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OPTOMETRY AND VISION SCIENCE

REVIEW

Binocular Vision and the Stroop Test

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ABSTRACT

Purpose. Recent studies report a link between optometric results, learning disabilities, and problems in reading. This study examines the correlations between optometric tests of binocular vision, namely, of vergence and accommodation, reading speed, and cognitive executive functions as measured by the Stroop test.

Methods. Fifty-one students (mean age, 20.43 ± 1.25 years) were given a complete eye examination. They then performed the reading test *L'Alouette* and the Stroop interference test at their usual reading distance. Criteria for selection were the absence of significant refractive uncorrected error, strabismus, amblyopia, color vision defects, and other neurologic findings.

Results. The results show a correlation between positive fusional vergences (PFVs) at near distance and the interference effect (IE) in the Stroop test: the higher the PFV value is, the less the IE. Furthermore, the subgroup of 11 students presenting convergence insufficiency, according to Scheiman and Wick criteria (2002), showed a significantly higher IE during the Stroop test than the other students (N = 18) who had normal binocular vision without symptoms at near. Importantly, there is no correlation between reading speed and PFV either for the entire sample or for the subgroups.

Conclusions. These results suggest for the first time a link between convergence capacity and the interference score in the Stroop test. Such a link is attributable to the fact that vergence control and cognitive functions mobilize the same cortical areas, for example, parietofrontal areas. The results are in favor of our hypothesis that vergence is a vector of attentional and cognitive functions.

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Key Words: optometric tests, vergence dysfunctions, Stroop test, reading, inhibition

Binocular Function and Academic Achievements

When binocular or accommodative disorders occur, specific symptoms such as double vision, blurred vision, headache, asthenopia, or loss of concentration are reported.[1,2] These ocular symptoms can have a negative impact on close work performance such as reading or academic achievement[2–4] and usually lead to frustration and avoidance in children.[5,6] Maples[7] and Vaughn et al.,[8] using similar methods of screening, have shown that the number of symptoms are negatively correlated with academic achievement in children. Maples[7] also argues that some visual factors were found to be much better predictors of scores on basic academic performance than either race or socioeconomic status. Grisham et al.[9] studied a sample of poor readers in high school and found that 80% of them presented specific dysfunctions, more related to binocularity and vergence than to accommodative deficiencies. The impact of an accommodative dysfunction appeared to be a less obvious factor[10–12] than vergence dysfunction on reading.[9,13–15]

Vergence dysfunctions are more common than we might think in the general population.[16,17] This is particularly true of convergence insufficiency (CI),[18] with about 7% of median prevalence in both children and adults.[19–21] Convergence insufficiency is a binocular vision disorder, initially defined by Duane[22] (with the following criteria: exophoria greater at near than at distance, near point of convergence >6 cm, decreased positive fusional vergence [PFV] at near).

Vergence is highly important in reading: the eyes have to converge to maintain single vision, and the focusing system increases the optical power of the eyes to maintain clear vision. In parallel, the eyes perform saccades to fixate one word after the other. Saccades must be highly coordinated to keep the same angle of vergence required for single vision, and accommodation has to stay stable. Problems with accommodation, vergence, or bad synergy between the two can certainly have an impact on reading performance. Indeed, some studies have shown that poor coordination in saccadic eye movement during reading is usually found in people with vergence dysfunction.[23,24] Moreover, Alvarez and Kim[25] and Alvarez et al.[26] showed that people

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diagnosed as having CI also had coordination problems during vergence movements, that is, a longer latency and nonsymmetrical peak velocity for the two eyes during symmetrical convergence compared with binocularly normal control subjects.

Vergence Problems, Attention Problems, and Cognitive Executive Functions

Convergence insufficiency has also been associated with attention problems.[20,27] Borsting et al.[28] showed that schoolchildren diagnosed as having CI or accommodative dysfunctions frequently exhibited attention deficit issues and attention deficit hyperactivity disorder (ADHD) symptoms.

The capacity to focus attention is imperative to perform specific cognitive executive functions. These cognitive processes refer to the higher-level cognitive skills, including reasoning, working memory, and task flexibility. Recent studies have linked comprehension in reading with cognitive executive functions like inhibition. Protopapas et al.[29] used the Stroop test[30,31] (whereby the subject must inhibit a reading response in favor of a less obvious response [color denomination]) on poor readers without dyslexia and showed that they took longer to perform this task than normal readers. Difficulty to inhibit a task in favor of another is also found by Cain[32] in children with problems of memory and reading comprehension. In fact, reading and Stroop interference tests share common processes relative to executive functions, such as inhibition and attention. Moreover, inhibitory processes are also linked with attention disorders and symptoms related to ADHD.[33]

Goal of the Study

Given that eye movements are strongly linked to attention,[34] we hypothesize that accommodation or vergence dysfunctions could have a relationship with both reading and cognitive executive functions. Our major interest is to seek possible correlations between reading speed, Stroop test results, and optometric measurements. Comparing these results in isolating control subjects and subjects showing specific vergence and/or accommodation dysfunctions might shed light on the presence of significant correlations between optometric results and reading measurements or Stroop test results. To test this, this study uses both the Stroop test and the *L'Alouette* reading test. The major questions asked are as follows:

- In young healthy adult subjects, what are the correlations among selected binocular vision skills and reading speed, as tested with the "Alouette" test or with the reading task of the Stroop test?
- In young healthy adult subjects, what are the correlations among selected binocular vision skills and cognitive executive functions, as tested with the Stroop test?
- Is there a mean group difference among young healthy asymptomatic adult subjects, presenting normal accommodative and binocular functions, and those with symptoms and presenting accommodative or vergence dysfunctions in terms of reading speed or Stroop test results?

We predict that vergence problems, potentially interfering with single binocular vision, might be more harmful than accommodative problems concerning reading and cognitive executive function as tested with the Stroop test.

METHODS

Subjects

A total of 51 voluntary students aged 18 to 24 years (mean, 20.43 ± 1.25 years; 17 men and 34 women) who were studying optics at the *Lycée d'Optique Fresnel* in Paris participated in this study. All subjects presented normal binocular vision: a minimum of 20/25 visual acuity for each eye, no signs of amblyopia or strabismus, and no neurological findings. In addition, they were excluded from the study if the following criteria were observed: vertical phoria greater than 1 prism diopter (Δ, PD); an antecedent of eye pathology or surgery that could affect visual acuity or motility; signs of color vision defects (checked with an Ishihara plate test), which would affect their ability to normally perform the Stroop test. In fact, they also had to be oblivious to the workings of both the "Alouette" reading test and the Stroop test.

