation of the visual information from the amblyopic eye, an explanation that has much support in the physiological literature (e.g., Shooner et al., 2015). Other suggestions, such as reduced efficiency for detecting signals in noise or that there is topographical disorder within the amblyopic visual system leading to the known spatial disorder, crowding, and mislocalizations, also have support in the physiological literature (Tao et al., 2014; Wang et al., 2017).

A recent approach is to investigate possible top-down influences on the information encoded neurons driven by the amblyopic eye. For example, another hypothesis that has been gaining momentum is that amblyopic individuals have deficiencies in attention and that this may explain their global perceptual deficits. Under this hypothesis, neural signals from the amblyopic eye may or may not carry appropriate information, but attentional selection favors the better, fellow eye. However, few studies have been conducted that directly assessed attentional capability in amblyopic individuals; most have evaluated performance on tasks that rely on the effective deployment of attention. For example, multiple-object tracking—the ability to keep track of certain moving objects in a display cluttered with moving objects—is a task that relies on object identification, object tracking, and sustained attention (see Meyerhoff et al., 2017, for review). Several studies suggest that amblyopes have weak capacity to keep track of multiple moving objects in a display cluttered with other identical moving objects. Giaschi and colleagues (Ho et al., 2006) found poorer identification of the tracking targets in amblyopic children (age 9–17 years) when there were four targets among eight moving elements. However, the deficit was present regardless of viewing eye and was absent for lower numbers of targets. Functional MRI results under similar viewing conditions showed reduced activation levels in dorsal stream visual areas for four—but not fewer—targets (Secen et al., 2011). On the other hand, Levi and Tripathy (2006), using a variant of the task that requires detection of a deviation in the trajectory of moving targets, found no deficit for amblyopic observers. In a follow-up study, Tripathy and Levi (2008) evaluated performance as a function of deviation amount and number of trajectories tracked. They found no consistent differences between amblyopic and fellow eyes across their observers, but when the data were pooled across observers, they found on average a 15% reduction in effective number of trajectories identified with the amblyopic eyes. Other tasks, such as the attentional blink, show abnormalities related to temporal order effects, wherein more errors occur reporting the initial target letter with amblyopic eye viewing than with the fellow eye but not with subsequent targets regardless of time lag (Popple & Levi, 2008). This pattern is different from typical observers who most often misidentify the second letter. Overall, these studies support the suggestion of a deficit in attentional processing under conditions of high, sustained attentional load, but clearly there are inconsistencies across studies, and in some cases, the deficiencies noted are quite small or absent.

A few studies have investigated visual search performance in amblyopia. High-level visual search tasks, such as conjunction search, require the deployment of selective attention to perform the task well. Two studies have evaluated conjunction search performance in amblyopic observers. Neri and Levi (2006) measured threshold for discriminating the presence or absence of a target that differed in two features (color and orientation) as a function of number of elements in the set and element size. They found elevated amblyopic eye size thresholds, especially for large set sizes. More recently, another study measured conjunction search performance (Gabor patch spatial frequency and orientation) in amblyopic observers, explicitly controlling for low-level visual losses, under central fixation (Tsirlin et al., 2018). They found longer reaction times and lower accuracy as the number of elements in the display increased for all observers and viewing conditions in conjunction search, as expected, but the impairment was greater with the amblyopic eye viewing under the higher load conditions. A feature search control condition—a low attentional load—was important in showing that the higher demand of attention in the conjunction search was likely to be responsible for the greater amblyopic deficit.

Another study monitored the strength of evoked potentials during a passive attention task under monocular viewing comparing conditions when a stimulus was attended versus ignored. They found that attention modulated the evoked response amplitude in both the amblyopic and fellow eyes, but there was a reduced amount of modulation when the amblyopic eye was viewing compared with fellow eye viewing (Hou et al., 2016). The attention modulation effect was significant for the primary visual cortex but, oddly, not for downstream extrastriate visual areas hV4 and hMT+. This suggests that the strength of attentional allocation is weaker with the amblyopic eye viewing, at least in early visual cortex. On the other hand, two psychophysical studies of covert spatial attention showed no obvious differences in performance between the amblyopic and fellow eye, or visually typical controls. First, Roberts et al. (2016) assessed orientation discrimination performance using a classic Posner spatial-cueing task and found that there were no significant differences between the performance of amblyopic and visually typical adults. Studying both exogenous and endogenous attention, amblyopic and visually typical individuals equally benefited from the valid attentional cue, with improved accuracy as well as decreased reaction time, regardless of which eye was viewing (Roberts et al., 2016). They also found that an invalid cue disrupted performance similarly for amblyopic and visually typical observers. Kiorpes and colleagues also showed that, when measuring ability to deploy attentional resources in amblyopic nonhuman primates, performance with each eye viewing was improved by a valid spatial cue (Pham et al., 2018). They measured full contrast response functions for a direction of motion discrimination and found in some cases greater enhancement of performance with the amblyopic eye viewing compared to the fellow eye. These studies showing intact benefit of cued attention are consistent with a previous report in which strabismic amblyopic observers' performance on a numerosity task—in which they routinely undercounted features in a display when viewing with the amblyopic eye—was modulated by a valid or invalid cue in the same manner as for visually typical observers (Sharma et al., 2000). These different sets of findings show that amblyopic adults have intact attentional capability, but they may fail to adequately deploy their attentional resources depending on task demands.

Another recent proposal suggests that fixational instability that is especially common in strabismic amblyopic observers produces abnormal selective attention (Verghese et al., 2019). The idea draws from considerable evidence that eye movements and attention are closely linked. There is a demonstrated link between circuits involved in the planning and execution of eye movements and those involved in spatial attention (Moore et al., 2003). Interestingly, during a covert attention task, visually typical participants tend to make microsaccades (small eye movements) toward the cued location (Hafed & Clark, 2002). The pattern of fixation eye movements in amblyopic and visually typical observers has been found to be different when viewing with the amblyopic eye; mainly, fixation stability is poorer (Chung et al., 2015; Gonzalez et al., 2012; see Niechwiej-Szwedo et al., 2019, for review). But there is no clear consensus from analyses of microsaccades as to the precise pattern of differences between the eyes of amblyopes during simple fixation. Gonzalez et al. (2012) reported no difference, Chen et al. (2018) reported a *reduced* rate of microsaccades during amblyopic eye viewing for fixation and in a scene search task, and Chung et al. (2015) reported an *increased* rate for amblyopic eye viewing compared to controls but not fellow eyes. Thus, while this is an intriguing hypothesis, the data are inconsistent, there are many potential variables to consider, and studies directly investigating any link between fixational stability, microsaccade parameters, and attentional deficits remain to be conducted.

