Abnormal spatial selection and tracking in children with amblyopia

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Abstract

We assessed 18 children with unilateral amblyopia and 30 age-matched controls on one low-level and three high-level motion tasks. Children with amblyopia showed similar performance to controls in both amblyopic and fellow eyes on a low-level global motion task and on a high-level 2-dot apparent motion task. Performance on both single-object and multiple-object attentive tracking tasks was significantly depressed in both amblyopic and fellow eyes relative to controls. These findings suggest that binocular regions of posterior parietal cortex likely contribute to a deficit in voluntary, spatial attention that is a component of amblyopia.
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1. Introduction

In the clinic, the defining characteristic of amblyopia is reduced visual acuity in an otherwise healthy, properly refracted eye (but see Ohlsson, 2005 for a discussion of this definition). The fellow eye is usually considered to be normal. Amblyopia may be associated with strabismus, anisometropia or both strabismus and anisometropia. In the psychophysics laboratory, several other types of visual loss are seen. In addition to reduced visual acuity, there are well-documented deficits in several other aspects of spatial vision such as low-contrast acuity, contrast sensitivity, position acuity, and spatial localization (reviewed in Levi, 1991). There are also reports of deficits in motion processing involving: oscillatory movement displacement (Buckingham, Watkins, Bansal, & Bamford, 1991; Kelly & Buckingham, 1998), motion-defined form (Giaschi, Regan, Kraft, & Hong, 1992; Ho et al., 2005), motion after-effect (Hess, Demanins, & Bex, 1997), maximum motion displacement (Ho & Giaschi, 2006; Ho et al., 2005), and

global motion (Simmers, Ledgeway, Hess, & McGraw, 2003). Motion deficits are likely not well accounted for by reduced visual acuity (Ho & Giaschi, 2006; Hess et al., 1997) especially since there have been numerous reports of abnormal motion perception in the fellow eye which has normal visual acuity (Giaschi et al., 1992; Ho & Giaschi, 2006; Ho et al., 2005; Simmers et al., 2003). Motion perception in amblyopia is not tested clinically, but deficits implicate regions of the extra-striate dorsal visual pathway (Ho et al., 2005; Simmers et al., 2003), in addition to the cortical regions implicated by visual acuity deficits.

Cavanagh (1992) proposed that humans have a high-level motion system that is mediated by visual attention. The mechanism of this high-level motion system is the "attentive tracking" of the moving, visible stimulus. In contrast, the low-level motion system has been linked to the directionally selective neurons of V1 and the "motion area" MT in the dorsal pathway that can function passively without reliance on visual attention. Motion aftereffects show dramatically different properties for the two types of motion (Culham, Verstraten, Ashida, & Cavanagh, 2000) suggesting that attentive tracking does not simply enhance low-level motion signals but, rather, acts at a different stage of processing.

Functional magnetic resonance imaging (fMRI) has revealed that the posterior parietal cortex of the dorsal pathway is activated during attentive tracking (Culham et al., 1998). Patients with deficits in selective spatial attention due to parietal lesions show deficits in motion perception for high- but not low-level tasks (Battelli et al., 2001).

Previous reports have implicated posterior parietal cortex dysfunction in strabismic amblyopia using several high-level non-motion tasks. High-level deficits in the processing of static stimuli in amblyopia include: underestimation in visual object enumeration (Sharma, Levi, & Klein, 2000); and a prolonged attentional blink, which is an impairment in the detection of the second of two rapidly sequential targets (Asper, Crewther, & Crewther, 2003). Both of these tasks have been reported to involve the posterior parietal cortex (Sathian et al., 1999 (enumeration); Marios, Chun, & Gore, 2000 (attentional blink)). Visual object enumeration has been linked to attentive, multiple-object tracking (Trick, Audet, & Dales, 2003). Based on this, one might expect object tracking deficits to exist in amblyopia also.

To date, the possibility that amblyopic children have deficits on high-level, attentive tracking has not been investigated. Deficits for a high-level, maximum motion displacement task have been reported to exist in amblyopic children (Ho & Giaschi, 2006). We suggested in the previous study that high-level, feature-matching motion mechanisms may be affected by amblyopia. The aim of the current study was to investigate the extent to which the high-level motion system (and posterior parietal cortex function) is impaired in amblyopia. We assessed children with amblyopia and controls on one low-level task and three high-level motion tasks known to reveal deficits specific to high-level motion in patients with parietal lesions (Battelli et al., 2001). Of the three high-level motion tasks, one examined the maximum rate at which apparent motion

could be seen, whereas the other two examined spatial selection and tracking of one or more targets among distractors.