The investigation adhered to the tenets of the Declaration of Helsinki and was approved by the local human experimentation committee, the *Comité de Protection des Personnes* Ile de France VI (No: 07035), Necker Hospital, in Paris. Written informed consent was obtained from all subjects after the nature of the procedure was explained.

Procedure and Testing

Every student had to fill in a questionnaire about their case history, including ocular and systemic conditions. To determine if there were visual symptoms at near, we also used the Convergence Insufficiency Symptom Survey (CISS), which allows us to determine specific symptoms experienced by people with vergence or accommodative dysfunctions at near. A score equal to or higher than 16 is deemed to be significant to consider the presence of CI in a subject.[35]

The subjects' refraction was then objectively tested with an Autorefractor ARK-1 Nidek and subjectively with a Phoropter Nidek RT-600 to determine the best correction (monocular fogging method to a standard endpoint of maximum plus) to obtain optimal visual acuity. All subsequent measures were done with the optimum correction using the Phoropter or a Trial Frame (Oculus Adult UB4, Zeiss) in free space:

Visual Acuity

Measured in monocular and binocular vision at 5 m (using a distance Snellen chart projector, endpoint 20/15; Essilor) and at near distance (using the Optoprox, Snellen near chart, endpoint 20/16; Essilor).

Binocular Vision

Evaluated with the Wirt Rings Stereo Test to determine the stereopsis (results in seconds of arc; Stereo Optical Company) and with the Mallett Fixation Disparity Test to determine and measure central suppression and horizontal and/or vertical fixation disparity (Mallett Dual Fixation Disparity Test Unit and Mallett Near Vision Unit NV5). The horizontal and/or vertical associated phoria was measured in PDs with a prism bar, representing the minimum amount of prism to reduce the fixation disparity to zero.

Vergence

The near point of convergence (NPC) was measured in free space with a fixation stick (Bernell Corp.) and a millimeter ruler, distance measured from the outer canthus, results are in centimeters. The convergence and divergence fusional ranges at distance and near vision were measured with the Phoropter using rotary prisms (base-out [BO] for convergence and base-in [BI] for divergence). We recorded the usual extreme points in PD: "blur" as soon as the subject reported blurry vision, "break" as soon as they reported double vision, and "recovery" as soon as they reported single vision again. Fusion ranges are more representative when compared with phoria than isolated. We used the measurement of the phoria as the basis to calculate the exact effort in convergence and divergence.[36] The total fusional vergence (TFV) range represents the highest effort the subject can make to keep clear and single vision from phoria to the blur point or to the break point when there was no blur. We decided to use the PFV and negative fusional vergence (NFV), measured from the phoria position, to obtain more practical measurements according to Sheard's criterion.[37] The TFV represents the total range of single and clear vision, including the total convergence and divergence fusional ranges. The vergence facility, testing the ability of the fusional vergence system to respond rapidly and accurately to changing vergence demands across time (defined as the number of cycles per minute that a stimulus can be fused through alternating BI and BO prisms), using 8BI/16BO flipper lenses at near distance in free space, was measured. A previous study used and validated a 3BI/12BO flipper lenses as a reference to diagnose flexibility problems.[38] We wanted to test stronger variation on vergence demand and to compare the levels of vergence facility measured in other studies using the same amount of prisms.[39,40]

Accommodation

Binocular fused cross cylinders were used to evaluate the response of accommodation at 40 cm (Jackson Cross as a target). Negative and positive relative accommodations were measured using the Phoropter, increasing (NRA) or decreasing (PRA) the spherical lens power binocularly in 0.25-D increments until the subject reported the first sustained blur. Monocular and binocular accommodative ranges (near point of accommodation [NPA]) were measured in free space with the Donder's push-up method and a millimeter rule. All measurements were repeated three times, and the average was used for the analysis in converting the distance in millimeters to diopters. We measured the binocular and monocular accommodative facilities, testing the ability of the accommodative system to respond rapidly and accurately to changing accommodative demands across time (defined as the number of cycles per minute that a stimulus can be seen clearly through alternating plus and minus lenses), using ±2D flipper lenses in free space. We recorded the numbers of entire cycles performed in 1 min. We took the average between right and left monocular facility as a result for this task.

Phorias and AC/A Ratio

Distance and near horizontal and vertical dissociated phorias were measured with the phoropter using Von Graefe's method, and vertical phoria was checked again with a Maddox rod. On the basis of the phorias, we calculated the AC/A ratio, that is, the far-near AC/A, with the following formula: (15 - distance phoria + near phoria)/2.5.[37,41] Near horizontal phoria was then taken, again adding +1D and -1D, to measure the gradient AC/A ratio. We calculated the gradient AC/A ratio with the following formula: (near phoria with -1D – near phoria with +1D)/2.

Classification

In accordance with Scheiman and Wick,[42] we compared the results of each test with the norms they established. Vergence and accommodative dysfunctions were classified by taking into account the number of signs used in the studies of Porcar and Martinez-Palomera[18] and Shin et al.[3] This classification of the sample and the most important optometric measures mean values and standard deviations are shown in Table 1 (standard deviations are in parentheses): group 1 (N = 21), subjects presenting no vergence or accommodative dysfunctions; group 2 (N = 8), subjects presenting CI without accommodative dysfunctions; group 3 (N = 2), subjects presenting CI and accommodative insufficiency; group 4 (N = 3), subjects presenting convergence excess without accommodative dysfunction; group 5 (N = 2), subjects presenting basic esophoria without accommodative dysfunction; group 6 (N = 11), subjects presenting accommodative excess (AE) without vergence dysfunction; and group 7 (N = 2), subjects presenting accommodative infacility without vergence dysfunction. One subject presented both basic esophoria and accommodative insufficiency, and one other subject presented both CI and AE.

Experimental Tests

The "Alouette" Reading Test

Subjects read aloud a 265-word text in French,[43,44] largely devoid of meaning, as quickly as possible and without making mistakes. This task was performed to have an initial idea of their reading speed. This test was first developed for children to evaluate their basic reading skills and their automatic lexical decoding but not necessarily their comprehension or memory. Time, corrected errors (when subjects make mistakes but correct them immediately after), and uncorrected errors were measured for each subject. We calculated the reading speed by dividing the numbers of words/items by the time spent (words per minute).

