Eye Tracking Abnormalities in School-Aged Children With Strabismus and With and Without Amblyopia

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ABSTRACT

Purpose: To detect eye tracking abnormalities in children with strabismus in the absence or presence of amblyopia.

Methods: A total of 100 patients aged 7 to 17 years were enrolled prospectively for 2 years from the pediatric ophthalmology clinic of the American University of Beirut Medical Center: 50 children with strabismus (including 24 with amblyopia) and 50 age- and gender-matched controls. Eye tracking with different paradigms was performed.

Results: Mean age was 10.66 ± 2.90 years in the strabismus group and 10.02 ± 2.75 years in the control group. Demographic characteristics were similar with respect to vision, gender, and refraction. Four paradigms were tested using the eye tracker: (1) distance/near paradigm: patients with strabismus showed a lower fixation count and longer fixation at both distances and a tendency for decreased latency and percentage of fixation in distant elements; (2) reading paradigm: the strabismus group had a higher fixation count and duration, especially those without amblyopia; (3) location identification paradigm: strabismus group without amblyopia fixated less and with shorter duration on the most flagrant element; and (4) video paradigm: no differences in eye movements were noted.

Conclusions: Significant eye movement deficits were demonstrated in patients with strabismus compared to controls while reading text and identifying prominent elements in a crowded photograph. This was significant in the non-amblyopic subgroup.

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INTRODUCTION

Eye movement recording is a sensor technology that enables a device to locate, follow, and record the movement of the point of gaze. It determines presence, attention, focus, drowsiness, consciousness, or other mental states.[1] It is the process of electronically locating the point of a person's gaze, or following and recording the movement of the point of gaze. The main factors affecting children's eye movement recordings are: social cognition, object representation, categorization, and visual attention.[2] However, the child may have a preference for one stimulus over the other, which can be observed and studied during eye movement recording testing.[3]

Strabismus can lead to amblyopia, which is the most prevalent cause of visual impairment among the pediatric population.[4] Up to 5% of all children in a United Kingdom study had some type or degree of strabismus.[5] Children with strabismus who had amblyopia had problems with reading in fixational patterns due to increased saccades[6] and were found to make more saccades than controls, thus making

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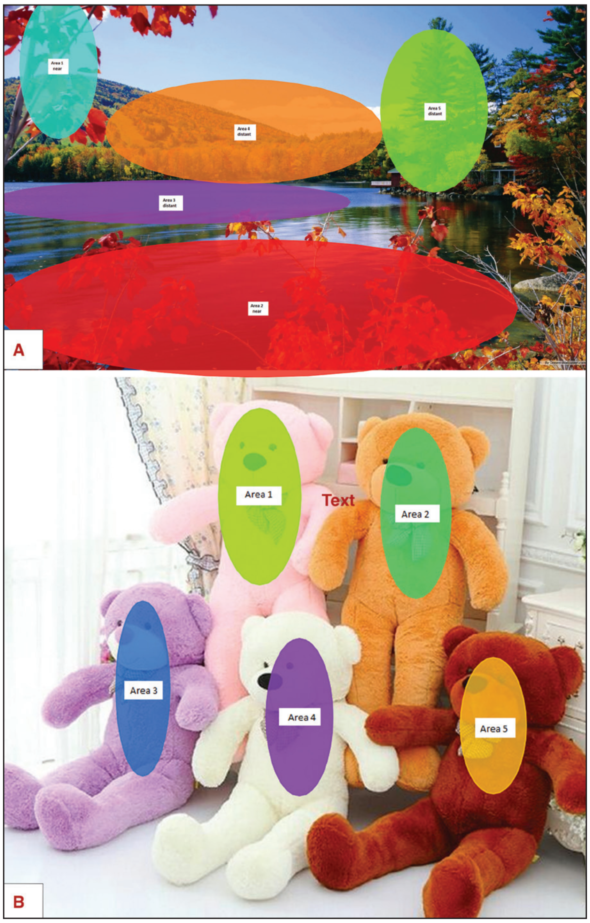

Figure 1. (A) Distance/near paradigm. (B) Location identification paradigm.

reading speed slower in the former group.[7] Many were forced to follow the line with their fingers.

The aim of this study was to detect eye movement recording abnormalities using different paradigms in children with strabismus in the absence or presence of amblyopia and compare these findings with age-matched children without strabismus.