2. Procedure

2.1. Participants

2.1.1. Control group

The control group consisted of 30 children, aged 9 to 17 years (mean = 12.1, $SD = 1.81$), with normal or corrected to normal visual acuity (Regan 96% contrast letter chart) and normal stereoacuity (Randot circles test, Stereo Optical Co. Inc.). Visual acuity (VA) and stereoacuity needed to be at least 20/20 and 40 s of arc, respectively. The Regan 96% contrast letter chart was used to measure VA because it has letter spacing designed to minimize crowding effects and has a logarithmic progression of letter size (Regan, 1988a). No subject had a history of ocular disease or abnormal development.

2.1.2. Amblyopic group

The patient group consisted of 18 children, aged 9 to 17 years (mean = 12.3; $SD = 2.62$), with a history of treated unilateral amblyopia. The subjects were referred from the Department of Ophthalmology at the Children's and Women's Health Centre of British Columbia. They were clinically evaluated by author RC, and classified into anisometropic, strabismic, and aniso-strabismic subtypes. The clinical details of the children with amblyopia are summarized in Table 1. Unilateral amblyopia was defined in our study as: (1) a history of reduced VA in one eye, with an interocular difference in VA, for which no organic cause can be found; (2) the presence of an amblyogenic factor (anisometropia, strabismus or both) during visual

Table 1
Summary of details for the participants with amblyopia

Patient	Diagnosis	Age (years)	Sex	Decimal visual acuity—amblyopic eye	Decimal visual acuity—fellow eye	Stereoacuity
1	A	9.98	M	0.625	1.40	50
2	A	10.25	F	0.65	1.03	30
3	A	10.33	F	0.88[*]	1.30[*]	400
4	A	10.75	F	0.40	1.03	30
5	A	13.16	F	0.69	1.00	20
6	A	13.67	F	0.68	1.20[*]	30
7	A	14.17	M	0.30	1.30	20
8	A	15.21	M	0.70[*]	0.90	50
9	A	15.50	M	0.50	1.08	30
10	A	16.33	M	1.23	1.48	70
11	S	9.00	F	0.83	1.20	100
12	S	9.67	M	0.50	1.00	70
13	S	10.63	F	0.5	0.90	400
14	S + A	9.25	F	1.05	1.43	40
15	S + A	10.33	F	0.83	0.90	25
16	S + A	10.78	M	.675	1.20	500
17	S + A	15.00	F	0.63	1.03	30
18	S + A	16.67	M	1.28	1.30	400

A, anisometropic amblyopia; S, strabismic amblyopia; S + A, aniso-strabismic amblyopia.
[*] Denotes coherence thresholds at least 1.97 greater than the control group mean threshold.

maturation; and (3) subnormal VA that is treatable with occlusion therapy (Ohlsson, 2005). None of the subjects included had eccentric fixation, latent or manifest nystagmus, anomalous retinal correspondence, or oculomotor dysfunction with the exception of strabismus. Both the amblyopic and fellow eyes were tested.

For some participants, the VAs measured at the time of testing (Table 1) represent the VA *after* completion of occlusion therapy. Some of these participants had normal acuity in both eyes due to successful treatment of their amblyopia. In a study of amblyopic children treated with occlusion therapy, Regan (1988b) demonstrated that children can show a relative improvement in VA at high-contrast levels (such as with the Regan 96% contrast chart used in this study), but subnormal VA at low and intermediate contrast levels after treatment. Thus, children who have recovered VA at high-contrast levels should still be classified as amblyopic even though the interocular difference in VA may be marginal.

2.2. Methods

The study was approved by the University of British Columbia's Behavioural Research Ethics Board. All testing was completed in one session that lasted approximately 1.5 h. Prescribed optical correction was worn throughout testing for subjects requiring refractive correction. Testing was performed under diffuse illumination with lights directed away from the display screen to prevent glare. The non-tested eye was occluded with an opaque black patch. Each task was preceded by a practice session that was performed binocularly. Test distance was monitored throughout all the experimental trials to ensure that it remained constant. Subjects were asked to complete all four tasks in the same order. The eye that was tested first was varied between subjects. For the amblyopic group, some were tested in the fellow eye first and others the amblyopic eye first. For the control group, the first eye tested varied between right and left eyes. In the means analyses below, the left control eyes comprised the control for the fellow eyes and the right control eyes comprised the control group for the amblyopic eyes.

3. Experiment 1: Global motion (low-level motion task)

Newsome and Paré (1988) provided the first evidence that the middle temporal (MT) area of monkeys (which comprises directionally selective neurons with large receptive fields) is important for the perception of motion in a global dot-motion task. After a unilateral lesion to area MT, rhesus monkeys showed extremely elevated coherence thresholds for displays presented in the visual field contralateral to the lesion. We suggest that coherence thresholds on a global dot-motion task reflect the performance of the low-level motion system because these thresholds are determined by direction-selective neurons in area MT.