The Stroop Test

The version that we used is made up of three different tasks: in the "reading" task, the subject has to read aloud a succession of words designating colors (red, green, blue, or yellow) written in black; in the "denomination" phase, the subject has to name a succession of dots of color (red, green, blue, or yellow); in the "interference" phase, the subject has to name the color of the print of the word, printed in an incongruent color (red, green, blue, or yellow), for example, the word "blue" printed in green. Each trial contains 100 items (10-line or 10-column matrix) randomly placed, and subjects were instructed to finish as quickly as possible without making mistakes or omissions. For this analysis, we used similar methods to those used by Kapoula et al.[45] Time, corrected errors (when the subject made a mistake but corrected it immediately after), and uncorrected errors were measured for each task and for each subject. We calculated the reading or color denomination speed by dividing

TABLE 1.
Mean values relative to vergence and accommodative functions per group

	Group 1 NBV + NAD	Group 2 CI	Group 3 CI + AIS	Group 4 CE
N	21	8	2	3
CISS score	12.52 (±6.83)	21.5 (±6.57)	26 (±12.73)	14.33 (±15.31)
NPC, cm	7.93 (±3.78)	10.5 (±2.98)	14.5 (±2.12)	10.33 (±5.13)
Distance phoria, PD	0.98 (±3.78)	–2.43 (±1.92)	–1 (±1.41)	5.66 (±4.48)
Distance NFV, PD	11.74 (±5.57)	7.56 (±2.38)	13 (±7.07)	11.67 (±5.84)
Distance PFV, PD	11.31 (±4.91)	10.69 (±4.17)	12 (±5.66)	12.33 (±8.13)
Near phoria, PD	–0.76 (±3.08)	–8.75 (±3.74)	–8 (±2.83)	9.33 (±7.37)
Near NFV, PD	15.76 (±5.09)	6.86 (±3.19)	6.5 (±7.78)	19 (±3)
Near PFV, PD	23.33 (±6.62)	22.5 (±7.08)	17.5 (±0.71)	23.33 (±2.89)
Cal. AC/A, PD/D	5.32 (±1.34)	3.5 (±0.89)	3.2 (±0.57)	7.47 (±1.2)
Gradient AC/A, PD/D	3.42 (±1.63)	2.78 (±0.69)	1.38 (±0.88)	4.67 (±2.02)
Monocular NPA, D	10.63 (±2.83)	9.52 (±1.19)	4.66 (±0.86)	8.96 (±3.92)
Binocular NPA, D	12.58 (±2.71)	6.5 (±4.02)	5.99 (±1.39)	10 (±4.29)
Monocular accommodative facility, c./min	11.17 (±5.66)	7.66 (±4.73)	1.5 (±1.41)	10.17 (±1.26)
Binocular accommodative facility, c./min	9.40 (±4.63)	6.5 (±4.02)	0.5 (±0)	5.33 (±4.25)
Vergence facility, c./min	10.62 (±3.79)	8.31 (±3.81)	4.25 (±5.30)	5.5 (±4.44)
NRA, D	1.9 (±0.35)	1.69 (±0.46)	1.63 (±0.88)	2.25 (±0.43)
PRA, D	2.45 (±1.28)	5.5 (±1.41)	5.5 (±1.41)	1.08 (±0.76)

	Group 5 BES	Group 6 AE	Group 7 AIF	CI + AE	BES + AIS
N	2	11	2	1	1
CISS score	21 (±1.41)	19.27 (±11.57)	12 (±12.73)	35	20
NPC, cm	8.5 (±4.95)	6.55 (±2.58)	8 (±2.82)	12	12
Distance phoria, PD	9.5 (±2.12)	–0.36 (±2.00)	0.5 (±0.71)	2	2
Distance NFV, PD	20 (±4.24)	8.82 (±1.74)	15 (±5.66)	9	10
Distance PFV, PD	5.5 (±6.36)	12.09 (±7.72)	9.5 (±4.95)	4	6
Near phoria, PD	8.25 (±0.35)	–2.27 (±3.07)	–2.5 (±6.36)	–7	3.5
Near NFV, PD	19.75 (±0.35)	11.73 (±4.54)	11.5 (±0.71)	10	9.5
Near PFV, PD	15.75 (±8.83)	24.45 (±5.01)	24.5 (±6.36)	13	18.5
Cal. AC/A, PD/D	5.5 (±0.99)	5.24 (±0.85)	4.8 (±2.26)	2.4	6.6
Gradient AC/A, PD/D	5.25 (±0.35)	3.5 (±1.79)	2.75 (±0.35)	1.5	4.5
Monocular NPA, D	10.57 (±2.38)	10.29 (±1.27)	8.96 (±0.8)	8.69	7.77
Binocular NPA, D	13.33 (±4.71)	12.41 (±2.17)	11.52 (±2.15)	10	9.52
Monocular accommodative facility, c./min	9.5 (±12.73)	2.52 (±1.65)	2.25 (±1.06)	0.75	3.25
Binocular accommodative facility, c./min	12 (±11.31)	2.59 (±2.92)	2 (±0)	0.5	5
Vergence facility, c./min	13.75 (±7.42)	10.5 (±4.69)	6.25 (±1.06)	0.5	5.5
NRA, D	2 (±0)	1.61 (±0.26)	1.75 (±0)	0.75	2.25
PRA, D	1.25 (±0.35)	2.57 (±1.40)	2.63 (±2.65)	4	1.5

AE, accommodative excess; AIF, accommodative infacility; AIS, accommodative insufficiency; BES, basic esophoria; CE, convergence excess; CI, convergence insufficiency; CISS, Convergence Insufficiency Symptom Survey; NBV + NAD, no vergence or accommodative dysfunction; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; NRA, negative relative accommodation; PFV, positive fusional vergence; PRA, positive relative accommodation.

the numbers of words/items by the time spent (words or items per minute). The error rate (ER) was also calculated with this formula:

$$\text{ER} = \text{numbers of corrected errors} + (\text{numbers of uncorrected errors} \times 2)$$

An uncorrected error had to represent a higher importance than a corrected one. Such weighting is usually applied to clinical use of the test (Victoria test adapted for French)[45] because uncorrected errors may represent a higher loss of attention. To evaluate the flexibility between tasks in Stroop, we also calculated the time differences. According to MacLeod[31] and Jensen and Rohwer,[46] time differences are believed to be more appropriate to evaluate Stroop interference. As in the study of Stuss et al.,[47] we opted for the following formulas:

$$\text{Color Effect} = \text{Color naming} - \text{Reading};$$

$$\text{Interference Effect} = \text{Interference} - \text{Color naming}.$$

Statistical Analysis

Linear regressions were applied to search for correlations, with independent variables as the optometric results and experimental tests results as the dependent variables.