Most of the relevant studies reviewed above have been conducted with amblyopic adults or older children. Relatively little is known about attentional effects in young children. It is important to study this in children because, first and foremost, amblyopia is a developmental disorder. Moreover, even if amblyopic adults show no deficits in spatial attentional processing, children could have a deficit that they learn to compensate for over time. As noted above, older children with unilateral amblyopia show marked performance deficits for both eyes on high-level dynamic attention tasks such as tracking multiple objects at high speeds (Ho et al., 2006). Another study showed that amblyopic children between ages 9 and 11 years, while achieving similar performance accuracy, demonstrated longer latencies on a modified Stroop task when compared to visually typical children (Zhou et al., 2015). This result on the Stroop task, a task assessing selective visual attention by looking at the interference between colors and meaning of the same stimulus, shows that while amblyopic children have similar attention allocation capability as visually typical children, they show slower processing speed on both stimulus and response conflict stages.

So, the larger question is, are the attentional processes that seem to be intact in adults a result of behavioral compensation over time or present even in children? Hence, in order to further understand this problem, we sought to answer the following question: Do children with amblyopia show typical attentional processing with each eye viewing? How do they compare with typically developing children?

To address this question, we assessed amblyopic children's covert endogenous attention with a classical spatial-cueing paradigm and compared performance across eyes and between amblyopic and visually typical children. We tested 5- to 10-year-old children—an age range when many visual functions are approaching maturity. We predicted that if endogenous attention was intact, accuracy would be higher and response latency shorter on validly cued trials for all children. Indeed, we found that all children, despite visual condition, benefited from attentional cueing: They performed significantly better on trials with a valid cue than with the neutral, uninformative cue. Response latencies were also significantly shorter for the valid cue condition. No statistically significant difference was found between the performance of the amblyopic and visually typical children, or between dominant and nondominant eyes of all children. The results showed that covert spatial attention is intact in amblyopic and visually typical children and is therefore not likely to account for higher-order perceptual losses in amblyopia.

Methods

Participants

Eleven visually typical and 13 amblyopic children between the ages of 5 and 10 years participated. The visually typical children (six females; *M* age = 8.2 ± 1.6 years) were recruited through flyers posted around New York University and were tested in a study room at New York University. Amblyopic children, with the exception of one child, were recruited from and tested in Dr. Mark Steele's pediatric ophthalmology clinic (Pediatric Ophthalmic Consultants) in New York, New York. The other amblyopic child was recruited from Bellevue Hospital Center Pediatric Ophthalmology Clinics and was tested in the study room at New York University. Children were predominantly White and were mainly raised in middle-class families.

Amblyopic children were diagnosed by a pediatric ophthalmologist at Pediatric Ophthalmic Consultants or a referring practice. Table 1 shows the diagnosis and age at diagnosis for each child, the age at testing, gender, visual acuity at testing, acuity difference, stereoacuity, refractive errors, and presence of strabismus at the time of testing. In order to participate in our experiment, amblyopic children had to have been diagnosed with amblyopia with strabismus, anisometropia, or mixed strabismus/anisometropia. The eyes could not be dilated at the time of testing. The inclusion criteria were visual acuity of 20/30 or worse in one eye or at least two-line difference between the eyes; however, several of the children had a one-line difference; these children are identified as a separate "mild" group in the figures. Note that the clinical data were provided after the child was tested so as to avoid any possibility of experimenter bias. It is important to note also that most of these children were actively under treatment for amblyopia or had completed treatment. Strabismus and anisometropia vary over time in children and can normalize with treatment. We report the visual status at the time of testing for each child in Table 1. The visual status of the visually typical children was provided by the children's parents. Parents confirmed that their child's vision was tested by a physician and was deemed to be typical for each eye. Children in both groups were only eligible to participate in the study if they had no history of other eye/vision disorders, attention deficit hyperactivity disorder (ADHD)/attention deficit disorder (ADD), epilepsy, neurological disorders, and/or diagnosed developmental delays.

Visits

Children were told they will be playing a custom videogame called "Shape Speed" on a touch-sensitive display screen while the caregiver(s) and the experimenter were also in the room. They were told the game had four sessions in total and that if they were to complete each session, they would receive a toy. Before testing began, the experimenter debriefed and consented the caregiver(s) and child about the experiment. All experimental procedures were approved by the University Committee on Activities Involving Human Subjects at New York University and New York University Langone Medical Center and were in agreement with the Declaration of Helsinki. The child was then led to sit in a chair situated directly in front of a touchscreen monitor. An eye tracker was located directly below the screen, pointed toward the child. The experimenter explained to the child the rules of the game and led the child through a practice session. Once the child understood the game, the experimenter proceeded with the real game (data collection).

Apparatus and setup

Participants were tested in a dimly lit room. Stimuli were presented at a viewing distance of 50 cm on a Planar PT1745R touchscreen monitor (1,280-pixel × 1,024-pixel resolution, 56- to 75-Hz refresh rate) for the visually typical children (and for the one amblyopic child tested at New York University) and on a Acer T232HL Abmjjz touch screen monitor (1,920-pixel × 1,080-pixel resolution, 60-Hz refresh rate) for the amblyopic children. Although the monitors were different across the two setups, identical stimulus patch size and visual angle were maintained across both setups. Eye movements were monitored using a Tobii 4C eye tracker (Tobii Technology, Frankfurt am Main, Germany) in both setups.

