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Analysis of the potential impact of strabismus with and without amblyopia on visual-perceptual and visual-motor skills evaluated using TVPS-3 and VMI-6 tests

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KEYWORDS
Visual-perceptual skills;
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Abstract
Purpose: To investigate the potential impact of strabismus and amblyopia on visual-perceptual skills (VPS) and visual-motor skills (VMS) of patients according to the type of strabismus, visual acuity (VA), state of binocularity, and sex.
Methods: This observational, transverse, prospective study analyzed a sample of 146 children with strabismus (88 male and 58 female) aged 5–15 years from Querétaro, México. To determine the strabismus type, we considered the deviation direction, frequency, binocularity state, and associated and dissociated elements. VPS and VMS were evaluated using the Test of Visual-Perceptual Skills 3rd ed. (TVPS-3) and Visual-Motor Integration Test of Beery 6th ed. (VMI-6).
Results: Sex was the main variable associated with the performance of the analyzed patients on TVPS-3 and VMI-6 ($p < 0.05$); boys obtained better scores than girls in all evaluated aspects.

Abbreviations: AET, accommodative esotropia; ASET+S, associated esotropia with stereopsis; ASET-S, associated esotropia without stereopsis; ASXT+S, associated exotropia with stereopsis; ASXT-S, associated exotropia without stereopsis; BCVA, best-corrected visual acuity; DET, dissociated esotropia; DIS, discrimination; DVD, dissociated vertical deviation; DXT, dissociated exotropia; ET, esotropia; F-CON, form constancy; F-G, figure-ground; fMRI, functional magnetic resonance; GEN, general VMI; HI, horizontal incomitancies; MEM, Memory; MIT, Macular Integration Test; MN, manifest nystagmus; MOT, motor VMI; SD, standard deviation; S-MEM, sequential memory; SP-RL, spatial relationships; VA, visual acuity; VMS, visual-motor skills; VPS, visual-perceptual skills; V-C, visual closure; VMI, visual-motor integration; TVPS-3, Test of Visual-Perceptual Skills 3rd ed.; VMI-6, Visual-Motor Integration Test of Beery 6th ed.; XT+S, exotropia and stereopsis; XT−S, exotropia without stereopsis; X(t), intermittent exotropia; XT, exotropia.

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Stereopsis was not a determinant of the patients' performance level but was associated with the far and near angles of deviation in both types of strabismus, esotropia and exotropia. Amblyopia was associated with the spatial relationship ($p = 0.001$) and visual closure abilities ($p = 0.044$). Form constancy skill scores diminished in both types of strabismus (esotropia: $p = 0.011$; exotropia: $p = 0.004$), and VMS were the most affected in patients with strabismus.
Conclusions: The performance of patients with strabismus with and without amblyopia on TVPS-3 and VMI-6 suggests that they adopt a mechanism to compensate for the impact of strabismus on their VPS and VMS.

Introduction

Strabismus is a visual disorder that affects 2–5% of preschool and school-aged children[1] and could lead to abnormal development of the visual system, in particular by affecting binocularity and stereopsis.[2] Binocularity allows the retinal fusion of the images perceived by each eye, while stereopsis refers to the ability to perceive depth and three-dimensional objects.[3] Strabismus is generally followed by cortico-visual adaptations, such as suppression, anomalous retinal correspondence, and amblyopia.[4] Amblyopia affects 1–4% of the population worldwide.[5] and has been related to deficits in oculomotricity,[6] eye-hand coordination,[7] visual-guided reaching movement,[8] and visuomotor behavior.[9] The above-mentioned abilities are considered as crucial elements involved in the writing and reading process; these deficiencies are observed in patients with strabismus and amblyopia.[10–12]

In patients with strabismus and amblyopia, changes have not only been seen in first-(luminance-based) and second-order (texture-based) processing of visual information[13] but also at deeper cortical levels.[14] Differences found in brain activity patterns,[15,16] cortical thickness,[17] and functional connectivity[18] relate strabismus with changes in the white and gray matter, depending on its type and time of appearance.[17–20] More specifically, in the visual cortex, increased brain activity has been found in the lingual gyrus, which processes information such as shape, size, color, contour, and object recognition—all the essential elements for visual judgment and visual attention.[15,16] Changes have also been found in the frontal and supplementary eye field,[21] involved in the pathway of saccadic eye movements, as well as in midbrain regions, and cerebellum, which affect balance and posture.[22,23] The aforementioned information indicates that apart from the striate cortex (V1), the extrastriate cortex (V2–V3a) and dorsal and ventral pathways associated with memory, attention, and learning aspects are also affected.[21] Moreover, visual memory, visual-motor integration skills, and spatial visualization abilities have been positively correlated with academic achievement and mathematical problem-solving skills.[24–26] Therefore, the above provide a strong reason to investigate the repercussions of strabismus and amblyopia with regard to visual-perceptual skills (VPS) and visual-motor skills (VMS). Additionally, little research has focused on this area, paving the way for future investigation.