TABLE 2.
Mean values of the sample in the reading tasks and the Stroop test

	''Alouette'' reading task	Stroop reading task	Stroop denomination task	Stroop interference task	Stroop color effect (CE)	Stroop interference effect (IE)
Time, s	107.8 (±53.51)	41.83 (±6.78)	60.83 (±10.91)	93.89 (±19.33)	19 (±8.16)	33.06 (±11.25)
Error rate	11.23 (±7.45)	0.15 (±0.41)	1.51 (±2.06)	3.91 (±3.36)	—	—

In addition, comparisons between subgroups (symptomatic vs. nonsymptomatic subjects, normal subjects vs. subjects presenting dysfunctions of vergence or accommodation) were carried out. We used the Shapiro-Wilk test to test for the normality of the data distribution. As normality failed, nonparametric Kruskal-Wallis analysis of variance (ANOVA) and nonparametric Mann-Whitney U tests were performed to compare the groups with each other. Comparisons were done for all parameters of the reading and Stroop tests.

RESULTS

General Reading and Stroop Test Results

The mean group values and standard deviations for the reading test and Stroop test are shown in Table 2 (standard deviations are in parentheses). As expected, the reading speeds (words per minute) during the Stroop reading task and during the task *L'Alouette* were correlated ($R^2 = 0.49$, $p < 0.001$).

Correlations between the CISS Score, Reading Speed, and Stroop IE Results

The linear regression model showed a significant mild correlation between the CISS score and the reading speed during the reading Stroop task ($R^2 = 0.08$, $p < 0.05$): the higher the CISS score, the slower the reading speed was. Yet, no significant correlation between the CISS score and the reading speed during the ''Alouette'' task ($p > 0.05$) was found. The linear regression model also showed a significant moderate correlation between the CISS score and the Stroop interference effect (IE) ($R^2 = 0.11$, $p < 0.03$; Fig. 1).

To analyze the incidence of the reported near-vision symptoms as calculated by the CISS on the reading speed or the Stroop test results, we decided to divide the sample in two different groups, the nonsymptomatic subjects and the symptomatic subjects, using a cutoff point of higher than or equal to 16 at the CISS test to distinguish between subjects with symptoms relative to near vision from those without said symptoms.[35] Twenty-six subjects (50.98%) were classified as nonsymptomatic, and 25 subjects (49.02%) were classified as symptomatic. The Mann-Whitney U test did not show a significant difference between nonsymptomatic (mean group, 149.27 ± 24.53) and symptomatic subjects (mean group, 144.86 ± 23.69) in terms of reading speed (words per minute) during the Stroop reading task ($U = 291$, $p = 0.52$), but it did show a significant difference between nonsymptomatic (mean group, 29.48 ± 9.92 s) and symptomatic subjects (mean group, 36.92 ± 11.90 s) in terms of Stroop IE ($U = 184.5$, $p < 0.01$).

Correlations between the Optometric Results, Reading Speed, and Stroop Test Results

Each of the measured parameters of the reading and the Stroop tasks was cross correlated with each of the optometric measurements (CISS score; NPC; distance and near phoria; distance and near PFV, NFV, and TFV; monocular and binocular NPA; vergence and accommodative facility; NRA and PRA). No significant correlations were found between the Stroop Color Effect, the Denomination ER, the Interference ER, and the optometric findings ($p > 0.05$).

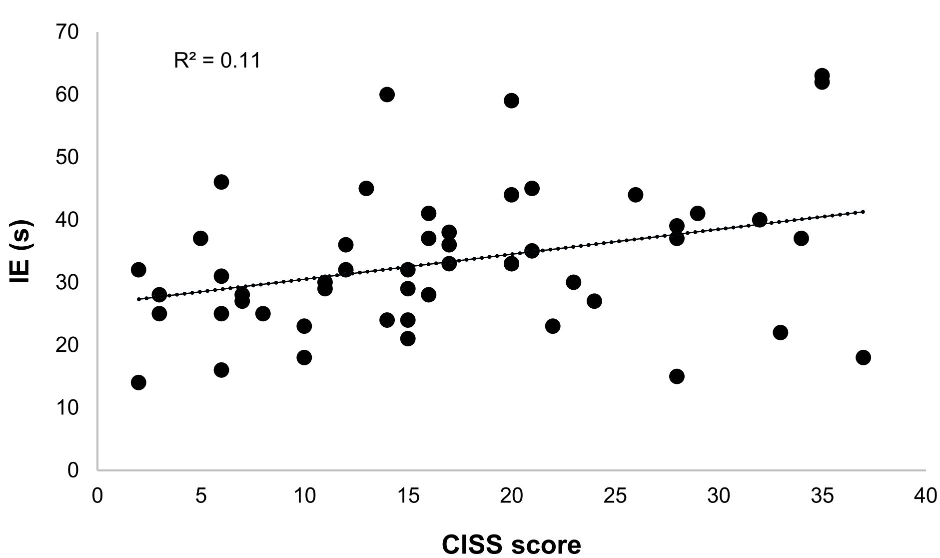

FIGURE 1.
Linear regression plot of the interference effect (IE) in seconds (s) as a function of the Convergence Insufficiency Symptom Survey (CISS) score.

Linear regression results (r^2) in the entire group are shown in Table 3; significant correlations ($p < 0.05$) are marked with an asterisk.

Major Findings

Reading Measures versus Measures of Binocular and Accommodative Functions

We did not find significant correlations ($p > 0.05$) whether between reading speed, number of corrected or uncorrected errors, or ER and optometric results.

Interference Effect and Binocular Function

The linear regression model showed significant moderate correlations between the near PFV and the IE ($R^2 = 0.16$, $p < 0.004$) and between near TFV and IE ($R^2 = 0.18$, $p < 0.002$) in the Stroop test. The higher the vergence range, the better the performance in the interference task, that is, the interference time effect was smaller.

A significant mild correlation was also found in the same way between IE and NPC ($R^2 = 0.09$, $p < 0.03$): the closer the point of convergence shown by the subject, the more efficient he or she was for the interference task.

Applying a Bonferroni correction in terms of tests relative to near-vision binocular function (NPC, PFV, NFV, near phoria, calculated AC/A ratio, binocular accommodative and vergence facility), p values for significant correlation had to be lower than 0.007. Correlations between Stroop IE and near PFV and between Stroop IE and near TFV remain significant (Figs. 2 and 3).

Interference Effect and Accommodative Function

Significant mild correlations were found in the same way between IE and monocular NPA ($R^2 = 0.13$, $p < 0.01$) and between IE and binocular NPA ($R^2 = 0.11$, $p = 0.02$): the closer the point of accommodation or convergence the subject showed, the better his or her performance was for the interference task.

Applying Bonferroni correction in terms of tests relative to accommodative function (monocular and binocular accommodative facility, monocular NPA, NRA, and PRA), p values for significant correlation had to be lower than 0.01. Correlation between Stroop IE and monocular NPA remains significant (Fig. 4).