Stimuli

Participants were asked to fixate on a white, centrally placed cross (1 degree across) on a gray background throughout the trial. The sequence of stages of each trial is illustrated in Figure 1. Four light gray placeholders—each represented by a circle (2 degrees radius)—were concentrically arranged around the cross indicating the location of an upcoming shape stimulus. The target and three distractor stimuli (white solid shapes: square, circle, diamond, triangle), all 1 degree in diameter, were placed one inside each of the four placeholders. Their location was randomized across trials. To manipulate endogenous attention, either one (valid precue) or all four (neutral precue) white arrows (0.33 degrees) were presented before the shapes appeared. A response cue followed, whereby one of the light gray placeholders changed from gray to white, indicating the location of the reporting target. Then, a response screen was displayed, where all four shapes

Subject	Age at testing (years)	Gender	Visual acuity at testing (snellen)	Interocular acuity difference (logMAR)	Stereoacuity (arc sec)	Diagnosis	Age at diagnosis	Refractive error	Deviation of eye
1	8.0	Male	OD: 20/20 OS: 20/25	0.097	200	Anisometropia/ strabismic amblyopia OS	4 years	OD: +0.50 – 0.50 × 70 OS: –4.50 – 0.75 × 65	
2	8.9	Male	OD: 20/20 OS: 20/30	0.176	200	Strabismic amblyopia OS	2 years	OD: +0.75 – 1.00 × 180 OS: –2.25 – 1.75 × 165	Exotropia (XT)
3	10.3	Male	OD: 20/60 OS: 20/20	0.477	700	Strabismic amblyopia OD	20 months old	OD: +0.50 – 1.00 × 175 OS: +0.50 – 0.50 × 170	
4	7.1	Male	OD: 20/25 OS: 20/20	0.097	100	Anisometropic amblyopia OD	5 years	OD: +4.00 sphere OS: +1.75 sphere	
5	8.3	Female	OD: 20/20 OS: 20/60	0.477	200	Anisometropic amblyopia OS	5 years	OD: +0.50 – 0.50 × 70 OS: –4.50 – 0.75 × 65	
6	7.4	Male	OD: 20/60 OS: 20/20	0.477	100	Anisometropic amblyopia OD	6 years	OD: +3.50 – 0.50 × 160 OS: +3.50 – 0.75 × 10	
7	7.5	Female	OD: 20/20 OS: 20/30	0.176	100	Anisometropic amblyopia OS	7 years	OD: +3.50 sphere OS: +7.50 – 0.50 × 25	
8	5.5	Female	OD: 20/20 OS: 20/30	0.176	100	Anisometropic amblyopia OS	5 years	OD: +0.25 – 0.75 × 165 OS: +0.75 – 2.50 × 175	
9	5.2	Female	OD: 20/30 OS: 20/20	0.176	100	Strabismic amblyopia OD	2 years	OD: +12.50 – 0.75 × 160 OS: +12.00 – 1.00 × 20	Accommodative esotropia (ET), variable without glasses
10	6.6	Male	OD: 20/20 OS: 20/25	0.097	100	Anisometropic amblyopia OS	6 years	OD: +0.50 – 0.75 × 105 OS: +2.50 – 2.75 × 60	
11	9.3	Male	OD: 20/20 OS: 20/25	0.097	100	Anisometropic amblyopia OS	8 years	OD: +0.50 sphere OS: +2.50 – 0.50 × 1,700	
12	6.6	Male	OD: 20/20 OS: 20/30	0.176	100	Anisometropic amblyopia OS	5 years	OD: +1.50 – 0.50 × 165 OS: +8.75 – 1.75 × 1,650	
13	6.8	Male	OD: 20/20 OS: 20/30	0.176	100	Strabismic amblyopia OS	3 years	OD: +3.50 sphere OS: +4.00 sphere	Accommodative esotropia (ET), variable without glasses

Table 1. Amblyopic children. This table provides the diagnosis, age at diagnosis, age at testing, gender, visual acuity (Snellen) at testing, interocular acuity difference (dominant – nondominant eye in logMAR), stereoacuity (100 arc sec was the finest test level; Titmus Test, Stereo Optical, Chicago, IL), refractive error, and deviation present at the time of testing for the amblyopic children. OD = Right eye; OS = Left eye.

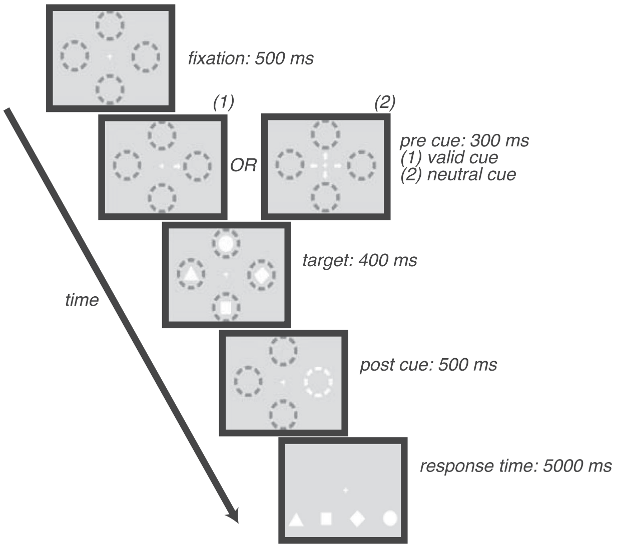

Figure 1. The "shape speed" paradigm, with cartoon versions of the stimuli.

presented before were lined up along the bottom of the screen, waiting for the participant's touch response, which ended the trial.

Paradigm

Four different shapes were simultaneously presented on the touch-sensitive display screen for 400 ms while the child maintained monocular central fixation; the nonfixating eye was temporarily covered with a cloth eyepatch. Following a short 500-ms delay, a response cue appeared to indicate which of the four locations the child must report on. The task was split into four blocks ("sessions"), each containing 24 trials. The task was to select the shape that had appeared at the location indicated by the postcue as quickly as possible. Attention was manipulated by preceding stimulus presentation by a brief informative cue (small white arrow) that accurately predicted the location of the upcoming target on half of the trials, or, on the other trials, stimuli were preceded by a neutral, uninformative cue (four arrows indicating all placeholders).

The child performed the first two blocks with his or her dominant eye and the last two blocks with the nondominant eye. This was done to afford the benefit of any potential practice effect to the nondominant or amblyopic eye. Visually typical children chose their preferred eye to be their dominant eye. After the child's eye was covered with an eyepatch, the viewing eye was calibrated using the eye tracker. The child's eyes were tracked and his or her touch responses were recorded. Analyses of randomly selected eye-tracking epochs confirmed that children maintained central fixation throughout each target display, within ∼0.4 degrees of the fixation point. The experimenter sat adjacent to the child, monitoring the sessions' progress on a computer. The caregiver(s) sat near the entrance to the room. At the end of the study, the child was rewarded with age-appropriate toys and the caregiver(s) was offered cash as compensation for their travel to the study site.