PATIENTS AND METHODS

Study Population

Participants were prospectively recruited from the pediatric ophthalmology service at the American University of Beirut Medical Center. A total of 100 participants were enrolled in this study over a 2-year period: 50 participants with strabismus (24 with amblyopia) between 7 and 17 years of age and 50 healthy age- and gender-matched controls. The study was approved by the institutional review board at the American University of Beirut. Written informed consents were obtained from parents or legal guardians and assent forms were provided.

Demographic data of age, gender, systemic diseases, and ophthalmic examination records including visual acuity (logarithm of the minimum angle of resolution [logMAR]), cycloplegic refraction converted to spherical equivalent in diopters, ocular motility measurements in prism diopters (distance and near), ductions, funduscopy, and type of strabismus were obtained. Strabismus was defined as a constant or intermittent tropia measuring 8 prism diopters or more. Amblyopia was defined as Early Treatment Diabetic Retinopathy Study (ETDRS) visual acuity of worse than 20/30 in one eye (logMAR visual acuity of more than 0.18 in one eye) or at least a two-line interocular difference in visual acuity.

Eye Tracking

Eye tracking testing using different paradigms was performed during the clinic visit using the Tobii 1750 Eye Tracker (Danderyd, Sweden), integrated with a 17-inch monitor, while the child was seated on the parent's lap approximately 65 cm from the monitor. A 5-point calibration was administered prior to the assessment, where the gaze of the child was calibrated by comparing it to known points on the screen, provided by the manufacturer. The participant viewed a target-patterned "attention-getter," looming/contracting in synchrony with a rhythmic sound. The attention-getter was presented at five locations on the monitor, and the participant looked at each in turn. Four paradigms were studied.

Task 1. The distance/near paradigm evaluated attention to near versus distance elements in a still image. Fixation to five different areas in the photograph was studied: area 1: represented near bottom gaze at tree branch, area 2: nearest middle front view, area 3: distant water scene, area 4: distant mountain view, and area 5: distant tree view (**Figure 1A**).

Task 2. The reading paradigm evaluated reading a simple excerpt from the book *Winnie the Pooh.* Two areas of interest were studied: the text as a whole and a keyword. A question followed this paradigm, with this specific keyword being the answer.

Task 3. The location identification paradigm presented a picture of teddy bears of different colors and asked the participant to locate a specific element; five areas of interest were present, one on each teddy bear (**Figure 1B**). A question about this paradigm followed, asking the participants the color of the teddy bear that was located in the middle.

Task 4. The moving target paradigm used a video to assess eye movements in different directions:

TABLE 1

Participant Demographics

Characteristic	Strabismus (n = 50) Amblyopia (n = 24)	Strabismus (n = 50) Without Amblyopia (n = 26)	Control (n = 50)	P^a	P^b
Female:male	1:1	1:1	3:2		
Mean ± SD age (years)	10.63 ± 2.67	10.69 ± 3.16	10.02 ± 2.75	.53	.51
Mean ± SD spherical equivalent (D)	2.41 ± 2.98 (amb)	1.40 ± 2.81 OD	0.12 ± 1.44 OD	< .001	< .001
	2.25 ± 2.32	1.36 ± 2.95 OS	0.08 ± 1.46 OS	< .001	< .001
Mean ± SD visual acuity (logMAR)	0.25 ± 0.11 (amb)	0.03 ± 0.05 OD	0.06 ± 0.12 OD	.15	.05
	0.09 ± 0.11	0.03 ± 0.05 OS	0.06 ± 0.12 OS		
Strabismus types (n)					
Esotropia	18	15			
Exotropia	6	11			

SD = standard deviation; D = diopters; amb = amblyopic eye; OD = right eye; OS = left eye; logMAR = logarithm of the minimum angle of resolution
[a]Amblyopia vs control group.
[b]Without amblyopia vs control group.

vertical, horizontal, and oblique directions were evaluated with a moving area of interest containing a twinkling star.

Five parameters were analyzed in every paradigm: (1) latency or time to first fixation in seconds, which represents the time from the start of the stimulus display until the participant fixates on an area of interest for the first time; (2) first fixation duration in seconds; (3) total fixation duration in seconds: duration of all fixations within an area of interest; (4) fixation count: number of times the participant fixated on an area of interest; and (5) percentage of fixation (a proportion), which represents the percentage of participants that fixated at least once on an area of interest.