Interference and Reading Results in Subjects with and without Near Fixation Disparity

To analyze the potential incidence of fixation disparity, we divided our sample into two different groups: the one with subjects presenting no fixation disparity at near distance (N = 44) and the one with subjects presenting fixation disparity (N = 7). Four of them exhibited exo-disparity, and the other three exhibited eso-disparity. The Mann-Whitney U test did not show any significant difference between subjects with no fixation disparity and subjects presenting fixation disparity whether in terms of reading

TABLE 3.

Mean values relative to vergence and accommodative functions and their correlations (r^2) with reading speed, ER during reading tasks, and IE during the Stroop test in the entire sample

	Entire sample values		Bravais-Pearson's correlation results (r^2)				
	Mean	SD	"Alouette" reading speed	ER "Alouette"	Stroop reading speed	ER Stroop reading	Stroop IE
CISS Score	16.92	9.59	<0.01	0.01	0.08*	0.02	0.11*
NPC, cm	8.62	3.72	<0.01	0.02	0.01	<0.01	0.09*
Distance PH, PD	0.66	3.76	<0.01	0.01	<0.01	0.02	<0.01
Distance TFV, PD	21.78	7.21	0.01	<0.01	0.01	0.01	0.01
Distance NFV, PD	10.86	4.95	0.01	<0.01	0.03	<0.01	<0.01
Distance PFV, PD	10.92	5.64	0.04	<0.01	0.07	0.02	0.02
Near PH, PD	–1.80	5.67	0.01	<0.01	0.03	0.03	0.01
Near TFV, PD	35.75	8.80	0.01	0.02	0.03	<0.01	0.18*
Near NFV, PD	13.08	5.77	<0.01	<0.01	<0.01	<0.01	0.06
Near PFV, PD	22.67	6.21	0.04	0.06	0.06	<0.01	0.16*
NRA, D	1.80	0.41	0.02	<0.01	0.05	0.02	<0.01
PRA, D	2.53	1.47	0.01	0.07	<0.01	0.03	<0.01
Monocular NPA, D	9.89	2.47	<0.01	0.01	0.04	0.06	0.13*
Binocular NPA, D	11.89	2.84	<0.01	<0.01	0.01	0.02	0.11*
Monocular accommodative facility, c./min	7.54	5.95	0.01	0.02	<0.01	<0.01	<0.01
Binocular accommodative facility, c./min	6.45	5.19	<0.01	0.03	<0.01	<0.01	0.01
Vergence facility, c./min	9.33	4.55	<0.01	<0.01	0.01	0.02	0.04

*Significant correlation ($p < 0.05$).

ER, error rate; IE, interference effect; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; NRA, negative relative accommodation; PFV, positive fusional vergence; PH, phoria; PRA, positive relative accommodation; SD, standard deviation; TFV, total fusional vergence.

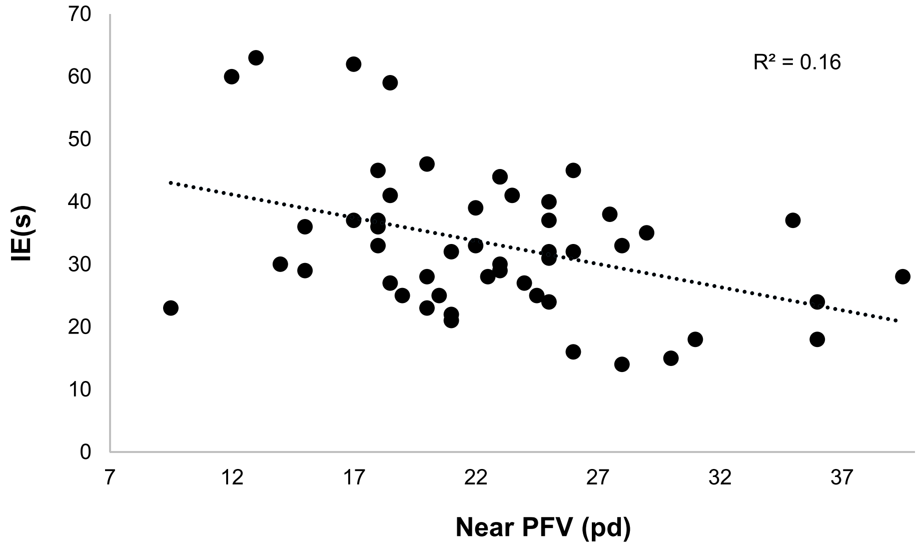

FIGURE 2.
Linear regression plot of the interference effect (IE) in seconds (s) as a function of the near positive fusional vergence (Near PFV) in prism diopters (pd).

speed in the "Alouette" task (mean values, 149.6 ± 26.5 vs. 154.4 ± 51.1; U = 146.0, p = 0.83), in terms of reading speed with the Stroop reading task (mean values, 146.1 ± 19.5 vs. 153.1 ± 44.9; U = 153.5, p = 0.98), or in terms of Stroop IE values (mean values, 32.2 ±10.3 s vs. 40.1 ± 16.6 s; U = 103.5, p = 0.17); there was no difference either between eso- and exo-disparity subjects (p > 0.05), although the two subgroups were of a small size.

Interference and Reading Results According to the Percival's Criterion

Percival proposed a rule to anticipate visual discomfort in connection with fusion ranges: the point-of-zero demand should fall in the middle third of the TFV for comfortable binocular vision.[48] To analyze if meeting Percival's criterion at near distance could have an incidence on reading speed or on Stroop interference performance, we divided our sample into two different groups: one with subjects meeting Percival's criterion (N = 38) and the other with subjects failing to meet Percival's criterion (N = 13). The Mann-Whitney U test did not show any significant difference between subjects meeting Percival's criterion and subjects failing to meet Percival's criterion in terms of reading speed in the "Alouette" task (mean values, 145.7 ± 29.0 vs. 163.8 ± 31.2; U = 172.5, p = 0.11), in terms of reading speed in the Stroop reading task (mean values, 143.5 ± 20.6 vs. 157.3 ± 30.6; U = 187.5, p = 0.19), and in terms of Stroop IE (mean values, 32.36 ± 10.37 vs. 35.92 ± 14.45; U = 211.5, p = 0.44).