3.1. Apparatus

Stimuli were displayed on a Macintosh 8500 computer. The random-dot display comprised high-contrast white dots (75 cd/m^2; 0.013 deg diameter) that were displaced 0.127 deg between each of four successively presented frames. The luminance of the black background was 0.2 cd/m^2. Each frame of dots was presented for 107 ms, resulting in a total trial length of 428 ms. The dot density was 32 dots/deg^2. Observers viewed the display in a dimly lit room at a distance of 1.4 m. Subjects entered their responses using a customized McGravis gamepad.

3.2. Procedure

The global motion task was presented as a 2-alternative forced-choice procedure. The subject indicated whether the dots moved to the right or to the left on each trial. On the first trial, 100% of the dots moved in the same direction. As the coherence level was reduced below 100%, the subject indicated whether *most* of the dots moved to the right or to the left. Coherence level was reduced according to a staircase algorithm with a 2 down–1 up rule and with step size halved after each response reversal. A run ended after 40 trials or 10 response reversals.

Thresholds were determined by fitting a Weibull function to the data for each participant using a maximum-likelihood minimization procedure (Watson, 1979). Threshold was defined as the point of maximum slope on the fitted curve, which occurs at 82% correct in a 2AFC procedure (Strasburger, 2001). A χ^2 test was performed to ensure that threshold estimates were valid by confirming that the Weibull function adequately fit the data for each child.

3.3. Results

A mixed design ANOVA with one between factor (group: control, amblyopic), and one within factor (eye: amblyopic, fellow), showed no main effect of group ($F_{1,90} = 1.008$, $p = .32$), or eye ($F_{1,90} = .833$, $p = .36$) nor a significant group × eye interaction ($F_{1,90} = .087$, $p = .77$). The effect size for both group ($\eta_p^2 = .011$) and eye ($\eta_p^2 = .009$) main effects was very small. These results (illustrated in Fig. 1) suggest that there is no deficit in direction discrimination on a global motion task in either eye of children with unilateral amblyopia. An ANOVA that split the children with amblyopia into two groups–those with associated strabismus and those without–showed the same pattern of results as the initial ANOVA. Task performance was not significantly correlated with visual acuity or stereopsis.

When individual threshold scores were compared to the mean threshold score for the control group, all patients with amblyopia associated with strabismus fell within normal limits relative to the control group. A cut off criteria of 1.97 standard deviations, which represents a one-tailed 95% confidence limit, was used. Three of the 10 patients
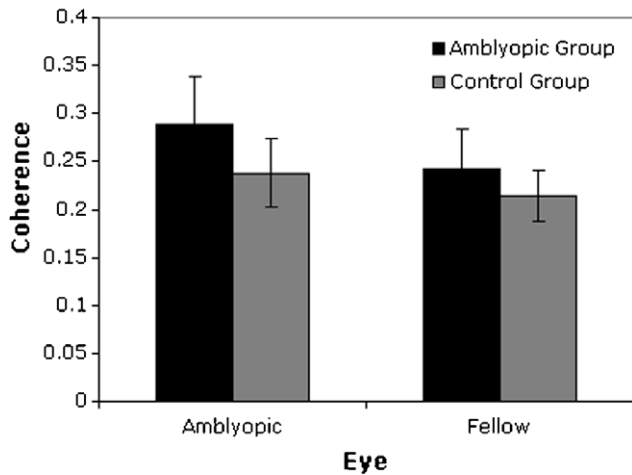
Fig. 1. Mean coherence thresholds obtained from Experiment 1. These thresholds represent the percentage of dots that must move coherently for 82% correct direction discrimination. Thresholds for amblyopic and fellow eyes are illustrated beside the control threshold that they were compared against. Lower threshold values correspond to better performance. Error bars represent standard errors.

with pure anisometropic amblyopia (shown in Table 1) had abnormally high coherence thresholds in at least one eye that was greater than 1.97 standard deviations above the control-group mean. The eyes with abnormal performance are marked in Table 1.

3.4. Discussion

As a group, the amblyopic children showed normal performance on this low-level motion task. Coherence thresholds have been previously assessed in the fellow eyes of amblyopic children (Ho et al., 2005; Wang, Ho, & Giaschi, 2006) and results from these studies also suggest that there is no group global motion deficit, at least with this particular stimulus. It appears, however, that a small proportion of individual children with anisometropic amblyopia may have a low-level motion deficit. This is consistent with previous findings suggesting that amblyopic children with strabismus have better performance on global motion than those with anisometropia (Ho et al., 2005).

The global motion deficit in some children with amblyopia is likely not due to reduced visual acuity because these children did not have the lowest acuity scores. In addition, visual coherence thresholds for the stimuli used here are not affected when visual acuity is reduced by optical blur (Zwicker, Hoag, Edwards, Boden, & Giaschi, 2006). Similarly, the majority of children tested did not appear to have difficulty with the task despite being asked to discriminate horizontal directions of motion. Nasal-temporal asymmetries that could be associated with strabismic amblyopia did not appear to affect coherence thresholds in this group of subjects.