Statistical Analysis

SPSS software (version 17.0J; SPSS Japan, Inc., Tokyo, Japan) was used to perform statistical analysis. The differences in tracking parameters of the children with strabismus compared to the controls were assessed by a paired t test. A P value of less than .05 was considered statistically significant. Also, subgroup analysis of non-parametric variables between the strabismus with amblyopia, strabismus without amblyopia, and control groups was performed with the Mann–Whitney test.

RESULTS

Demographics

A total of 100 participants between 7 and 17 years of age were enrolled in this study over a 2-year period. The 50 who had strabismus were divided into two subgroups: amblyopia (n = 24) and without amblyopia (n = 26) with a female-to-male ratio of 1:1 and a mean age of 10.66 ± 2.90 years. The 50 healthy age-and gender-matched controls had a female-to-male ratio of 3:2 and a mean age of 10.02 ± 2.75 years (P = .25). Of the 24 participants with amblyopia, 3 had severe amblyopia with a logMAR visual acuity of greater than 0.4 in one eye.

Demographics of the study participants are presented in **Table 1**. Significant differences were observed between the amblyopia and without amblyopia groups by comparison to the control group with respect to mean spherical equivalent for both eyes (P < .001). Also, the amblyopia subgroup had a lower mean visual acuity in both eyes compared to the control and without amblyopia groups. In the amblyopia group, mean visual acuity in the amblyopic eye was 0.25 ± 0.11 logMAR and mean spherical equivalent was 2.41 ± 2.98 diopters (**Table 1**).

Eye Tracking Paradigms

Task 1: Distance/Near Paradigm (Figure 1A, Table 2). Time to first fixation was not significantly different when comparing participants with strabismus (both with and without amblyopia) to controls and for both distance and near elements. This was lower in the without amblyopia group compared to the control group for only one of the distant scenes (area 3) (P = .04).

TABLE 2

Eye Tracking Parameters for the Image With Distance and Near Elements Paradigm (Mean ± SD)

	Strabismus (n = 50)				
Parameter	Amblyopia (n = 24)	Without Amblyopia (n = 26)	Control (n = 50)	P^a	P^b
Time to first fixation (seconds)					
Area 1	3.48 ± 1.51	6.58 ± 2.41	5.05 ± 3.16	.28	.33
Area 2	2.64 ± 2.44	3.01 ± 3.21	3.35 ± 2.90	.35	.69
Area 3	1.62 ± 2.30	1.13 ± 1.21	1.17 ± 1.82	.57	.04
Area 4	3.68 ± 2.66	3.71 ± 2.57	3.39 ± 2.35	.69	.65
Area 5	1.61 ± 2.31	1.35 ± 1.90	2.00 ± 2.29	.44	.68
First fixation duration (seconds)					
Area 1	0.19 ± 0.14	0.34 ± 0.11	0.18 ± 0.07	.94	.02
Area 2	0.33 ± 0.09	0.32 ± 0.20	0.19 ± 0.08	< .001	.01
Area 3	0.27 ± 0.14	0.36 ± 0.17	0.23 ± 0.12	.99	.05
Area 4	0.41 ± 0.24	0.39 ± 0.13	0.23 ± 0.21	.01	< .001
Area 5	0.29 ± 0.11	0.27 ± 0.12	0.26 ± 0.23	.03	.19
Total fixation duration (seconds)					
Area 1	0.40 ± 0.16	0.34 ± 0.11	0.29 ± 0.16	.37	.52
Area 2	1.35 ± 1.14	1.96 ± 1.42	0.67 ± 0.62	.03	< .001
Area 3	2.54 ± 1.38	2.43 ± 1.60	1.61 ± 1.62	.12	.20
Area 4	1.68 ± 1.34	0.88 ± 0.53	1.03 ± 1.16	.08	.50
Area 5	2.49 ± 2.16	1.70 ± 1.95	1.91 ± 1.24	.11	.85
Fixation count					
Area 1	1.67 ± 0.58	1.00 ± 0.00	1.78 ± 0.83	.81	.02
Area 2	3.35 ± 2.18	5.30 ± 4.20	3.24 ± 2.44	.86	.05
Area 3	6.88 ± 3.52	6.00 ± 3.69	6.74 ± 5.70	.39	.08
Area 4	4.16 ± 3.56	2.35 ± 1.62	4.18 ± 3.73	.98	.01
Area 5	6.67 ± 5.30	4.47 ± 4.63	7.82 ± 4.50	.96	.07
Percentage of fixation					
Area 1	0.13 ± 0.34	0.16 ± 0.36	0.18 ± 0.39	.59	.083
Area 2	0.74 ± 0.45	0.78 ± 0.42	0.84 ± 0.37	.35	.52
Area 3	0.70 ± 0.47	0.78 ± 0.42	0.94 ± 0.24	.01	.02
Area 4	0.83 ± 0.39	0.70 ± 0.47	0.78 ± 0.42	.65	.48
Area 5	0.91 ± 0.29	1.00 ± 0.00	0.98 ± 0.14	.70	.08