Interference and Reading Results According to Sheard's Criterion

Sheard[37] also proposed a rule to anticipate vision discomfort regarding fusion ranges and phorias: the fusional vergence reserve

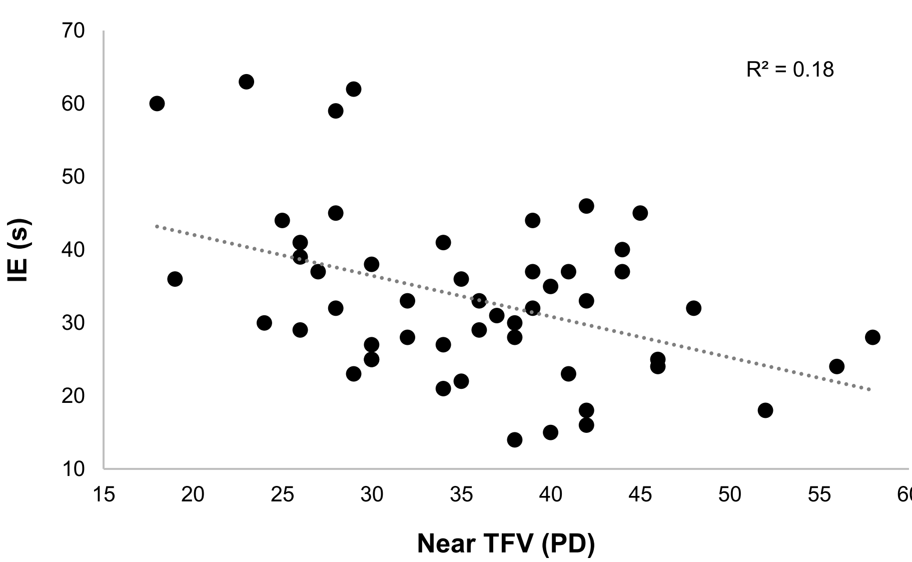

FIGURE 3.
Linear regression plot of the interference effect (IE) in seconds as a function of the total fusional vergence (TFV) in prism diopters (PD).

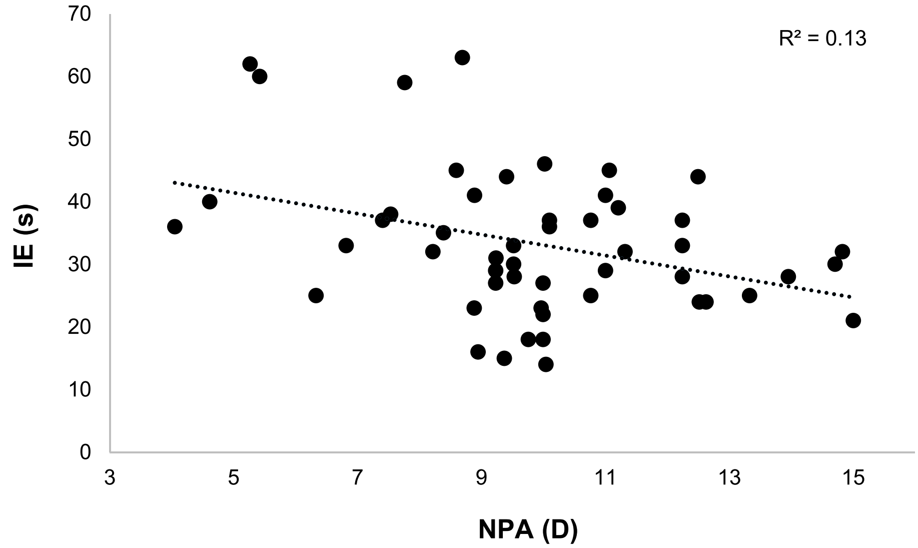

FIGURE 4.

Linear regression plot of the interference effect (IE) in seconds (s) as a function of the monocular near point of accommodation (NPA) in diopters (D).

has to be at least twice the fusional vergence demand for comfortable binocular vision. To analyze if meeting Sheard's criterion at near distance could have a relationship with reading speed or Stroop interference performance, we divided our sample into two different groups: one with subjects meeting the Sheard's criterion (N = 37) and the other with subjects failing to meet Sheard's criterion (N = 14, 9 with exophoria and 5 with esophoria). The Mann-Whitney U test did not show any significant difference between subjects meeting Sheard's criterion and subjects failing to meet Sheard's criterion in terms of reading speed in the "Alouette" task (149.7 ± 31.4 vs. 151.9 ± 28.6; U = 237.5, p = 0.65) and in terms of reading speed with the Stroop reading task (mean values, 146.6 ± 23.2 vs. 148.2 ± 26.7; U = 242.0, p = 0.72). Yet, there was a significant difference in terms of Stroop IE (30.27 ± 9.83 vs. 41.21 ± 12.14; U = 116.0, p < 0.01): subjects failing to meet Sheard's criterion did not perform as well in the interference task, that is, their interference time effect was higher than that of the subjects meeting Sheard's criterion (Fig. 5).

Results for Asymptomatic versus Symptomatic Subjects with Vergence or Accommodative Dysfunctions

Using the classification of Scheiman and Wick,[42] we first classified vergence and accommodation dysfunctions by taking into account the number of signs used in the studies of Porcar and Martinez-Palomera[18] and Shin et al.[3] In addition, we decided to use the CISS as supplementary criteria to classify the symptomatic students. We took a cutoff point of higher than or equal to 16 to distinguish students with symptoms relative to near vision from those without such symptoms.[35]

With this specific classification, we found three major groups in our sample: a control group (N = 18) with subjects presenting no accommodative or vergence dysfunctions and less than 16 at the CISS score; a symptomatic CI group (SCI group, N = 11) with subjects presenting CI and a CISS score higher than or equal to 16; and a symptomatic accommodative excess group (SAE group, N = 7) with subjects presenting accommodative excess without vergence dysfunctions and a CISS score higher than or equal to 16.

Correlations in Each Group

Mean group values, standard deviations, and linear regressions (r^2) to search for correlations, with independent variables as the optometric results and the results of the experimental tests as the dependent variables, are shown for the control group (Table 4), the SCI group (Table 5), and the SAE group (Table 6). Significant correlations ($p < 0.05$) are marked with an asterisk.

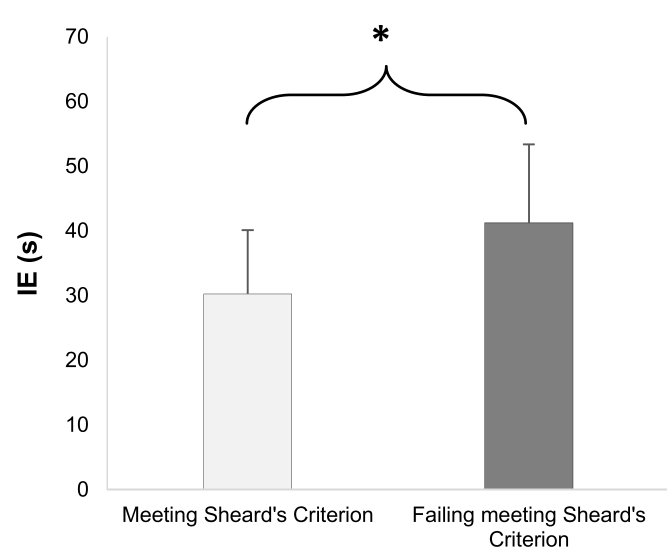

FIGURE 5.