Data analysis

A paired t test was used to evaluate the results. We determined whether there was a statistically significant difference between the performance of the two groups of participants (amblyopic and visually typical children) and between response latency of the two groups for valid and neutral cue conditions. We also evaluated whether performance differed between the eyes (dominant and nondominant eyes) within each of the two groups of participants. A Pearson product-moment correlation coefficient was computed to assess two relationships: (a) the performance difference between viewing with the two eyes as a function of the interocular acuity difference and (b) the relationship between performance and age for both valid and neutral cue conditions. A Fisher's r-to-z transformation was performed to test for differences between the correlations of performance across eyes within participants.

Results

Effect of cueing attention on children's performance

The goal of our study was to establish whether endogenous spatial attention was similar in visually typical and amblyopic children. First, we wanted to establish whether cueing attention has an effect on children's performance, as it does in adults. To understand this, we compared the performance of children between the two different cue conditions: valid cue and neutral cue. Again, the valid cue is informative, indicating to the child the location of the upcoming target shape. On the other hand, the neutral cue is ambiguous and is therefore considered to represent baseline performance. Children's performance is plotted in Figure 2**.** Accuracy (percent correct) is plotted for the two different cue conditions, for both the dominant (Figure 2A) and nondominant eyes (Figure 2B) of amblyopic and visually typical children. Each open shape represents the performance of an individual child; the height of the horizontal bars indicates the mean for the group and condition. The children with mild amblyopia are indicated in orange in all figures.

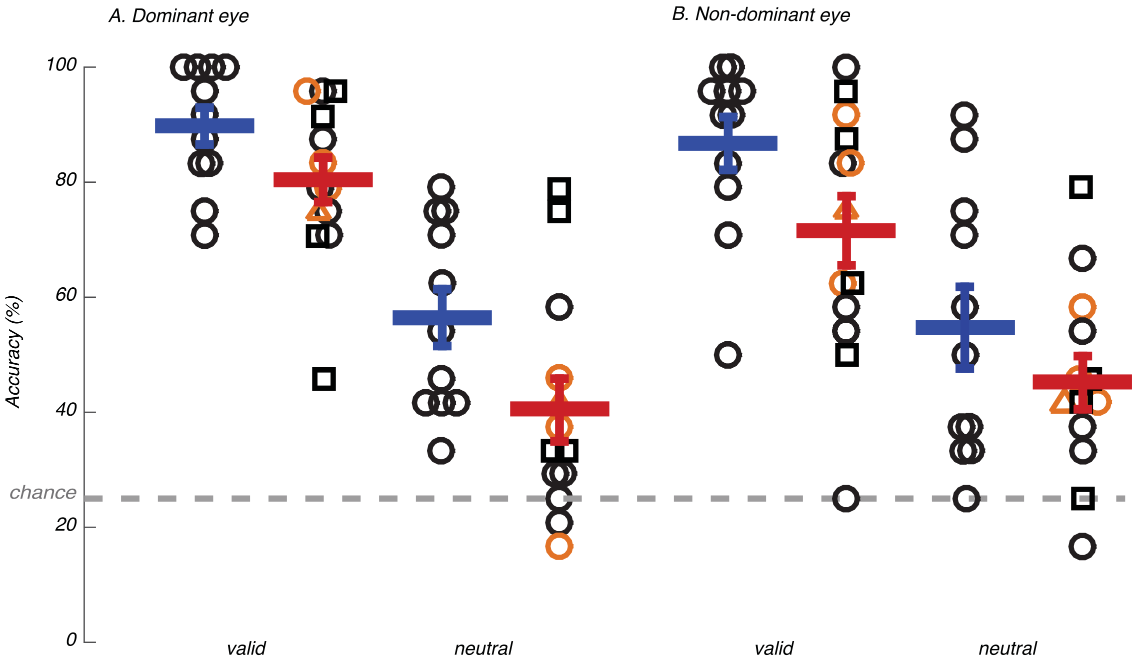

Figure 2. Performance (percent accuracy) of children in the spatial-cueing task is plotted as a function of the two cue (valid and neutral) conditions: (A) dominant eyes and (B) nondominant eyes. The horizontal bar height shows the group mean. Each child's performance is plotted as a black/orange open shape. Error bars are ± *SEM*. Chance performance is indicated by the dotted gray line. Blue = visually typical children; red = moderately amblyopic children (two lines or greater difference); orange shapes = mildly amblyopic children (one-line difference); the different shapes within the amblyopic population denote the type of amblyopia diagnosed: circle = anisometropic, square = strabismic, triangle = strabismic/anisometropic (which we will refer to as "mixed" from here on). The offset jitter of some points is purely for visualization purposes.

Participants	Cue condition	Mean (% accuracy)	Standard deviation (% accuracy)	Comparison *t* test result
Visually typical	Valid	89.76	10.61	$t(10) = 7.15, p < 0.05$
Visually typical	Neutral	56.40	16.60	
Amblyopic	Valid	80.43	13.97	$t(12) = 8.35, p < 0.05$
Amblyopic	Neutral	40.36	19.56	

Table 2. Performance with the dominant eye.

We found that the children across both groups (amblyopic and visually typical) showed increased accuracy in the valid cue condition with either the dominant or fellow eye viewing, compared to the neutral cue condition. The group means for dominant eye viewing are listed in Table 2.

The same trend can be seen for the nondominant eyes (Figure 2B) as well. We found that the children across both groups (amblyopic and visually typical) performed significantly better in the valid cue condition with nondominant or amblyopic eye viewing, compared to the neutral cue condition. The group means for nondominant eye viewing are listed in Table 3.

Although the amblyopic children, on average, had decreased accuracy when compared to the visually typical children regardless of cue condition or viewing eye, these differences were not statistically significant ($p > 0.05$). However, it is important to note that some amblyopic children performed at chance level (25%) in the neutral cue condition with each eye and one amblyopic child did not benefit at all from the valid cue; she performed similarly during both cue conditions. Nevertheless, overall, amblyopic as well as visually typical children showed the expected benefit of the valid spatial cue.

The reaction time results for the children are plotted in Figure 3. Reaction time was measured as

Participants	Cue condition	Mean (% accuracy)	Standard deviation (% accuracy)	Comparison *t* test result
Visually typical	Valid	86.72	15.24	$t(10) = 5.23, p < 0.05$
Visually typical	Neutral	54.51	23.53	
Amblyopic	Valid	71.45	21.65	$t(12) = 5.86, p < 0.05$
Amblyopic	Neutral	45.16	16.64	

Table 3. Performance with the nondominant eye.