A literature search linking strabismus with impaired VPS and VMS revealed few studies showing a significant relationship of strabismus with constructive praxia, visual memory, strategy formation, and drawing quality.[27] Stereopsis has also been associated to the patients' performance in these areas, whereas the type of strabismus has been associated to esotropia, with a significantly lower constructive praxia, visual memory, strategy formation, and representational dimension of drawings.[27] Additionally, the analysis of visual-attentional abilities assessed by paper-and-pencil tasks has shown that patients with visual deficiencies, such as refractive disorders, strabismus, amblyopia, cataract, and nystagmus, experience difficulties in visuospatial tasks, more prominently at 4 years and less at 7 years of age, despite correcting to normal visual acuity (VA).[28] Even though cortical deficits have been implicated in strabismus and amblyopia, evidence suggests that these patients could adapt mechanisms to compensate for its impact on their visual deficiencies.[29] Additionally, the extent to which the cortical changes found in neuroimaging studies affect VPS and VMS of patients with strabismus with and without amblyopia remains unknown.

Hence, considering the reported neurological and clinical antecedents of patients with strabismus and amblyopia, this study assessed the VPS and VMS of patients with esotropia and exotropia, as they can be predictive of reading and writing achievement. The patients' strengths and weaknesses on VPS and VMS were evaluated using the Test of Visual-Perceptual Skills 3rd ed. (TVPS-3) and the Visual-Motor Integration Test of Beery 6th ed. (VMI-6).

Methods

Participants

This observational, transverse, prospective study included 146 Mexican children with strabismus, of a similar economic status. Data on medical history and clinical examinations were collected at the Institute of Congenital Diseases of Querétaro, México, from 2017 to 2018. The study conformed to the principles of the Declaration of Helsinki. Consent from the participants and parents was obtained before performing any procedure. The number of patients who came to the center and met the inclusion criteria determined the size of the sample. Eligibility was established over a three-day period based on the following inclusion/exclusion criteria:

Inclusion criteria: diagnosis of primary strabismus with no previous optometric or ophthalmologic treatment, except the use of previous ophthalmologic prescription; best-corrected VA (BCVA) >20/100; age 5–15 years; and average IQ score for their chronological age, as reported by their school.

Exclusion Criteria: diagnosis of secondary strabismus (neurological, traumas, diseases) and/or a history of vision therapy; presence of conditions such as attention-deficit/hyperactivity disorder, epilepsy, dyslexia, and depression; use of medications that could affect the central nervous system; and premature birth.

Data collection

On the first day, a detailed medical history regarding strabismus was obtained. The following tests were then performed: near and distance VA, lensometry of the participants' optical correction, noncycloplegic objective refraction, cycloplegic objective refraction using 2 drops of 1% tropicamide (TP), and ophthalmoscopy to establish the type of fixation under the cycloplegic effect.

Even though cyclopentolate is recommended for esotropes to obtain a correct objective refraction, all patients included in this study and enrolled at the Institute of Congenital Diseases of Querétaro, México, already had a medical history of strabismus, and were previously refracted with atropine drops every six months or a year, as the case required, by the same ophthalmologist qualified in strabismus, with no significant changes during routine revisions. Moreover, patients included in this study were aged 5–15 years, and research has shown no significant differences between tropicamide and cyclopentolate after 5 years of age.[30] Furthermore, a metanalysis suggested that TP can still be used as an effective cycloplegic drug in children, when the clinical data are consistent and there is no variability on the findings,[31] as was the case of this study. For this reason, the ophthalmological revision was made under the effect of 2 drops of 1% TP.

On the second day, subjective refraction for the best optical correction was performed. Subsequently, the following tests were performed: repetition of near and distance VA examination with the new prescription, measurement of the deviation and magnitude of strabismus, motor and sensory fusion, fixation and correspondence using Macular Integration Test (MIT) and Bagolini lenses, motility (checking for paresis and paralysis), pupillary reflex, hyper-hypotropia (HT, hT), as well as dissociated elements, such as latent (LN) or manifest nystagmus (MN), dissociated vertical deviation (DVD), angle variability, and limitation in abduction followed by horizontal incomitancies (HI). Patients with a VA ≤20/40 were reexamined after they wore the newly prescribed glasses for four weeks. The type of strabismus was established on the basis of the clinical data collected, as described above. An ophthalmologist collaborated with the optometrist, to achieve an accurate diagnosis of strabismus and amblyopia.

On the third day, patients who met the inclusion criteria were scheduled for the TVPS-3 and VMI-6 evaluation.

Clinical testing

Testing procedures were identical for all patients and were divided into two parts—motor and sensorial—to establish an accurate diagnosis of each patient.