The results from our studies were obtained using a relatively slow speed of motion. Motion signals were traditionally assumed to be carried exclusively by the sub-cortical M pathway, but emerging evidence indicates a role for the chromatically sensitive P pathway in motion perception (Anderson, Drasdo, & Thompson, 1995; Cavanagh & Anstis, 1991; Edwards & Badcock, 1996). Our previous work with M-pathway disruption techniques confirms M-pathway involvement for the speed of global motion used in the present study (Chapman, Hoag, & Giaschi, 2004). We cannot, however, rule out a P-pathway contribution to motion perception at this speed. There have been reports of global motion deficits in amblyopic individuals when faster speeds were used. Simmers and colleagues (2003) identified global motion deficits in amblyopic adults and Ellemberg and colleagues (Ellemberg, Lewis, Maurer, Brar, & Brent, 2002) found global motion deficits in amblyopic individuals with congenital deprivation amblyopia but *not* in those with non-congenital deprivation amblyopia. The extent and speed tuning of global motion deficits in amblyopia has not been established.

4. Experiment 2: Classic 2-dot apparent motion (high-level motion task)

Two similar stimuli presented successively at an appropriate temporal and spatial separation, are perceived as one object in motion, rather than two successive objects. When the spatial separation is such that the two stimuli do not fall within the receptive field of a single motion detector (and therefore do not activate the low-level motion system), attention is believed to be necessary to achieve this type of "classic" apparent motion perception (Dick, Ullman, & Sagi, 1991; Horowitz & Treisman, 1994; Wertheimer, 1912/1961; Verstraten, Cavanagh, & Labianca, 2000). Battelli and colleagues (Battelli, Cavanagh, Martini, & Barton, 2003) investigated patients with parietal damage and suggested that temporal attention is critical for apparent motion. Loss in apparent motion for these patients was attributed to a loss in the ability to attend to and process the temporal profile of a stimulus in order to register appearances and disappearances of objects.

4.1. Apparatus

Stimuli were displayed on a Macintosh 8500 computer. White dots (62 cd/m^2; 0.5 deg) were presented on a gray background (16 cd/m^2) to create two types of displays. The apparent motion display was created by alternating two visual frames: in frame 1, two white dots were arrayed on diagonally opposed vertices of a square (measuring 3 deg by 3 deg); in frame 2, the dots were arrayed on the opposite pair of vertices. The flickering dots display was also created by alternating two visual frames: in frame 1, four white dots were presented; in frame 2, no dots were presented. A fixation dot was always present in the centre of both displays. The distance from the fixation dot to a white dot was 2 deg. For this experiment and each

subsequent experiment, observers viewed the displays at a distance of 57 cm in a dimly lit room.

For both displays, the cycle length (the time from the onset of frame 1 to the offset of frame 2) was varied. For example, a cycle length of 140 ms would correspond to presenting frame 1 for 70 ms and frame 2 for 70 ms. There were eight cycle lengths generated: 26.67, 45.33, 65.33, 84.00, 102.67, 121.33, 141.33, 160 ms.

4.2. Procedure

In this 2-alternative forced-choice task, the subject fixated on the central dot and reported whether he/she saw two dots moving back and forth or four dots flashing on and off on each trial. The cycle lengths were presented 4 times each in random order according to the method of constant stimuli. Each subject performed 16 practice trials followed by a block of 64 test trials. Each trial was 1000 ms long.

Data were combined across motion and flicker trials. The threshold cycle length was taken as the point on the psychometric function at which the subject correctly distinguished motion from flicker 75% of the time. The task increased with difficulty as the cycle length was shortened, so a shorter cycle length represents better performance.

4.3. Results

A mixed design ANOVA with one between factor (group: control, amblyopic) and one within factor (eye: first, second) showed no main effect of group ($F_{1,92} = .804$, $p = .37$) or eye ($F_{1,92} = .018$, $p = .89$), nor a significant group × eye interaction ($F_{1,92} = 1.00$, $p = .32$). The effect sizes for group ($\eta_p^2 = .009$) and eye ($\eta_p^2 = .000$) were very small (Fig. 2). A separate ANOVA showed that group mean performance
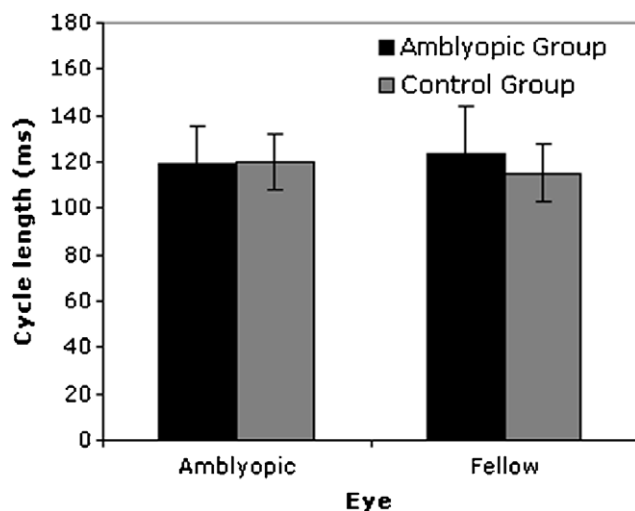