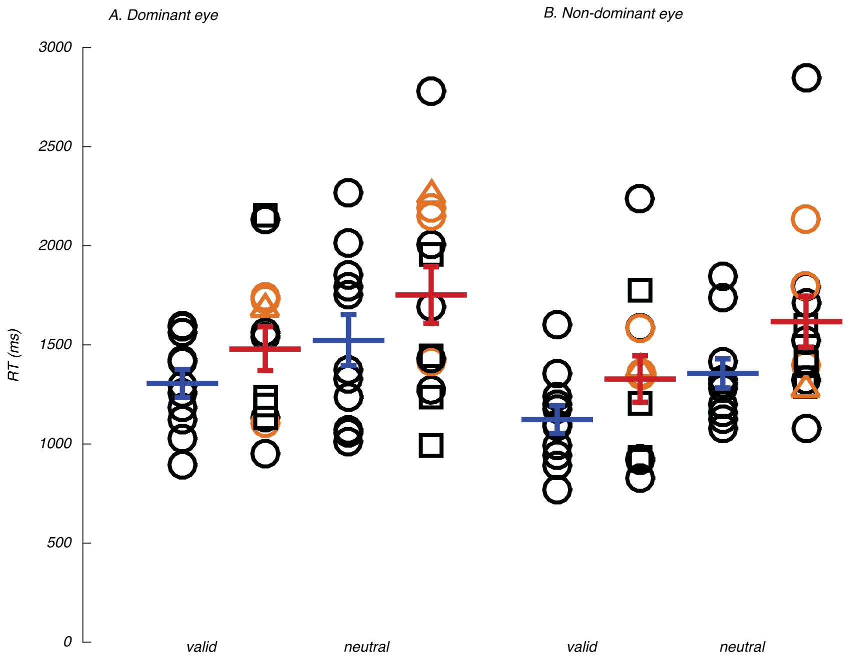

Figure 3. Reaction time (milliseconds) of children in the spatial-cueing task is plotted as a function of the two cue (valid and neutral) conditions: (A) dominant eyes and (B) nondominant eyes. The horizontal bar height shows the group mean. Each child's performance is plotted as a black/orange open shape. Error bars are ± *SEM*. Chance performance is indicated by the dotted gray line. Blue = visually typical children; red = moderately amblyopic children (two lines or greater difference); orange shapes = mildly amblyopic children (one-line difference); the different shapes within the amblyopic population denote the type of amblyopia diagnosed: circle = anisometropic, square = strabismic, triangle = mixed.

the time it took for the child to touch the screen to select a shape after the response screen was displayed. Reaction time is plotted for each of the two cue conditions, for both the dominant and nondominant eye viewing of amblyopic and visually typical children. The children across both groups (amblyopic and visually typical) exhibited significantly shorter reaction time in the valid cue condition, with dominant eye viewing (Figure 3A), compared to the neutral cue condition. Visually typical and amblyopic participants as a group produced decreased latency for valid cue conditions when compared to the neutral cue condition, as detailed in Table 4. The same trend can be seen for the nondominant eyes (Figure 3B) as well. We found that the children across both groups (amblyopic and visually typical) showed a latency decrease in the valid cue condition compared to the neutral cue condition with nondominant eye viewing as well (see Table 5). Interestingly, these reaction times reveal faster responses with the nondominant eyes than with the dominant eyes across all conditions, which could be due to testing the nondominant eye second. It is important to note, again, that although the amblyopic children on average show longer reaction time when compared to the visually typical children, this difference is not statistically significant ($p > 0.05$). Altogether, amblyopic and visually typical children performed similarly.

Overall, we found that spatial cueing of attention benefits dominant and nondominant eye performance

Participants	Cue condition	Mean (s)	Standard deviation (s)	Comparison *t* test result
Visually typical	Valid	1.31	0.23	$t(10) = -2.42, p < 0.05$
Visually typical	Neutral	1.52	0.43	
Amblyopic	Valid	1.48	0.39	$t(12) = -3.29, p < 0.05$
Amblyopic	Neutral	1.75	1.51	

Table 4. Latency with the dominant eye.

Participants	Cue condition	Mean (s)	Standard deviation (s)	Comparison *t* test result
Visually typical	Valid	1.12	0.23	$t(10) = -4.97, p < 0.05$
Visually typical	Neutral	1.35	0.25	
Amblyopic	Valid	1.32	0.42	$t(12) = -4.16, p < 0.05$
Amblyopic	Neutral	1.62	0.46	

Table 5. Latency with the nondominant eye.

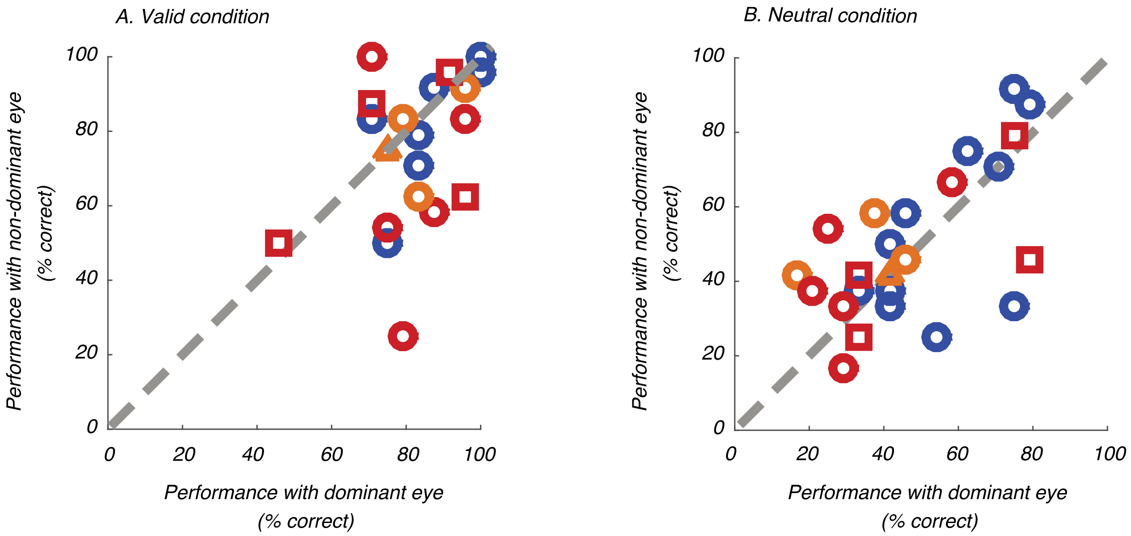

Figure 4. Performance across eyes within participants is plotted: (A) valid condition and (B) neutral condition. Each child's performance is plotted as an open shape. Blue circles = visually typical children; orange shapes = mildly amblyopic children (one-line difference); red shapes = moderately amblyopic children (two lines or greater difference); different red/orange shapes denote type of amblyopia diagnosed: circle = anisometropic, square = strabismic, triangle = mixed.

for amblyopic and typical children and that, as in adults (Roberts et al., 2016), cueing attention improves accuracy and shortens reaction time. We did not find that the most mildly amblyopic children stood out from the other amblyopic children. Their performance was neither consistently better nor poorer than the other more moderate to deeper amblyopic children.