Motor clinical testing: The direction and magnitude of deviation were established using the cover and Krimsky tests. Even if the cover over test is considered the most indicated to measure the angle of strabismus,[32] the Krimsky test is preferred in children with poor collaboration. However, both tests were performed in the included children with the help of the ophthalmologist who participated in the process of evaluation.

Two versions of the distant and near cover test were performed using the Spielmann translucent occluder. The cover-uncover test was performed to establish the presence of a tropia state, and the deviation was neutralized with the Berens prism bar, while the alternating cover test was performed to determine the total magnitude of the deviation on the basis of the phoria and tropia state of the patient. The maneuver of Posner was used to define the exact amount of HT-hT in the presence of DVD. Two translucent Spielmann occluders and the Berens prism bar were used. An ophthalmologist and an optometrist performed the cover test.

The Krimsky test was performed in its direct and indirect version, placing the Berens prism bar in front of the deviated eye in the first case and the non-deviating eye in the second case.

Hyper- and hypo-functioning extraocular muscles were classified in crosses of +1 to +4 and −1 to −4, respectively. The Maples Oculomotor Test (NSUCO) helped evaluate saccades and pursuit movements.[33]

Sensorial clinical testing: Distant and near VA was measured using logMAR charts at a distance of 3 m and 40 cm, respectively. A difference of 0.20 logMAR (BCVA) between the two eyes was defined as unilateral amblyopia, while a BCVA lower by ≥0.20 logMAR than that according to the developmental norm at a given age was considered bilateral amblyopia.[34]

The Worth Dot test was used to evaluate flat and peripheral fusion and to detect any suppression. It was performed using red-green lenses over the optical correction of the patient at three different distances: close, intermediate, and far.

The Lang Test, which detects disparities from 1200 to 550 arcmin, was used to evaluate gross fusion in patients without polarized lenses, which could dissociate the binocular system. The test avoids monocular contours but still offers monocular cues if the patient does not remain stationary relative to the image. The test was repeated under monocular viewing conditions to ensure the result. Patients who obtained the same score under monocular and binocular viewing and had no stereopsis, as shown by the Random Dot test, were classified as stereoblind.

The Random Dot test was used to evaluate depth perception using contour (local) and global stimuli to measure stereopsis. The test was applied only at close distances with polarized glasses over the optical correction of the patient. The test detects disparities ranging from gross to fine stereopsis (2000–40 arcmin).

In all patients, fixation was first measured by direct ophthalmoscopy under cycloplegia.

The Bagolini lens test was administered to assess sensory correspondence and detect suppression. Striated lenses were used over the optical correction of the patient, with the spotlight at 40 cm.

The MIT was performed for sensory correspondence and fixation in a dim-lit room, with the patients wearing correction glasses. An afterimage (AI) was used for this purpose, as proposed by Bielchowsky.

Evaluation of VPS and VMS using the TVPS-3 and VMI-6 tests

TVPS-3[35] and VMI-6[36] were administered, and raw scores were used to ultimately determine scaled scores, standard scores, percentiles, and perceptual ages.

TVPS-3 evaluates the following seven areas: visual discrimination, visual memory, spatial relationships, form constancy, sequential memory, figure-ground, and visual closure. Scaled scores were used to analyze each subtest, and standard scores were used to analyze groups of abilities as defined in the literature[35]: (i) overall performance: includes all seven areas; (ii) basic performance: includes the first four areas; (iii) sequencing: includes only sequential visual memory; and (iv) complex performance: includes only the last two areas.

Only two of the three areas of VMI-6 were analyzed, i.e., the general and motor VMI, directly related to the gross and fine hand motor coordination. The perceptual part of VMI-6 was excluded as it does not include handwriting during the evaluation. For statistical analysis and the purpose of this study, raw scores were then converted into scaled and standard scores.

Statistical analysis

To detect statistically significant differences between groups, non-parametric and parametric tests were performed using the SPSS Statistics Base 22.0 program.

For statistical analysis, when the number of patients on the same group was smaller than 30 ($n < 30$), the non-parametric tests of Kruskal–Wallis (χ^2) for three or more groups and Mann–Whitney (U) for two groups were performed. ANOVA for three or more groups and independent T-test for two groups were used to compute the statistics when the number of patients was at least 30 or larger than 30 ($n \geq 30$). The confidence level (CI) used in this study was 95%, with alpha = 0.05 ($\alpha = 0.05$).

Results

A total of 146 patients participated in this study, 79 patients with esotropia (54.1%) and 67 with exotropia (45.9%). The VPS and VMS were analyzed according to the following: direction of strabismus, VA, state of binocularity, and sex.