Fig. 2. Mean cycle length thresholds obtained from Experiment 2. These thresholds represent the cycle length for 75% correct discrimination between motion and flicker. Thresholds for amblyopic and fellow eyes are illustrated beside the control threshold that they were compared against. Higher threshold values correspond to better performance. Error bars represent standard errors.

did not significantly differ for patients with anisometropic amblyopia and those with amblyopia associated with strabismus. Task performance was not significantly correlated with visual acuity or stereopsis.

4.4. Discussion

These findings suggest that the perception of classic apparent motion is normal in both the amblyopic and fellow eye of children with unilateral amblyopia. Battelli and colleagues (2001) have shown that individuals with visual attention deficits following parietal damage show a deficit on this task. A subsequent paper (Battelli et al., 2003) indicated that the deficit was not one of voluntary spatial attention, but of transient attention. The patients had difficulty differentiating onset from offset transients, a necessary step in linking the offset of one stimulus with the onset of the next to produce apparent motion. The children with amblyopia show no deficit in this apparent motion task, suggesting that they have no deficit in transient attention. In contrast, the next two high-level motion tasks, unlike apparent motion, require focused spatial selection, attending to target locations and rejecting distractors.

5. Experiment 3: Single-object tracking (high-level motion task)

To further investigate the role of attention in motion perception in amblyopia we investigated a task that required *spatial selection:* attentive tracking. In this experiment, we measured the subject's ability to track one moving object amongst identical moving distractor objects while he/she maintained fixation on the centre of the display. The target and distractors were displaced in steps that were too large to activate low-level motion detectors (Verstraten et al., 2000). This task not only involved simple high-level apparent motion mechanisms as in the previous experiment, but also required voluntary tracking.

5.1. Apparatus

Three arrays of four discs were alternated in space and time to create the perception of four white discs (size: 0.8 deg; 62 cd/m^2) rotating around a central target (size: 2 deg; 37 cd/m^2) (see Verstraten et al., 2000). The central target and white discs were presented on a gray background (16 cd/m^2). The distance from the central target to each white disc was kept constant at 9 deg. Each disc completed 12 "steps" in one revolution. Eight different rotation speeds were presented in random order: 0.05, 0.114, 0.179, 0.243, 0.307, 0.371, 0.436, 0.50 revolutions/s.

5.2. Procedure

In this 2-alternative forced-choice paradigm, the observer's task was to attentively track one white disc (target), while maintaining fixation on the central fixation target.

The importance of maintaining fixation was emphasized to each subject. The experimenter monitored fixation subjectively throughout the task. At the beginning of each trial, the white disc that was to be attentively tracked turned red for 2000 ms then changed back to white again. The participant attentively tracked the target disc for 1500 ms. At the end of each trial, one of the white discs turned red again and the subject was to indicate whether the disc that turned red was the same disc that they were tracking.

Each subject completed 16 practice trials, followed by one block of 64 test trials (8 trials per rotation speed). The percent correct target identification was plotted as a function of rotation speed. Speed threshold was taken as the point on this psychometric function at which the subject correctly identified the target 75% of the time. The task became more difficult as speed increased. A higher speed threshold represents better performance. Only data for which a psychometric function could be reliably fit were used in the group means analysis. Data from 16 of the 18 amblyopic and 27 of the 30 control subjects were included in the ANOVA.

5.3. Results and discussion

A mixed design ANOVA with one between factor (group: control, amblyopic) and one within factor (eye: first, second) showed a significant main effect of group ($F_{1,82} = 7.684$, $p < .01$) but no significant main effect of eye ($F_{1,82} = .327$, $p = .57$), nor a significant group × eye interaction ($F_{1,82} = .44$, $p = .51$). The effect sizes for the main effects of group ($\eta_p^2 = .094$) and eye ($\eta_p^2 = .009$) were, respectively, moderate and very small (Fig. 3). A separate ANOVA showed that group mean performance did not significantly differ for patients with anisometropic amblyopia and those with amblyopia associated with strabismus.
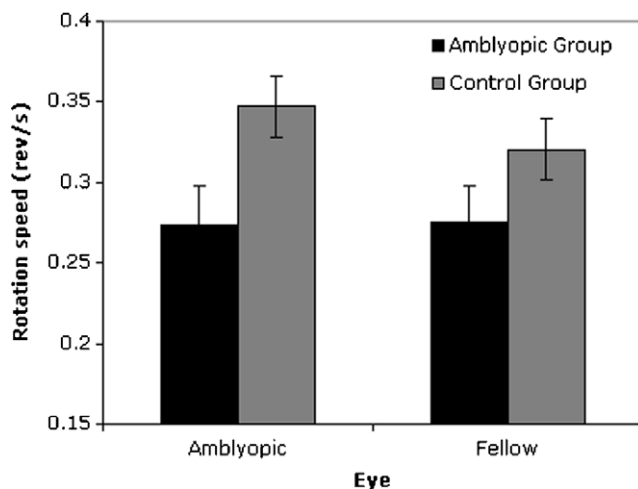