Effect of viewing eye on children's performance

The representation of data as group means and separated by condition (as in Figures 2 and 3) does not allow for comparison of performance across the eyes of an individual. To explore this, we directly compared the performance of individual children when viewing with the dominant and nondominant eyes for each cue condition. Performance across eyes, within subjects, is plotted in Figure 4. For the valid cue condition (Figure 4A), the data straddle the line of unity (dashed diagonal line), showing that there is little advantage of the dominant eye over the nondominant eye across children, regardless of the visual condition. A similar pattern can be seen for the neutral, baseline condition (Figure 4B). A Fisher's r-to-z transformation was performed to test for differences between the correlation across eyes by group. For the valid cue condition (Figure 4A), the correlation between the visually typical and amblyopic children's performance was found to be not significantly different ($z = 1.62$, $p > 0.05$). For

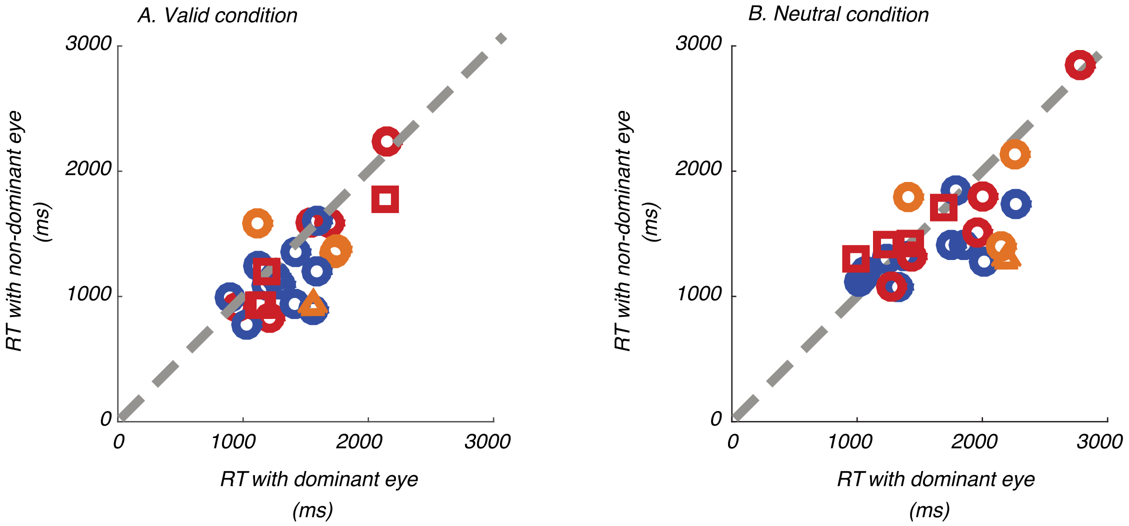

Figure 5. The reaction time (milliseconds) of subjects across eyes within participants is plotted: (A) valid condition and (B) neutral condition. Each child's reaction time is plotted as an open shape. Blue circles = visually typical children; orange shapes = mildly amblyopic children (one-line difference); red shapes = moderately amblyopic children (two lines or greater difference); different red/orange shapes denote type of amblyopia diagnosed: circle = anisometropic, square = strabismic, triangle = mixed.

the neutral cue condition (Figure 4B), the correlation between the visually typical and amblyopic children's performance was also found to be not significantly different ($z = 0.17$, $p > 0.05$).

The reaction time of children across eyes, within subjects, is plotted in Figure 5 for the valid condition (Figure 5A) and for the neutral cue (Figure 5B). For both conditions, again the data straddle the unity line so there seems to be no advantage of the dominant eye over the nondominant eye across children. A Fisher's r-to-z transformation was performed to test for differences between the correlation of response latency across eyes by group. For the valid cue condition (Figure 5A), the relationship between the visually typical and amblyopic children's latency was found to be not significantly different ($z = –1.12$, $p > 0.05$). For the neutral cue condition (Figure 4B), this relationship was also found to be not significantly different ($z = 0.09$, $p > 0.05$). This indicates that there is no consistent performance difference between the eyes of children in both groups.

Overall, we found that children's response accuracy and latency did not depend on which eye is viewing for either the valid or neutral cue condition. Therefore, the amblyopic children showed no performance advantage of the fellow eye over the amblyopic eye.

Effect of visual acuity on amblyopic children's performance

To establish whether amblyopic children's performance depended on their visual acuity, we compared the accuracy of amblyopic children on the task to their reported visual acuity. The amblyopic children's performance difference when viewing with each eye is plotted in Figure 6 as a function the interocular acuity difference (in logMAR). No significant correlation was found. The correlation coefficient is small for both valid trials ($r = .14$, $p > 0.05$, with $R^2 = .0202$) and for neutral trials ($r = .33$, $p > 0.05$, with $R^2 = .1138$), showing that any difference in children's performance with each eye viewing is not correlated with their interocular acuity difference. Interestingly, some children performed *better* with their amblyopic eye, which again may be related to the testing order. Also, in a substantial number of children in our sample, the interocular acuity difference was small. Regardless, overall, it is clear that the amblyopic children's performance did not depend on their depth of amblyopia.