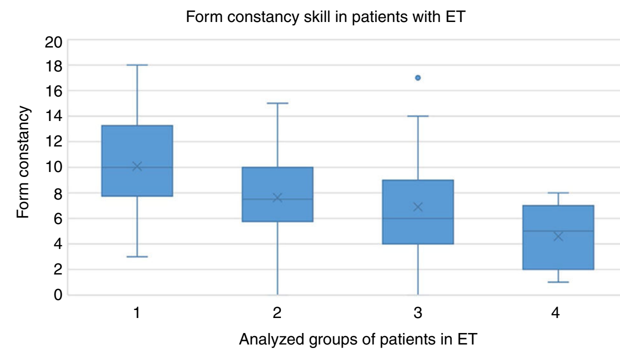

Figure 1 Form constancy skill in patients with ET. Mean and SD of the four analyzed groups: AET (10.1 ± 3.9; $n = 14$), ASET−S (7.6 ± 3.4; $n = 30$), DET (6.9 ± 3.7; $n = 30$), and ASET+S (4.6 ± 2.7; $n = 5$).

Statistics of patients with esotropia

Among the 79 patients with esotropia, 31 (39.2%) were girls (mean age 9.2 ± 3.7 years), and 48 (60.8%) boys (mean age 9.4 ± 3.4 years).

The mean age of all participants with esotropia was 9.4 ± 3.5 years (range, 5.9–14.1 years). Only 19 patients (24.5%) with esotropia presented stereopsis. For statistical purposes, patients with esotropia were divided into four groups as follows: (i) patients with accommodative esotropia (AET) (14 patients, 8 boys and 6 girls; mean age 8.5 ± 2.2 years)—patients had a certain degree of stereopsis, a mean value of 212.1 ± 222.5 arcmin, and the angle of deviation was compensated by lenses; (ii) patients with associated esotropia with stereopsis (ASET+S) (5 patients, 3 boys and 2 girls; mean age 11.1 ± 2.9 years)—patients with intermittent esotropia and partially accommodative esotropias with stereopsis, with a mean value of 200 ± 227.6 arcmin; (iii) patients with associated esotropia without stereopsis (ASET-S) (30 patients, 16 boys and 14 girls; mean age 8.8 ± 2.9 years)—patients with constant, non-accommodative and partially accommodative esotropia without stereoscopic vision; and (iv) patients with dissociated esotropia (DET), (30 patients, 21 boys and 9 girls; mean age 10.3 ± 3.5 years)—patients with dissociated elements such as DVD, LN, MN, angle variability, and HI.

The Kruskal–Wallis test revealed a statistically significant difference in the form constancy skill. The value of this variable decreased from the first to the fourth group ($p = 0.011$) as presented in Fig. 1. The AET group obtained higher scores than the other three groups. Patients with associated esotropia obtained lower scores than those in the other groups, despite showing a small degree of stereopsis.

No differences were found in the VPS and VMS when data were analyzed according to the presence and magnitude of stereopsis. However, patients with stereopsis presented a smaller angle of deviation at both distances, far ($p = 0.032$) and near ($p = 0.010$). Based on sex, boys displayed better visual closure skills ($p = 0.019$) and motor VMI perfor-

Table 1 Comparison of variables of interest between boys and girls with esotropia and exotropia.

Variables for esotropia	Patients ($n = 79$) Mean ± SD	Boys ($n = 48$) Mean ± SD	Girls ($n = 31$) Mean ± SD	p-Value[a]
Visual closure	8.3 ± 3.6	9.1 ± 3.6	7.1 ± 3.3	0.019
Motor VMI	90.0 ± 15.6	94.7 ± 14.0	83.2 ± 19.6	0.003
Variables for exotropia	Patients ($n = 67$) Mean ± SD	Boys ($n = 39$) Mean ± SD	Girls ($n = 28$) Mean ± SD	p-Value[b]
Sequential memory	9.1 ± 3.3	9.9 ± 3.4	8.0 ± 3.0	0.005
General VMI	93.7 ± 13.9	96.3 ± 12.4	90.0 ± 15.1	0.017

[a] Independent *T*-test.
[b] Mann–Whitney test.
SD, standard deviation; VMI, visual-motor integration.

mance ($p = 0.002$) than girls (Table 1), based on independent T-test. The mean, standard deviation (SD), and p-value for all patients, boys, and girls are presented separately in Table 1.

Statistics of patients with exotropia

The same variables were analyzed for patients with exotropia. Sixty-seven patients with exotropia participated in this study, 39 boys (58.2%; mean age 8.8 ± 3.0 years) and 28 girls (41.8%; mean age 9.7 ± 3.4 years). The mean age of all participants with exotropia was 9.2 ± 3.2 years (range, 5.2–14.6 years). Forty-nine patients (73.1%) with exotropia had stereopsis. For a detailed statistical analysis, patients with exotropia were divided into four groups on the basis of the associated and dissociated elements that accompany strabismus, as mentioned previously: (i) patients with intermittent exotropia $X(t)$ ($n = 37$, 22 boys and 15 girls; mean age 7.4 ± 2.1 years) with a mean value for stereopsis of 60.8 ± 35.8 arcmin; (ii) patients with associated exotropia with stereopsis (ASXT+S) ($n = 12$, 7 boys and 5 girls; mean age 9.4 ± 4.0 years) with a mean value for stereopsis of 195 ± 231.3 arcmin; (iii) patients with associated exotropia without stereopsis (ASXT−S) ($n = 14$, 8 boys and 6 girls; mean age 10.2 ± 4.3 years); and (iv) patients with dissociated exotropia (DXT) ($n = 4$, 2 boys and 2 girls; mean age 11.4 ± 3.0 years).