Fig. 3. Mean rotation speed thresholds obtained from Experiment 3. These thresholds represents the rotation speed for 75% correct target identification. Thresholds for amblyopic and fellow eyes are illustrated beside the control threshold that they were compared against. Higher threshold values correspond to better performance. Error bars represent standard errors.

Task performance was not significantly correlated with visual acuity or stereopsis.

The threshold rate for amblyopic eyes was 0.274 revolutions per second. Since each target takes 12 steps to complete one revolution, the target is presented for about 300 ms at each location before moving to the adjacent location (and about 240 ms at threshold for the controls). This is a much longer duration than was found for the threshold of perceiving apparent motion on its own in Experiment 2 (120 ms). Clearly, the limitation on tracking the individual target among distractors here is not the visibility of the motion from each location to the next.

These results suggest that, overall, amblyopic and fellow eyes demonstrate an attentive tracking deficit relative to control eyes that results from the spatial selection requirements of the task and not the response to the motion of each target. The children with amblyopia do not appear to have a general deficit in high-level motion. Their perception of apparent motion was unaffected in Experiment 2. Their loss is limited to the attentive tracking functions of high-level motion involving the spatial selection of targets and rejection of distractors. The results are discussed in Sections 6.4 and 7.

6. Experiment 4: Multiple-object tracking (high-level motion task)

Attentive tracking ability was further investigated in this experiment by varying the number of objects tracked. In a typical multiple-object tracking task, a subject is required to track a subset of target discs in a field of identical moving discs. Past research suggests that individuals can track up to four or five targets if they use concentrated effort (Pylyshyn & Storm, 1988). This is an attentive tracking task because rather than following the target(s) with their eyes (an impossible task when there is more than one target), the subject must fixate on the centre of the screen and direct attention to where each target is moving. Like the single-object tracking task, the subject must selectively attend to the target disc(s), while filtering out the distractor discs. Unlike the single-object tracking task in Experiment 3, the direction of motion in this stimulus randomly changes. The motion of each target is also continuous and capable of driving low-level motion detectors but this task is still considered high-level because the component of divided attention is essential to perform accurately.

6.1. Apparatus

The display was a 14×14 deg dark-gray square (0.8 cd/m²) in which eight identical green discs (1 deg; 53 cd/m²) moved in a semi-random fashion. Every 45 ms, each disc's trajectory was subject to random variations, which resulted in unpredictable paths. The discs "bounced" off the edge of the square and each other. Thus, the discs never occluded or collided with each other. The velocity of the discs was a constant 6 deg/s.

6.2. Procedure

The subject's task was to track 1, 2, 3, or 4 disc(s), while maintaining fixation on a central dot. The subjects were told the importance of maintaining fixation, and the experimenter monitored fixation throughout each trial. At the beginning of each trial, the target disc(s) turned red (20 cd/m^2) for 1200 ms. When the discs turned back to green, the subject attentively tracked the target disc(s) for 5000 ms. At the end of each trial, the disc(s) stopped moving and the subject clicked with a mouse to select each of the target disc(s) that were being tracked.

Each subject performed 10 practice trials, followed by 40 test trials (10 trials for each tracking condition). The proportion of correct responses was recorded for each subject for each tracking condition (1 disc, 2 discs, 3 discs, 4 discs). The probability of correctly guessing a tracked target ball depends on the number of targets (e.g., chance is 1/8 when there is one target but 4/8 when there are four targets). The tracking accuracy was therefore corrected for guessing with this formula where c is the proportion of correct responses and n is the number of targets:

Tracking accuracy $= 100 * (c - n/8)/(1 - n/8)$.

Data were obtained for 17 amblyopic and 27 control children. This experiment was conducted at the end of the testing session and several participants did not complete this task due to fatigue and/or restlessness.