Mean values and standard deviations concerning interference effect (IE) in seconds (s) in subjects meeting Sheard's criterion (N = 37) and in subjects failing to meet Sheard's criterion (N = 14).

TABLE 4.

Mean values relative to vergence and accommodative functions and their correlations (r^2) with reading speed, ER during reading tasks, and IE during the Stroop test in the control group

	Control group values		Bravais-Pearson's correlation results (r^2)				
	Mean	SD	"Alouette" reading speed	ER "Alouette"	Stroop reading speed	ER Stroop reading	Stroop IE
CISS	10.39	4.33	0.19	0.02	0.23*	0.06	0.18
NPC, cm	7.33	2.91	0.01	0.03	<0.01	0.17	<0.01
Distance phoria, PD	1.16	4.03	0.07	0.17	0.03	0.02	0.04
Distance TFV, PD	23.33	7.77	0.01	<0.01	0.01	0.33*	0.01
Distance NFV, PD	11.83	5.79	0.05	0.06	<0.01	0.08	<0.01
Distance PFV, PD	11.5	5.02	0.01	0.05	0.01	0.33*	0.07
Near phoria, PD	–0.5	3.15	0.08	0.06	<0.01	0.02	<0.01
Near TFV, PD	39.22	9.97	0.22*	0.12	0.11	<0.01	0.17
Near NFV, PD	15.67	5.16	0.33*	0.09	0.06	<0.01	0.06
Near PFV, PD	23.56	6.75	0.06	0.08	0.09	<0.01	0.17
NRA, D	1.93	0.36	0.01	<0.01	0.01	<0.01	0.02
PRA, D	2.54	1.33	0.24*	0.18	0.18	0.01	0.05
Monocular NPA, D	11.09	2.76	0.02	0.13	0.15	0.15	0.11
Binocular NPA, D	12.96	2.69	0.02	0.18	0.21	0.12	0.14
Monocular accommodative facility, c./min	11.28	6.09	<0.01	<0.01	0.01	0.04	0.05
Binocular accommodative facility, c./min	9.44	4.86	<0.01	0.08	0.02	0.05	0.05
Vergence facility, c./min	10.33	3.85	0.05	0.05	0.03	0.16	0.05

*Significant correlation ($p < 0.05$).

CISS, Convergence Insufficiency Symptom Survey; ER, error rate; IE, interference effect; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; NRA, negative relative accommodation; PFV, positive fusional vergence; PRA, positive relative accommodation; SD, standard deviation; TFV, total fusional vergence.

CISS Score

There was a significant mild correlation between the CISS score and the reading speed in the Stroop reading task in the control group ($R^2 = 0.23$, $p < 0.05$): the higher the CISS score, the slower the reading speed was. Yet, there was no significant correlation between the CISS score and reading speed in the "Alouette" task.

There was a significant moderate correlation between the CISS score and the IE in the Stroop test in the SCI group ($R^2 = 0.43$, $p< 0.03$): the higher the CISS score, the poorer the performance in the interference task was, that is, the interference time effect was longer.

Results Relative to the Binocular and Accommodative Functions

We applied a Bonferroni correction in terms of tests relative to near-vision binocular function (NPC, PFV, NFV, near phoria, calculated AC/A ratio, binocular accommodative and vergence facility) and in terms of tests relative to accommodative function (monocular and binocular accommodative facility, monocular NPA, NRA, and PRA). Values of p for significant correlation had to be lower than 0.007 regarding binocular function tests and lower than 0.01 regarding accommodative function tests.

Finally, only one correlation between the distance NFV and in the Stroop reading task ($R^2 = 0.59$, $p = 0.005$) remained significant in the SCI group: the higher the distance NFV, the slower the reading speed was. Yet, there was no significant correlation between distance NFV and the reading speed in the "Alouette" task.

Comparisons Between Groups

To search for differences between the control group, the SCI group, and the SAE group in terms of optometric results, reading speed results, or Stroop IE results, we first used a nonparametric Kruskal-Wallis ANOVA test. As expected, significant differences between groups were found in terms of optometric results: CISS score, NPC, distance phoria, near phoria, near TFV, near NFV, both monocular and binocular NPA, and accommodative facilities, as shown in Table 7 by asterisks. For each significant difference noted, we used a nonparametric Mann-Whitney U test to compare a group with another one and confirm the Kruskal-Wallis ANOVA test results, as shown in Table 8 with significant differences marked with asterisks. Next, we will present the results in terms of reading and Stroop interference test values:

Reading Tasks

The nonparametric Kruskal-Wallis ANOVA test did not show significant differences between the groups in terms of:

- Reading speed in the "Alouette" task ($H(2) = 1.82$, $p = 0.40$)
- Reading speed in the Stroop reading task ($H(2) = 0.07$, $p = 0.97$)

TABLE 5.

Mean values relative to vergence and accommodative functions and their correlations (r^2) with reading speed, ER during reading tasks, and IE during the Stroop test in the SCI group

	SCI group values		Bravais-Pearson's correlation results (r^2)				
	Mean	SD	"Alouette" reading speed	ER "Alouette"	Stroop reading speed	ER Stroop reading	Stroop IE
CISS	23.55	8	0.29	0.02	0.31	0.03	0.43*
NPC, cm	11.36	3.04	<0.01	<0.01	0.01	<0.01	0.01
Distance PH, PD	–1.77	2.16	0.13	0.29	0.25	0.22	0.52*
Distance TFV, PD	19	5.48	0.15	0.02	0.07	0.12	0.02
Distance NFV, PD	8.68	3.7	0.47*	0.41*	0.59*	0.34	0.53*
Distance PFV, PD	10.32	4.47	0.01	0.14	0.09	<0.01	0.17
Near PH, PD	–8.45	3.3	0.05	0.36	0.09	0.13	0.11
Near TFV, PD	27.81	6.48	0.05	<0.01	<0.01	0.31	0.02
Near NFV, PD	7.09	3.76	0.48*	0.37*	0.48*	0.1	0.24
Near PFV, PD	20.73	6.76	0.03	0.16	0.11	<0.01	0.16
NRA, D	1.59	0.55	0.17	0.13	0.15	0.08	0.21
PRA, D	3.34	1.69	<0.01	0.05	0.01	0.05	0.01
Monocular NPA, D	8.56	2.2	0.09	0.02	0.09	0.06	0.11
Binocular NPA, D	10.28	2.99	<0.01	0.08	0.01	0.01	0.03
Monocular accommodative facility, c./min	5.91	4.98	0.08	0.09	0.05	0.17	0.13
Binocular accommodative facility, c./min	4.86	4.38	0.01	0.09	0.02	0.05	0.13
Vergence facility, c./min	6.86	4.48	<0.01	0.04	<0.01	0.19	0.02

*Significant correlation ($p < 0.05$).