After analyzing the VPS and VMS, we detected a significant difference in the form constancy skill ($p = 0.004$, Kruskal–Wallis test) (Fig. 2). Notably the ASXT−S group showed higher scores than the X(t) group.

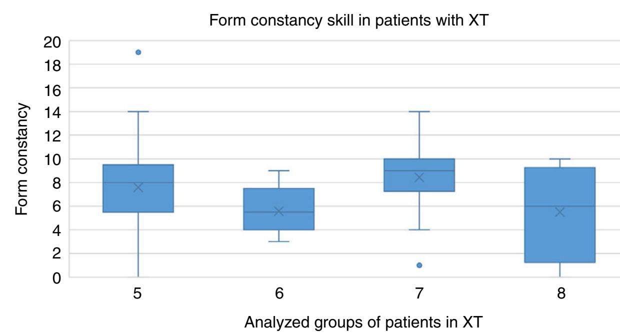

Figure 2 Form constancy skill in patients with XT. Mean and SD of the four analyzed groups: $X(t)$ (7.6 ± 3.7; $n = 37$), ASXT+S (5.6 ± 2.0; $n = 12$), ASXT−S (8.4 ± 3.2; $n = 14$), and DXT (5.5 ± 4.2; $n = 4$).

The state of stereopsis affected the memory skill ($p = 0.045$) and motor VMI achievement ($p = 0.017$). Table 2 presents the mean, SD, and p-value of patients with and without stereopsis. The angle of deviation was also smaller at both distances in patients with stereopsis ($p < 0.001$). Based on sex, differences were found in the sequential memory skill ($p = 0.005$) and general VMI performance ($p = 0.017$). Boys performed better than girls in both areas. Table 1 shows the mean, SD, and p-value for all patients, boys, and girls.

Comparison of patients with esotropia and exotropia

The VPS and VMS of all patients who participated in this study were analyzed on the basis of the direction of strabismus.

Table 2 Comparison of patients with exotropia based on the presence or absence of stereopsis.

Variables	Patients ($n = 67$) Mean ± SD	XT−S ($n = 18$) Mean ± SD	XT+S ($n = 49$) Mean ± SD	p-Value[a]
Memory	8.6 ± 3.7	10.1 ± 4.5	8.1 ± 3.3	0.045
Motor VMI	89.7 ± 13.5	83.0 ± 13.4	92.2 ± 12.8	0.017

[a] Mann–Whitney test.
XT+S, patients with exotropia and stereopsis; XT−S, patients with exotropia without stereopsis, SD, standard deviation; VMI, visual-motor integration.

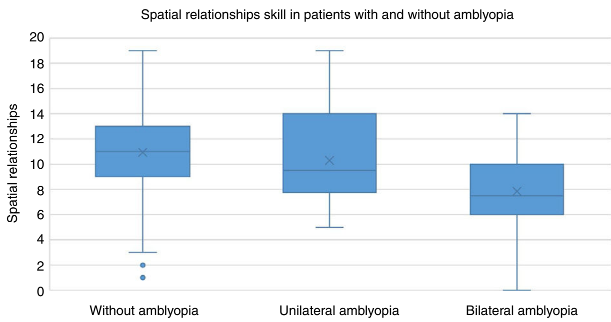

Figure 3 Spatial relationships skill in patients with and without amblyopia. A decrease in spatial relationship skills is seen when moving from the first to the third group of patients.

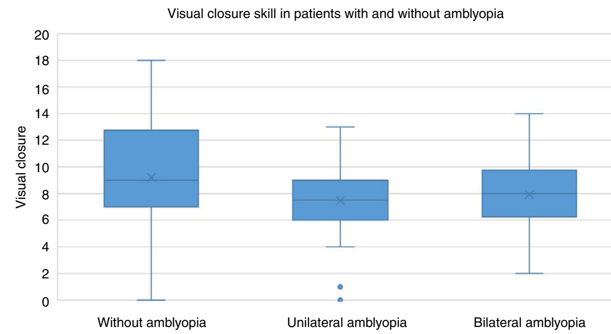

Figure 4 Visual closure skill in patients with and without amblyopia. Patients without amblyopia performed better in the visual closure skill than patients with unilateral and bilateral amblyopia. However, patients with bilateral amblyopia obtained higher scores than patients with unilateral amblyopia.