6.3. Results

A mixed design ANOVA with one between factor (group: control, amblyopic) and two within factors (eye: fellow, amblyopic; balls tracked: one, two, three, four) revealed significant main effects of group ($F_{1,86} = 7.849$, $p < .01$) and balls tracked ($F_{1,86} = 14.403$, $p = .00$) but not a significant main effect of eye ($F_{1,86} = .829$, $p = .36$). The effect sizes for group ($\eta_p^2 = .023$), balls tracked ($\eta_p^2 = .126$) and eye ($\eta_p^2 = .002$) were, respectively, small, moderate and very small. No interactions were significant ($p > .50$). The same pattern of results was found when the children with amblyopia were split into two groups (those with pure anisometropia and those with strabismus).

Probit curves were fit to the tracking accuracy as a function of number of targets. Results for control, amblyopic, and fellow eyes are illustrated in Fig. 4. For the controls, tracking accuracy was plotted for the average of both eyes. The horizontal dashed line represents the 75% performance level. The number of items tracked at this level was as follows: 5.16 (SE = 0.23) for control eyes, 4.00 (SE = 0.68) for fellow eyes, and 3.70 (SE = 0.75) for amblyopic eyes.

The results again indicate that amblyopic children have deficits in attentive tracking that affect *both* amblyopic and fellow eyes. On average, tracking capacity at 75% accuracy
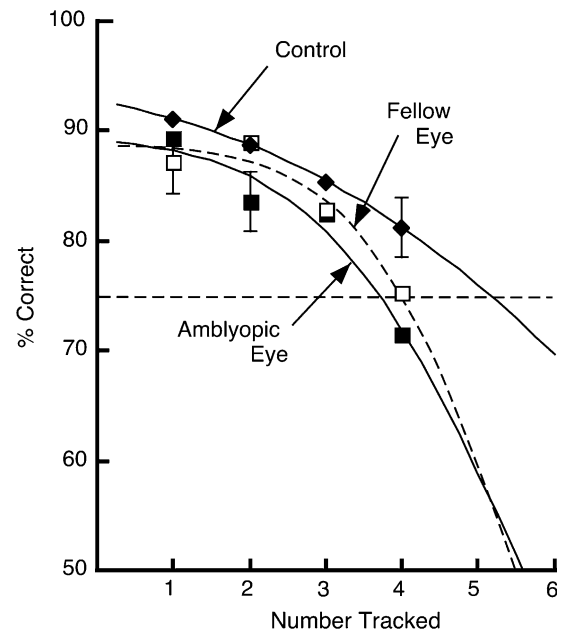

Fig. 4. Mean corrected-for-guessing accuracy scores obtained from Experiment 4. Probit curves were fit to the data for control, fellow, and amblyopic eyes. The graph depicts corrected-for-guessing accuracy scores plotted against number of balls tracked. The control data represent scores averaged across both eyes. The horizontal dashed line represents performance at a 75% accuracy level. The number of balls tracked at this level is 5.16, 4.00, and 3.70 for, respectively, control, fellow, and amblyopic eyes. Accuracy for all subjects declines as the number of balls tracked increases. Both the fellow and amblyopic eyes of amblyopic children are less accurate at tracking than control eyes regardless of the number of balls tracked. The departure from control performance, however, increases as the number of balls tracked increases.

is lower for amblyopic and fellow eyes than for control eyes.

Fig. 4 demonstrates that amblyopic observers likely have a generalized deficit in attentive tracking relative to controls. They have lower accuracy scores for all target set sizes (one, two, three, and four) but there is a greater departure from control performance as the target set size increases. For all observers, accuracy scores are significantly worse as the number of balls tracked increases.

6.4. Discussion

The amblyopic and fellow eye demonstrated attentive tracking deficits for single and multiple objects. The cortical areas activated during a multiple-object tracking task have been studied using fMRI (Culham et al., 1998). When contrasted with passive viewing of the "bouncing balls" display, attentive tracking produced bilateral activation in the intraparietal sulcus, the postcentral sulcus, the superior parietal lobule, and the precuneus of the parietal cortex. The attentive tracking deficits exhibited by children with amblyopia may be associated with impaired functioning of the parietal cortex.

7. General discussion and conclusions

Children with amblyopia showed similar performance to controls in both amblyopic and fellow eyes on low-level global motion and high-level 2-dot motion tasks. Performance on single-object and multiple-object tracking tasks was depressed in both amblyopic and fellow eyes. Although a low-level motion perception deficit cannot be ruled out, these results suggest a relative preservation of low-level motion perception and transient attention in amblyopia but notable deficits in attentive tracking even in the fellow eye.