Effect of age on children's performance

To establish whether the age of visually typical and amblyopic children affected their performance on the task, we compared the accuracy of both groups of children (with their dominant eye) on the task to their reported age. The visually typical children's performance with the dominant eye is plotted in Figure 7A as a function of age in years. No significant correlation was found for either cue condition. The correlation coefficient is small for valid trials ($r = 0.57$, $p > 0.05$, with $R^2 = 0.3234$) and for neutral trials ($r = –0.12$, $p > 0.05$, with a $R^2 = 0.013$), showing that children's

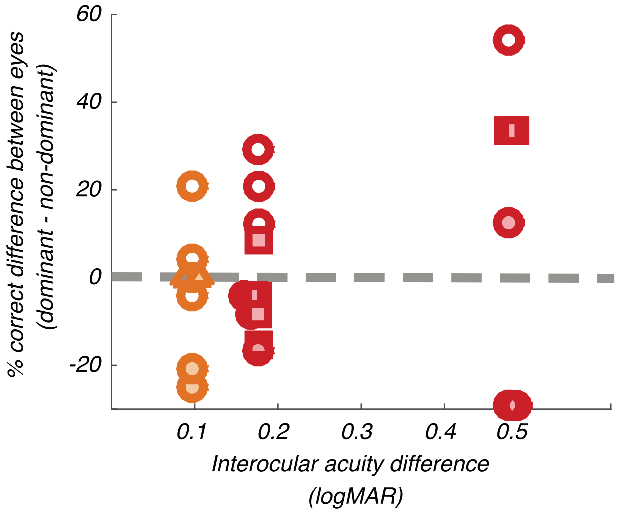

Figure 6. Difference in amblyopic children's performance between each eye viewing is plotted as a function the interocular acuity difference (logMAR). Each child is represented as a shape: orange = mildly amblyopic children (one-line difference); red = moderately amblyopic children (two lines or greater difference); different red/orange shapes denote type of amblyopia diagnosed: circle = anisometropic, square = strabismic, triangle = mixed). The valid condition data are plotted as open shapes and the neutral condition data are plotted as filled shapes. The jitter at each point is purely for visualization purposes.

performance with their dominant eye is not correlated with their age. The amblyopic children's performance with the dominant eye is plotted in Figure 7B as a function of age in years. In contrast to the visually typical group, a marginally positive correlation was found for valid trials ($r = 0.60$, $p < 0.05$, with $R^2 = 0.3651$). No significant correlation was found for the neutral trials ($r = 0.50$, $p > 0.05$, with $R^2 = 0.2512$), showing that amblyopic children's performance during the neutral condition with their dominant eye is not dependent on age. Overall, while amblyopic children did show a moderate increase in performance as a function of their age for the valid cue condition, age was not in general predictive of performance for visually typical children across both cue conditions and for amblyopic children's performance under the neutral cue condition.

Discussion

In this study, we directly manipulated and measured covert endogenous attention in amblyopic and visually typical children. Participants were cued to attend to either one or all possible target locations while monocularly performing a 4AFC shape discrimination. We found that amblyopic as well as visually typical children benefited from an attentional cue, demonstrating intact attentional function in each group. In addition, there was no significant difference in performance when the children were viewing with their amblyopic or fellow eye or between dominant and nondominant eye viewing in visually typical children.

In both groups of children, performance accuracy in the neutral cue condition did not significantly differ between the eyes within each group. Thus, task difficulty was well equated across all participants. Both amblyopes and controls demonstrated significant benefits of endogenous attention. In fact, children as young as 5 years showed typical effects of endogenous covert attention, as would be expected from adults. Both groups of participants exhibited increased accuracy and decreased reaction time in the shape discrimination task for the valid cue trials compared to neutral, uninformative cue trials. While to our knowledge, no prior studies comparable to ours have been conducted, a few studies have reported that children as young as age 6 are capable of covert spatial orienting (using detection), similarly to adults. But some performance differences have been reported in comparison with older children and adults (see Leclercq & Sieroff, 2013). In particular, performance accuracy and speed on these tasks improve with age (Schul et al., 2003) and are compromised in children who had experienced bilateral stimulus deprivation from congenital cataracts (Goldberg et al., 2001). Our results show that cueing endogenous attention both improves accuracy and shortens reaction time across children regardless of a diagnosis of amblyopia or age.

While this study demonstrates that amblyopic children have intact attentional capacity, we did note that there was *on average* a reduction in performance accuracy in amblyopic children—independently of viewing eye—when compared to that of the visually typical controls. Amblyopic children, on average, also exhibited slightly slower reaction time when compared to that of visually typical children. Although these differences are not statistically significant, it leaves open the possibility that there is a quantitative deficit in performance in amblyopic children that may be revealed with further study or with a larger sample of children. In fact, as we noted, one amblyopic child showed no benefit of the valid cue with either eye. We also note that our amblyopic children were all undergoing or had completed patching therapy or other amblyopia treatment, so it is unclear if that process had an effect on attention. The majority of our amblyopic children had as a result comparatively mild interocular differences. However, as can be seen in Figure 6, those children with the deepest amblyopia did not consistently show a large performance deficit on our task, nor did the children with the mildest amblyopia

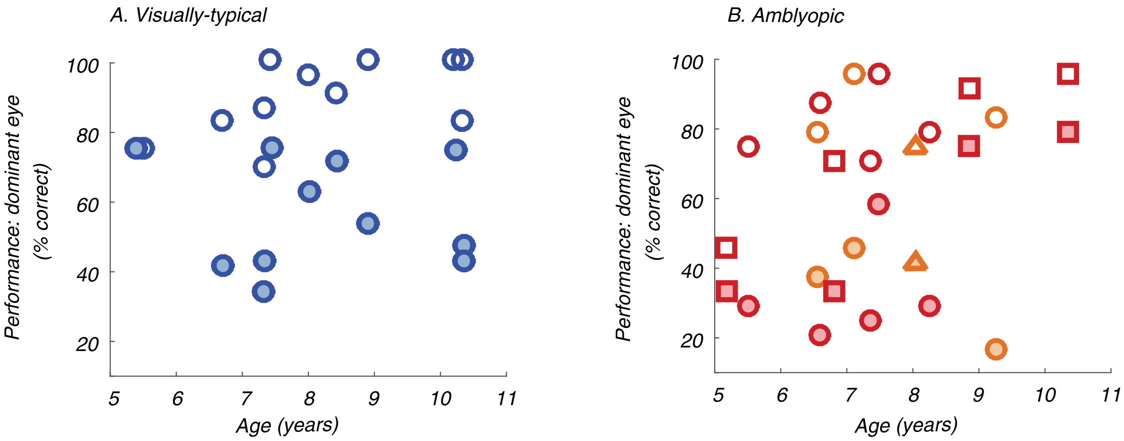

Figure 7. Children's performance as a function of age. (A) The visually typical children's performance with the dominant eye is plotted in blue circles as a function of their age in years. The valid condition data are plotted as open circles and the neutral condition data are plotted as filled circles. (B) The amblyopic children's performance with the dominant eye is plotted in red/orange as a function of their age in years. The valid condition data are plotted as open shapes and the neutral condition data are plotted as filled shapes. Orange = mildly amblyopic children (one-line difference); red = moderately amblyopic children (two lines or greater difference); different red/orange shapes denote type of amblyopia diagnosed: circle = anisometropic, square = strabismic, triangle = mixed.

perform better than the other children, so we think that this factor is unlikely to be very important. While we know of no evidence to suggest that stereopsis status affects attention performance on monocular tasks, some patterns of loss in amblyopia are different for participants who have poor binocular function (McKee et al., 2003). Most of the children in this study showed reasonable binocular function based on performance on the Titmus Test (see Table 1).