When $\alpha = 0.05$, a similar performance was observed in the VPS and VMS of patients with esotropia and exotropia based on the direction of the deviation, sex, and magnitude of stereopsis. In the absence of stereopsis, patients with esotropia presented better abilities in the motor VMI area (mean ± SD, 90.3 ± 18.1) than those with exotropia (mean ± SD, 83.0 ± 13.4; $p = 0.032$).

Sex was the main variable associated with the performance of patients with strabismus on TVPS-3 and VMI-6 tests (Table 3). The mean age for girls was 9.5 ± 3.5 while for boys 9.1 ± 3.2 years. As shown in Table 3, boys performed better than girls in figure-ground ($p = 0.043$) and visual closure skills ($p = 0.046$). They also obtained higher values in both parts of the VMI-6 test, general ($p = 0.014$) and motor VMI ($p = 0.002$).

Based on the presence of amblyopia, the non-parametric Wilcoxon test was applied. Table 4 presents mean, SD, and p-values of patients without amblyopia and those with unilateral and bilateral amblyopia. When $\alpha = 0.05$, patients without amblyopia showed greater values than other patients in spatial relationships ($p = 0.001$) and visual closure skills ($p = 0.044$). Figs. 3 and 4 show the mean and SD of patients without amblyopia and those with unilateral and bilateral amblyopia. No association was found between the magnitude of amblyopia and the performance of patients with strabismus on TVPS-3 and VMI-6 tests ($p > 0.05$).

Age-dependence was illustrated in TVPS-3 skills but not in VMI-6 performance. Patients were divided in three age groups: (I) 5.0–6.11, (II) 7.0–9.11, and (III) 10.0–15.0 years. This division was based on previous investigations[39,43] and on the small number of patients for each group. The non-parametric Kruskal–Wallis test was used for this statistical analysis.

Both girls ($n = 10$, 11, and 10, in each age group) and boys ($n = 15$, 17, and 16 in each age group) with esotropia showed statistically significant scores in the following groups of abilities of TVPS-3: overall performance (girls: $p = 0.001$; boys: $p < 0.001$), basic process (girls: $p = 0.011$; boys: $p = 0.029$), sequential memory process (girls: $p = 0.018$; boys: $p = 0.021$), and complex process (girls: $p = 0.019$; boys: $p < 0.001$). Patients aged 10–15 years performed better in all groups. When all patients with esotropia were analyzed ($n = 25$, 28, 26 for each age-group), patients 10–15 years old had a bet-

Table 3 Comparison of selected variables between all boys and girls.

Variables	Patients ($n = 146$) Mean ± SD	Boys ($n = 87$) Mean ± SD	Girls ($n = 59$) Mean ± SD	p-Value[a]
Figure-ground	8.8 ± 3.6	9.3 ± 3.4	8.1 ± 3.7	0.043
Visual closure	8.6 ± 3.6	9.1 ± 3.9	7.9 ± 3.2	0.046
General VMI	95.3 ± 12.9	97.5 ± 11.7	92.2 ± 13.9	0.014
Motor VMI	90.0 ± 15.6	93.2 ± 13.7	85.2 ± 17.1	0.002

[a] Independent T-test results.
SD, standard deviation; VMI, visual-motor integration.

Table 4 Comparison of spatial relationships and visual closure among patients without amblyopia and those with unilateral and bilateral amblyopia.

Variables	Without amblyopia ($n = 88$) Mean ± SD	Unilateral amblyopia ($n = 30$) Mean ± SD	Bilateral amblyopia ($n = 28$) Mean ± SD	p-Value[a]
Spatial relationships	10.9 ± 3.8	10.3 ± 3.6	7.9 ± 3.3	0.001
Visual closure	9.2 ± 4.0	7.5 ± 3.1	7.9 ± 2.6	0.044

[a] Wilcoxon test; SD, standard deviation.

Table 5 Statistically significant results in the seven analyzed areas of TVPS-3 test and the two areas of VMI-6 test.

	TVPS-3 areas							VMI-6 areas	
	DIS	MEM	SP-RL	F-CON	S-MEM	F-G	V-C	GEN	MOT
AET				X					
ASET+S									
ASET-S									
DET									
BOYS							X		X
X(t)									X
ASXT+S									X
ASXT-S		X		X					
DXT		X							
BOYS					X			X	
ALL BOYS (ET+XT)						X	X	X	X
WITHOUT AMBLYOPIA			X				X		

AET, accommodative esotropia; ASET+S, associated esotropia with stereopsis; ASET-S, associated esotropia without stereopsis; ASXT+S, associated exotropia with stereopsis; ASXT-S, associated exotropia without stereopsis; DET, dissociated esotropia; DIS, discrimination; DXT, dissociated exotropia; ET, esotropia; MEM, memory; SP-RL, spatial relationships; F-CON, form constancy; S-MEM, sequential memory; F-G, figure-ground; V-C, visual closure; GEN, general VMI; MOT, motor VMI; X(t), intermittent exotropia; XT, exotropia.
X demonstrates that greater values were obtained during the evaluation of skills on TVPS-3 and VMI-6 of patients with strabismus and amblyopia.

ter performance than those in other age groups ($p < 0.005$) in all four groups of abilities of TVPS.