It is sometimes assumed that because the fellow eye has normal acuity, this eye is "normal." The fellow eye is even sometimes used as the control eye for the amblyopic eye (e.g., Hess & Anderson, 1993). The depressed performance exhibited by the fellow eye on the multiple-object tracking task suggests that amblyopia does not just influence the amblyopic eye, and the fellow eye is not always an adequate control eye. This conclusion is in agreement with other studies reporting visual loss in fellow eyes on tasks of motion perception (Giaschi et al., 1992; Ho & Giaschi, 2006; Ho et al., 2005; Simmers et al., 2003), contrast sensitivity (Leguire, Rogers, & Bremer, 1990), and a variety of other subtle sensory and motor deficits (reviewed in Lewis, Maurer, Tytla, Bowering, & Brent, 1992). The results imply that dysfunctional regions of the parietal cortex that are involved in spatial attention and tracking in amblyopic children likely consist of high numbers of binocular neurons.

7.1. Etiology and binocularity

While some previous studies have found a difference between individuals with strabismic and anisometropic amblyopia on some psychophysical tasks (see Levi, 1991 for a review) and between amblyopic individuals with and without binocularity (McKee, Levi, & Movshon, 2003), the present study found that individuals with both types of amblyopia show a similar pattern of deficits in the fellow and amblyopic eyes. There were too few non-binocular subjects (stereoacuity >500 s) to determine statistically with an ANOVA whether there were group mean differences between binocular and non-binocular sub-groups. Stereoacuity was not significantly correlated to performance thresholds for any of our tasks.

McKee and colleagues (2003) found deficits on higher-level spatial tasks (letter and Vernier acuity) that were more pronounced in non-binocular than binocular observers with amblyopia. They suggested that these deficits might be due to impaired selective attention in the amblyopic eye caused by binocular disruption. Our findings suggest that attentional deficits can exist in amblyopic children with binocularity (14 out of our 18 subjects had measurable stereoacuity <100 s) and that the deficits are present in not only amblyopic eyes but also fellow eyes.

7.2. Role of visual attention

Attentive tracking involves aspects of both motion perception and visual attention. It is well known that some amblyopic eyes exhibit a larger-than-normal crowding effect. Visual acuity is higher when tested with isolated letters than when tested with several letters presented close together. This crowding phenomenon is present in all eyes to some extent. The findings of He and colleagues (He, Cavanagh, & Intriligator, 1996) suggested that the increased crowding effect observed in most amblyopic eyes (Flom, Weymouth, & Kahneman, 1963) is not due to spatial resolution limits per se, but to the limits placed on spatial resolution by the resolving power of visual attention. Thus, the increased crowding effect in amblyopia may reflect a visual attention deficit. Our findings agree with past studies that suggest there is a visual attention deficit in individuals with strabismus-associated amblyopia (Hariharan, Levi, & Klein, 2005; He et al., 1996; Levi, Hariharan, & Klein, 2002b; McKee et al., 2003; Sharma et al., 2000). Furthermore, Hess and colleagues (1997) reported a reduced motion aftereffect in amblyopic eyes of strabismic individuals. The motion aftereffect has a shorter duration under conditions of reduced attention (Chaudhuri, 1990; Shulman, 1993), therefore difficulty in allocating attention to stimuli presented to the amblyopic eye may account for some of the reduced aftereffect.

The results of these previous studies suggest that the resolving power of visual attention may be compromised in amblyopia, at least when it is associated with strabismus. This study presents findings supporting visual attention deficits in children with strabismic amblyopia but suggests also that similar deficits exist in children with anisometropic amblyopia. Ten of the 18 amblyopic children tested had pure anisometropia.

7.3. Role of retinal eccentricity

Levi and colleagues suggested that, in normal vision, foveal crowding is due to simple contrast masking (Levi, Klein, & Hariharan, 2002), and peripheral crowding reflects limitations imposed by the resolution of attention (Levi, Hariharan, & Klein, 2002a). If differences exist between foveal and peripheral amblyopic vision as well, then individuals with amblyopia should do worse on high-level motion tasks when the stimuli are presented peripherally than when the stimuli are foveal. In the present study, the retinal eccentricity of the stimuli varied across the high-level motion tasks. In the classic 2-dot apparent motion task (Experiment 2), the dots were 2 deg from fixation. In the single-object tracking task (Experiment 3), the discs were 8.5 deg from fixation. In the multiple-object tracking task (Experiment 4), the largest distance between two balls was 9.9 deg. Although we did not intentionally manipulate retinal eccentricity, the attentive tracking deficits were more pronounced with increasing eccentricity.

7.4. Conclusions

We have found evidence of a deficit of spatial attention and tracking in both amblyopic and fellow eyes of children with strabismic and anisometropic amblyopia. The deficit appears to be specific to the attentive tracking functions of high-level motion involving the spatial selection of targets and rejection of distractors and is particularly evident when multiple objects are tracked. Amblyopic children may have problems in the attentional pursuit of several moving objects while filtering out distractor items. Attentional deficits may be greatest when more of the peripheral retina is involved. Our findings suggest an involvement of binocular regions of posterior parietal cortex in the neural deficit underlying both strabismic and anisometropic amblyopia.

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