Another consideration is the fact that we tested the dominant eye first, which was done to ensure that any performance deficit with the amblyopic eye was not due to the novelty of the task. The testing order may have benefited the amblyopic eye to some degree, in which case our results may be treated as a conservative evaluation. Finally, we found a small but significant trend for the amblyopic children to perform with higher accuracy on valid-cue trials with age; this was evident independently of viewing eye. This finding hints at the possibility that amblyopic children may learn, either via amblyopia treatment or ordinary visual experience, to more effectively employ attentional engagement. Longitudinal study would be needed to resolve this question.

Although we used a manual reaching task as the response mechanism in this study, we did not find statistically significant differences in reaction time between amblyopic and fellow eyes or between amblyopic and control observers; amblyopic children were slower with each eye but not significantly so. This is unexpected in part because reach latency has been found to be delayed in some previous studies of amblyopia. Niechwiej-Szwedo et al. (2014) asked strabismic amblyopic adults to reach as quickly as possible to a target presented in one of four locations on a CRT monitor. They found that the amblyopic group had on average longer reaction times with the amblyopic eye viewing compared to the fellow eye or binocular viewing. However, strabismic nonamblyopic participants showed a similar elevation of reaction time with the nondominant eye. It is also important to note that this pattern is not seen in anisometropic amblyopic adults, who showed no particular elevation of reaction times with the amblyopic eye viewing (Niechwiej-Szwedo et al., 2011), so it is unclear whether in this case the strabismus was the more relevant factor. On the other hand, Hamasaki and Flynn (1981) found a significant interocular difference in reaction time for strabismic amblyopes that was not evident in strabismic nonamblyopes (see also Niechwiej-Szwedo et al., 2019). Our group of children consisted of a greater number of anisometropic than strabismic amblyopes, which may have contributed to the outcome. However, Suttle et al. (2011) showed that a mixed group of amblyopic children performed a reach-to-grasp task significantly slower under all viewing conditions (monocular and binocular) compared to control children, so task constraints may also be a factor. Amblyopic adults showed a similar pattern, although the delay was not as substantial as in the children. The reaction times in our study are overall longer than those in the Niechwiej-Szwedo studies, even though our children were similarly instructed to respond as quickly as possible. However, our children were performing a shape discrimination task, which is considerably more demanding than a simple target detection task, so it is not surprising that our reaction times are in general longer. Our reaction times are in the range of or perhaps slightly slower than those reported by Roberts et al. (2016) for amblyopic adults on a comparable task. They are also comparable with those reported by Tsirlin et al. (2018) for their large-set size conjunction search condition and Suttle et al. (2011); each of these two studies reported reaction time elevation with amblyopic viewing. Therefore, we do not believe that our failure to find a difference in reaction time between groups in our study is because our children were not responding quickly enough.

As described in the Introduction, two prior studies of endogenous spatial attention in amblyopia have been conducted, one in adult humans and one in adult macaques. Although the tasks differed—orientation discrimination versus contrast sensitivity for grating drift direction discrimination—both found that amblyopic as well as fellow eyes benefited from the presentation of a brief valid spatial cue, improving sensitivity or response accuracy and speeding reaction times (Pham et al., 2018; Roberts et al., 2016). In addition, Sharma et al. (2000), in a study that demonstrated deficits in enumeration of display elements, showed that a valid spatial cue enhanced performance (and an invalid cue disrupted performance) similarly for amblyopic and fellow eyes and visually typical observers. Thus, the results in the present study are completely consistent with those prior studies. Furthermore, some other types of attention tasks assessed in amblyopes demonstrated that attentional function is intact despite findings of mild to moderate losses, meaning that attention *can be* functionally deployed. For example, Hou et al. (2016) showed that attention in fact modulated steady state visually evoked potentials (SSVEP) responses in both eyes of amblyopes, although that modulation was weaker in the amblyopic eye. Levi and Tripathy in two studies found inconsistent deficits or none at all across observers on a multiple trajectory tracking task (Levi & Tripathy, 2006; Tripathy & Levi, 2008). Some types of deficits may instead represent differences in effectiveness or limitations of attentional deployment. For example, under conditions such as multiple-object tracking or conjunction visual search, differences between observers only become apparent with large sets of distractors (Ho et al., 2006; Neri & Levi, 2006). Delayed or overall slower processing of relevant compound stimuli may explain the increased reaction times found for amblyopic observers in conjunction visual search and Stroop performance (Tsirlin et al., 2018; Zhou et al., 2015). These explanations would support the existence of deficiencies in effectiveness of attentional deployment or perhaps limitations in attentional capacity on complex or high-demand tasks. But clearly, attention has been deployed and is therefore intact in amblyopic observers, both adults and children.

Conclusion

Our study demonstrates that despite their visual deficits, amblyopic children are able to significantly improve the quality of their visual performance with the deployment of spatial attention to the same degree as visually typical children and similarly to amblyopic adults. Our data suggest that the endogenous attentional processes that seem to be intact in amblyopic adults are present even in children and do not result from behavioral compensation over time. Given that amblyopic attentional capability is similar to that of visually typical children, future studies exploring the effect of attentional cueing on amblyopic perceptual deficits could be beneficial for considering novel therapies.

Keywords: amblyopia, attention, endogenous, children, visually typical, spatial cueing task

Acknowledgments

This research was supported by Research to Prevent Blindness, with a Walt & Lilly Disney Award for Amblyopia Research to LK. The authors thank Dr. Joel Schuman for his support and assistance for this project. They also thank Cindy Forestal, Dr. Chao Tang, and the Pediatric Ophthalmic Consultants (Rhodora Silang, Esther Suh, and the ophthalmology staff), the staff at Bellevue Pediatric Ophthalmology Clinic, and NYU Langone Health's Department of Ophthalmology for their important contributions to this project.

Commercial relationships: none.

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