SD = standard deviation

[a]Amblyopia vs control group.

[b]Without amblyopia vs control group.

As for first fixation duration, this was longer in the strabismus group (with and without amblyopia) and was statistically significant in most areas tested. However, the total fixation duration was not significantly different among groups, except in one area (area 2) as compared to controls (1.35 ± 1.14 versus 0.67 ± 0.62 seconds, $P = .03$ and 1.96 ± 1.42 versus 0.67 ± 0.62 seconds, $P < .001$) for those with and without amblyopia, respectively.

With respect to fixation count, only the without amblyopia group demonstrated significantly lower numbers than the control group for two areas only.

TABLE 3

Eye Tracking Parameters for the Reading Paradigm (Mean ± SD)

Parameter	Strabismus (n = 50) Amlyopia (n = 24)	Strabismus (n = 50) Without Amblyopia (n = 26)	Control (n = 50)	P^a	P^b
Time to first fixation (seconds)					
Keyword	4.91 ± 4.61	3.84 ± 2.99	3.79 ± 2.73	.44	.96
All text	0.14 ± 0.31	0.16 ± 0.29	0.22 ± 0.93	.58	.66
First fixation duration (seconds)					
Keyword	0.23 ± 0.10	0.21 ± 0.12	0.53 ± 1.09	< .01	< .01
All text	0.23 ± 0.13	0.19 ± 0.12	0.21 ± 0.08	.54	.51
Total fixation duration (seconds)					
Keyword	0.59 ± 0.40	0.97 ± 0.82	0.82 ± 0.79	.17	.52
All text	9.42 ± 2.27	7.48 ± 4.04	8.99 ± 3.00	.51	.09
Fixation count					
Keyword	2.32 ± 1.04	3.90 ± 2.47	3.18 ± 2.26	.07	.31
All text	36.33 ± 11.58	30.93 ± 14.83	40.81 ± 10.76	.14	< .01
Percentage of fixation					
Keyword	0.57 ± 0.51	0.63 ± 0.49	0.76 ± 0.43	.15	.25
All text	0.98 ± 0.14	1.00 ± 0.00	0.98 ± 0.14	.32	.32

SD = standard deviation
[a]Amblyopia vs control group.
[b]Without amblyopia vs control group.

Furthermore, all participants with strabismus demonstrated a lower percentage of fixation than controls for area 3 showing a distant water scene. There was also a trend of a lower percentage of fixation in most other areas.

Reading Paradigm (Table 3). Time to first fixation, total fixation duration, and percentage of fixation were similar among the groups whether on all of the text or the keyword. However, lower first fixation duration on the keyword was noted in the with and without amblyopia groups as compared to controls (0.23 ± 0.10 versus 0.53 ± 1.09 seconds, $P < .01$ and 0.21 ± 0.12 versus 0.53 ± 1.09 seconds, $P < .01$, respectively). Furthermore, both groups demonstrated a lower fixation count on all of the text, but this was statistically significant only for the without amblyopia group.

Location Identification Paradigm (Figure 1B, Table 4). When looking at the most prominent element in the image designated by area 2, only the without amblyopia group demonstrated lower total fixation duration and percentage of fixation (1.00 ± 0.85 versus 1.57 ± 1.09 seconds, $P = .04$ and 0.63 ± 0.49 versus 0.90 ± 0.30 seconds, $P = .01$). Percentage of fixation was also lower on other elements in the image. Time to first fixation, first fixation duration, and fixation count did not differ significantly among groups.