Girls with exotropia ($n = 8$, 10, and 10 for each age group) showed statistically significant scores in overall performance ($p < 0.001$) and sequential memory process ($p = 0.009$), whereas exotropic boys ($n = 12$, 15, and 12 for each age group) showed statistically significant scores in all four groups of abilities of TVPS: overall performance ($p < 0.001$), basic process ($p = 0.012$), sequential memory process ($p = 0.005$), and complex process ($p < 0.001$). Again, patients aged 10–15 years performed better than those in the rest of the groups. When all patients with exotropia were analyzed ($n = 20$, 25, 22 for each age group), patients 10–15 years-old had a better performance than the rest ($p < 0.005$) in all four groups of abilities of TVPS.

To summarize, when analyzed by age, boys and girls with both types of strabismus behaved similarly in TVPS performance. The older the patient, the better the performance in all four groups of abilities of TVPS. In contrast, VMI skills were not affected by age.

Table 5 illustrates the most statistically significant results obtained during the evaluation of the TVPS and VMI skills in patients with strabismus and amblyopia.

Discussion

In this study, optometric tests were used to assess the VPS and VMS of 146 patients (5–15 years old) with strabismus with and without amblyopia using TVPS-3 and VMI-6, with the purpose to investigate how visual-perceptual and visual-motor processes are affected by the visual condition of patients. Since only few studies have focused on clarifying the relationship between strabismus and VPS and VMS, this research is important for optometrists, health professionals, and teachers. Previous studies have shown that patients with strabismus and amblyopia have diminished non-verbal abilities and develop cortical adaptations to compensate for their visual disorders.[27–29] Therefore, this study focused on measuring the performance of these patients using the TVPS-3 and VMI-6 tests, in order to understand the potential of a strabismic and amblyopic brain to correct erroneous signals by rerouting them, thus overcoming these visual difficulties.

Patients included in this study had no other health conditions, nor previous treatments for any visual or learning difficulties. For the statistical analysis, variables such as stereopsis and VA were considered as essential visual patterns related to space perception and fine motor skills.[37]

Only ***the direction of strabismus*** demonstrated a statistically significant difference in motor VMI performance; patients with esotropia performed better than patients with exotropia in the absence of stereopsis. ***The state of stereopsis*** did not impact on the VPS and VMS of patients with esotropia; however, it was associated with smaller far and near angles of deviation ($p < 0.001$). With regard to exotropia, patients with stereopsis showed better memory skills and motor VMI performance compared to patients without stereopsis, as well as smaller far and near angles of deviation. ***With regard to sex***, boys showed a better performance than girls in the presence of both types of strabismus. Boys with esotropia obtained higher scores in visual closure and motor VMI, while those with exotropia obtained higher scores in sequential memory and general VMI. Significant differences were observed in figure-ground, visual closure, general VMI, and motor VMI abilities, with boys performing better than girls. Considering the ***presence of amblyopia***, patients with bilateral amblyopia obtained lower scores in the spatial relationships ability, while those with unilateral amblyopia obtained lower scores in the visual closure skills than those without amblyopia. On the contrary, ***the magnitude of amblyopia*** was not associated with the performance of the strabismic patients on TVPS-3 and VMI-6.

Based on a neuropsychological approach, previous studies have shown that visual conditions are associated with diminished visual-attentional abilities and visuospatial tasks, more prominent at 4 and less defined at 7 years of age.[28] Additionally, a link between strabismus and constructive praxia, visual memory, strategy formation, and the quality of drawings has already been demonstrated, with stereoscopic patients performing better in all evaluated areas, and esotropic patients obtaining lower values than exotropic ones.[27]

In our study, sex was the main variable associated with the performance of the analyzed patients on TVPS-3 and VMI-6. Sex has been related to cortical differences since birth.[38] Increased cortical gray matter in children supports the hypothesis that sex-related differences in brain size are related to differences in cortical neuronal density, even though such differences vary according to age.[38,39] Moreover, in patients with strabismus, white and gray matter changes have been related to strabismus type and time of appearance.[17–20] In addition, based on clinical and neuroimaging data, previous studies in healthy patients have found sex and age differences regarding cognitive abilities (verbal and nonverbal) in children and adolescents.[40] Even though data are inconsistent and controversial, some robust patterns have arisen.