Video Paradigm of a Moving Target. No significant differences could be detected among groups and no trend could be appreciated regarding all studied parameters in any of the different directions. The amblyopia group had a lower first fixation duration when compared to the without amblyopia group (0.26 ± 0.24 versus 0.50 ± 0.38 seconds; $P = .025$) and total fixation duration (0.67 ± 0.31 versus 0.89 ± 0.31 seconds; $P = .041$) on the star when it reached the bottom left part of the image.

Subgrouping by Strabismus Type. Subgroup analysis to look into strabismus type as a confounding factor was performed by dividing the study population into two groups: esotropia (n = 33) and exotropia (n = 17). The same above analysis was done showing findings similar to those for the whole group, with no noticeable differences between the two types of strabismus. The same statistically significant differences

TABLE 4

Eye Tracking Parameters for the Location Identification Paradigm (Mean ± SD)

Parameter	Strabismus (n = 50) Amblyopia (n = 24)	Without Amblyopia (n = 26)	Control (n = 50)	*P*[a]	*P*[b]
Time to first fixation (seconds)					
Area 1	2.85 ± 2.99	2.55 ± 3.34	1.91 ± 2.23	.23	.43
Area 2	4.08 ± 4.04	4.67 ± 2.76	3.13 ± 3.38	.39	.08
Area 3	4.73 ± 3.88	4.88 ± 4.08	5.10 ± 4.65	.77	.85
Area 4	2.38 ± 2.49	4.71 ± 4.65	3.24 ± 3.62	.30	.20
Area 5	3.21 ± 3.65	6.46 ± 4.70	6.06 ± 5.09	.04	.70
First fixation duration (seconds)					
Area 1	0.23 ± 0.15	0.19 ± 0.12	0.21 ± 0.12	.56	.63
Area 2	0.21 ± 0.10	0.25 ± 0.12	0.23 ± 0.16	.38	.84
Area 3	0.28 ± 0.10	0.21 ± 0.13	0.22 ± 0.13	.10	.60
Area 4	0.23 ± 0.14	0.19 ± 0.12	0.23 ± 0.12	.92	.32
Area 5	0.22 ± 0.07	0.29 ± 0.26	0.22 ± 0.16	.86	.34
Total fixation duration (seconds)					
Area 1	1.78 ± 1.53	1.22 ± 0.96	1.55 ± 0.95	.56	.19
Area 2	1.21 ± 1.22	1.00 ± 0.85	1.57 ± 1.09	.28	.04
Area 3	1.16 ± 0.87	1.20 ± 0.94	1.12 ± 1.05	.91	.79
Area 4	1.44 ± 0.90	1.67 ± 2.44	1.56 ± 1.80	.73	.85
Area 5	0.79 ± 0.62	0.98 ± 1.03	0.98 ± 0.68	.34	.98
Fixation count					
Area 1	3.91 ± 6.26	5.14 ± 3.37	6.34 ± 3.17	.93	.17
Area 2	4.35 ± 3.12	3.82 ± 3.23	5.96 ± 3.85	.10	.04
Area 3	4.29 ± 2.97	4.20 ± 2.76	4.09 ± 3.09	.83	.89
Area 4	5.83 ± 3.54	5.14 ± 3.57	5.50 ± 3.51	.74	.70
Area 5	3.15 ± 2.34	3.33 ± 2.77	4.07 ± 2.49	.21	.34
Percentage of fixation					
Area 1	0.30 ± 0.90	0.81 ± 0.40	0.92 ± 0.27	.84	.23
Area 2	0.95 ± 0.22	0.63 ± 0.49	0.90 ± 0.30	.42	.01
Area 3	0.67 ± 0.48	0.74 ± 0.45	0.86 ± 0.35	.07	.16
Area 4	0.36 ± 0.86	0.78 ± 0.42	0.94 ± 0.24	.34	.07
Area 5	0.62 ± 0.50	0.56 ± 0.50	0.84 ± 0.37	.08	.01

SD = standard deviation
[a]Amblyopia vs control group.
[b]Without amblyopia vs control group.

were noted in the respective paradigms regardless of the strabismus type when compared to controls.

DISCUSSION

In the distance/near paradigm, children with strabismus showed longer first fixation duration in most scenes and decreased fixation count. As for the reading paradigm, first fixation duration was decreased in the strabismus group and fixation count was lower in the without amblyopia group. In the location identification paradigm, the without amblyopia group fixated less and with a shorter duration on the most flagrant element. However, no significant differences were encountered in the moving target paradigm. Interestingly, impaired eye tracking was more significantly demonstrated in the strabismus without amblyopia group compared to the strabismus with amblyopia group. Findings were consistent regardless of the strabismus type.