Depending on age, boys have shown better abilities on visual-spatial skills, while girls have shown an advantage on processing speed, free-recall, and short-term memory.[39] Moreover, a significant positive and more robust correlation has been found for nonverbal cognitive abilities and brain activation in male subjects using functional magnetic resonance (fMRI),[40] suggesting that brain activation differs between males and females. fMRI studies have also shown different patterns of activation in males and females associated with neuropsychological processes, such as mental rotation tasks, favoring males in such areas.[41]

Regarding intelligence, girls aged 2–7 years demonstrate higher general intelligence, with higher processing speed at ages from 4 to 7 years. In contrast, a sex difference favoring boys in visual processing information emerges at 4 to 7 years of age, which may contribute to sex differences in later academic performance.[42] The same occurs in children from 7 to 11 years, where girls show an IQ advantage, while the later maturation of boys gives them an IQ advantage at the age of 16 years.[43] Even in young adults, sex affects the structure and function of brain regions associated with working memory, cognition, and intelligence, with males having higher accuracy than females.[44] It has also been seen that girls have a better involvement on writing and reading skills, while boys better engage in processes that involve manual skills, possibly associated with activities at school and home.[45] Thus, male and female brains find different patterns of function, with some of them being age dependent, showing preference on some abilities over others.

In this study, nonverbal cognitive abilities were evaluated, with boys performing better than girls in complex process analysis and VMS. Considering that the mean age of patients in the analyzed sub-groups (i.e., patients with esotropia, exotropia, etc.), as well as among groups was similar, these findings seem not to be age dependent. Nevertheless, these results could be explained based on the aforementioned fMRI evidence. Firstly, the activation of the right temporoparietal junction which is close to the junction of the dorsal and ventral visual pathways, is associated with the perceptual organization index, being more consistent in boys.[40] Considering that this area is involved in attention shifts and reorienting, it is suggested that when it comes to nonverbal cognitive abilities, boys use an attention reorienting strategy in visual perception more robust than girls do.[40] Secondly, different processing strategies are used by boys and girls in problem-solving situations. It is suggested that boys use a more ''gestalt strategy'' whereas girls use a more ''analytic strategy''.[46] Finally, these results could be also related to the children's engagements at home and/or school, and their preferences over some abilities than others. As it was already mentioned,[39] girls are better at writing, reading, and memory tasks, while boys are better at visual-spatial and mental rotation tasks and in processes that involve manual skills, which suggests that men and women have their own weak and strong areas, showing preferences over some skills than others, depending on the uniqueness of the brain sex.

In this study, the age-dependence was illustrated in TVPS skills but not in VMI performance. When analyzing each skill of TVPS separately, no relationship was found between age and performance. Nevertheless, when groups of abilities were analyzed (overall, basic, sequential and complex performance), age was an important variable which affected performance. This could explain why VMI performance was not affected by age.

Stereopsis was not a determinant of skill level, but it was associated with the far and near angles of deviation in patients with either type of strabismus. Amblyopia was associated with spatial relationships and visual closure, being the latter part of the complex process analysis. Form constancy was the only TVPS-3 skill that presented diminished values in both types of strabismus (esotropia and exotropia), while skills in paper-and-pencil tasks evaluated using VMI-6 were associated with stereopsis, sex, and direction of strabismus; visuomotor abilities were the most affected abilities in patients with strabismus and amblyopia.

This study agrees with the aforementioned regarding the difficulties encountered in the VMS, basic visual analysis, and complex processing information. However, a similar performance was observed in the VPS and VMS of patients with esotropia and exotropia, while the state of stereopsis did not have any impact on these abilities although it was associated with a smaller far and near angles of deviation. However, it is important to clarify that TVPS-3 and VMI-6 tests use an optometric and not a neuropsychological approach for the analyzed skills, which is a limitation of the current study. Such an approach could have provided important information on specific areas of the learning process.

Despite the differences found in the analyzed areas using TVPS-3 and VMI-6, the performance of patient with esotropia and exotropia follows the curve of normality (the data was within 3 SDs), having similar scores with their peers. This suggests that patients with strabismus adopt a mechanism to compensate for visual disorders and their implications. Additionally, these results re-affirm the ability of a child's brain to correct erroneous signals by rerouting them, thus overcoming visual difficulties. Our research confirms the plasticity of the human brain and its ability to modify its connections and re-wire itself. Nevertheless, considering the pyramid of learning, it remains unknown if such compensation could provoke a loss of balance and energy distribution in the brain network, affecting the process of cognitive and executive learning, as being the last to develop on a hierarchical scale.

Conclusions

Performance of patients with strabismus with and without amblyopia on TVPS-3 and VMI-6 suggests that they adopt a mechanism to compensate for the impact of strabismus on their VPS and VMS. Moreover, a similar performance was observed in the VPS and VMS of patients with esotropia and exotropia, with sex being the main variable associated with their performance. However, stereopsis, was related to smaller far and near angles of deviation. An age-dependence was found in TVPS skills but not VMI performance. The older the patient, the better his performance in all group of abilities of TVPS.

The proposed study provides optometrists a deeper understanding and a focused approach to provide necessary treatment. Moreover, it helps health professionals and teachers comprehend the potential of a strabismic brain and also clarify doubts regarding their everyday and academic performance.

Conflicts of interest

The authors have no conflicts of interest to declare.

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