Few previous studies have used an eye tracker to assess reading performance in patients with amblyopia.[3,6-8] In patients with strabismus who had amblyopia, impaired reading in both fixational (longer fixation durations on one element) and saccadic patterns (regressive saccades) was noted in binocular viewing and not only with the amblyopic eye.[9] These findings were reproducible in anisometropic amblyopia.[6] Another study was conducted to assess font size on reading performance with a normal reading speed and corrected visual acuity.[3] Increasing the font size did not eliminate these defects; thus, the authors concluded that they were not caused by crowding.[3] Furthermore, increased saccades and fixation instability have been associated with slower reading speed in school-aged children with amblyopia.[6-8] Central suppression scotomas in children with anisometropic amblyopia were shown to alter the visual span and increase the frequency of inappropriate saccades in linear reading.[7,10,11]

In contrast to the above studies, we analyzed patients with strabismus and both with and without amblyopia to identify differential eye movement recordings attributed to strabismus itself or the concurrent amblyopia. The findings were reproducible in both groups, more significantly in the with strabismus and without amblyopia group, making strabismus per se a cause of eye tracking deficits in those children. Kanonidou et al.[9] similarly demonstrated reading deficits in participants with strabismus during both binocular and monocular viewing (with the amblyopic and non-amblyopic eye), with longer fixation durations and regressive saccades. Our sample size was larger (n = 50 in each group) than most of the above studies. However, the most flagrant difference remained in the studied paradigms: whereas all other studies focused on reading a text when evaluating eye movements with an eye tracker, we used three additional different paradigms.

The first paradigm illustrated a picture with distance and near elements. Few significant differences were encountered in one of the distance elements and not in others, but because the image was two-dimensional, this could be attributed to the participants' attention being diverted toward the closer, brighter parts of the image in the "near scenes."

The second paradigm was a reading test, with two areas of interest: the whole text and one word that was the answer to the ensuing question. It was also adopted in our study to determine the effect of suppression scotomas well known in patients with strabismus, which altered the quality of reading. Stifter et al.[12] found that children with microstrabismus amblyopia had reduced maximum reading speed compared to controls. However, in contrast to our work, most studies have included patients with amblyopia regardless of whether they had strabismus or anisometropia and thus findings were mainly attributed to amblyopia. The crowding effect has been implicated in reducing the reading speed in amblyopic eyes.[13] Reading deficits associated with binocular viewing have been ascribed to the presence of suppression scotomas.[14] Effects of simulated central scotomas on reading speed have been demonstrated by other investigators.[15] This may partially explain our significant findings in participants with strabismus but without amblyopia compared to those with amblyopia; in the presence of amblyopia, most of the eye tracking would be done by the normal fellow eye and hence no significant differences were seen when compared to controls. The phenomenon of binocular inhibition in the strabismus without amblyopia group could also explain why binocular visual performance in this group was inferior to the mostly monocular visual performance of the better eye in the amblyopia group. Binocular inhibition has been demonstrated in patients with strabismus, especially with reduced contrast levels, and has been associated with lower quality of life scores.[16]

Our third paradigm was a still picture with six areas of interest to determine the speed with which the participants could locate the most flagrant element when questioned about it. Indeed the strabismus (without amblyopia) group showed shorter fixation duration and fewer counts than the control group on that element, probably due to the latter falling within the suppression scotoma during binocular viewing.

The last paradigm was a video of a moving target; no significant differences were noted in that regard, probably indicating that eye misalignment did not adversely affect the participant's ability to follow a moving target.

We acknowledge several limitations. Although the sample size was larger than that of previous studies, it was still too small to allow subgroup analyses by age and refractive error. Children with high refractive errors were not analyzed separately; patients with strabismus might have a concomitant high refractive error, especially in the accommodative esotropia group. This was the reason behind the significant difference noted in the spherical equivalent refraction in the left eyes, being more hyperopic in the strabismus group. Additionally, objective questions during paradigm testing may have been too simple to identify differences in comprehension ability.

This study demonstrated that strabismus influenced location identification in affected individuals. Also, patients with strabismus focused less and for a shorter time while reading. No differential pattern was noted when participants looked at an image with distance and near elements, neither while tracking a moving target. Strabismus type did not appear to be a confounding factor.

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