CISS, Convergence Insufficiency Symptom Survey; ER, error rate; IE, interference effect; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; NRA, negative relative accommodation; PFV, positive fusional vergence; PH, phoria; PRA, positive relative accommodation; SCI, symptomatic convergence insufficiency; SD, standard deviation; TFV, total fusional vergence.

- ER in the "Alouette" task ($H(2) = 3.21$, $p = 0.20$)
- ER in the Stroop reading task ($H(2) = 0.19$, $p = 0.91$)

Stroop IE

The nonparametric Kruskal-Wallis ANOVA test showed a significant difference between the groups in terms of Stroop IE mean values ($H(2) = 10.18$, $p < 0.01$). The control group showed a significantly lower Stroop IE mean value than the SCI group ($U = 23.5$, $p < 0.01$). Yet, the SCI group and the SAE group did not show any significant difference in terms of Stroop IE mean values ($U = 23.5$, $p = 0.17$). Similarly, the control group and the SAE group did not show any significant difference in terms of Stroop IE mean values ($U = 56.5$, $p = 0.69$; Fig. 6).

DISCUSSION

The main finding of the study is that the larger the vergence amplitude, the weaker the interference effect in the Stroop test. The same correlation was also found between the measure of the total range of convergence and divergence combined and the score of the interference effect. Similarly, monocular NPA is also positively correlated with the interference score: the more remote the distance of accommodation, the lower the performance in the Stroop test. These results show that the amplitude of the response in vergence and accommodation evaluated by optometric tests is positively correlated with the performance of the cognitive executive functions, as measured by the Stroop test. Importantly, vergence seemingly has no effect on reading speed.

Another important result is that subdivision of the subjects into three groups, the one with asymptomatic subjects showing normal binocular vision, the one with symptomatic subjects showing CI (SCI), and the one with symptomatic subjects showing AE (SAE) according to the classification of Scheiman and Wick,[42] corroborates further the correlations presented above: the group with normal binocular vision shows significantly better performance in the Stroop interference test than the group with SCI.

Vergence and Interference Effect: Sensory Hypothesis

Vergence was measured with rotary prisms inducing binocular disparity, this vergence is driven by the detection of binocular disparity that stimulates the vergence oculomotor response. Binocular disparity is processed by many cortical areas (visual cortex, parietal and frontal lobe).[49–51] On the other hand, the cortical areas associated with cognitive control can be presented in two parts[52–54]: first, the top-down frontal cortex structures, including the dorsolateral prefrontal cortex, responsible for integrating information from other brain regions and initiating top-down response preference based on task demands, and the anterior cingulate cortex,[55,56] responsible for conflict monitoring.[57] Second, there are also the response organization areas, including the posterior parietal cortex, modulating attentional orientation to task-relevant information and creating stimulus response mapping,[58] and the supplementary motor areas

TABLE 6.

Mean values relative to vergence and accommodative functions and their correlations (r^2) with reading speed, ER during reading tasks, and IE during the Stroop test in the SAE group

	SAE group values		Bravais-Pearson's correlation results (r^2)				
	Mean	SD	"Alouette" reading speed	ER "Alouette"	Stroop reading speed	ER Stroop reading	Stroop IE
CISS	26.43	16.28	0.24	0.41	0.09	0.16	0.21
NPC, cm	6.0	2.08	0.26	0.56	0.22	0.18	0.24
Distance phoria, PD	–0.79	2.12	0.04	0.43	0.09	0.06	0.62*
Distance TFV, PD	21	5.39	<0.01	0.02	0.26	0.11	0.02
Distance NFV, PD	8.93	1.37	0.22	0.55	0.17	0.12	0.02
Distance PFV, PD	12.07	4.90	0.03	<0.01	0.45	0.20	0.01
Near phoria, PD	–3.14	3.19	<0.01	0.22	0.16	<0.01	0.25
Near TFV, PD	34.71	5.77	0.15	0.01	0.23	<0.01	0.19
Near NFV, PD	10.71	5.16	0.47	0.31	0.33	0.08	0.05
Near PFV, PD	24.00	3.23	0.16	0.49	<0.01	0.17	0.19
NRA, D	1.64	0.32	0.14	0.02	<0.01	0.02	0.56
PRA, D	2.29	1.05	0.03	<0.01	0.02	0.52	0.06
Monocular NPA, D	10.74	1.22	0.39	0.52	0.05	0.07	0.08
Binocular NPA, D	13.41	1.54	0.03	0.09	0.13	0.43	0.09
Monocular accommodative facility, c./min	2.82	1.87	0.16	0.02	0.06	0.29	0.64*
Binocular accommodative facility, c./min	3.5	3.36	0.21	0.02	<0.01	0.15	0.02
Vergence facility, c./min	8.5	4.29	0.04	0.03	0.39	0.44	0.06

*Significant correlation ($p < 0.05$).

CISS, Convergence Insufficiency Symptom Survey; ER, error rate; IE, interference effect; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; NRA, negative relative accommodation; PFV, positive fusional vergence; PRA, positive relative accommodation; SAE, symptomatic accommodative excess; SD, standard deviation; TFV, total fusional vergence.

and the pre–supplementary motor areas, both play a role in the selection and the execution of responses.[59] Some of these areas are therefore highly involved in the cognitive task of inhibition as measured with the Stroop test: the dorsolateral prefrontal cortex, the anterior cingulate cortex, especially the dorsal subdivision, and the posterior parietal cortex.[52,60–66] The correlation between vergence capability and Stroop performance could be attributed to the fact that these areas are highly involved in both tasks—vergence control and inhibition—which both require attention deployment. Note that our Stroop test was of a relatively short duration (100 items) and the subjects had only minor dysfunction in their binocular vision. We predict that further studies with longer tests and/or more severe dysfunctions of binocular vision would produce stronger correlations.

Complementary Hypothesis: Attentional-Motor Hypothesis

Based on the pre–motor theory of visual attention,[34] shifting attention is a by-product of saccade preparation. This theory could be enlarged to include vergence, which is also important for obtaining single binocular vision. If the control of vergence is poor, the eyes do not intersect at the appropriate depth. Consequently, single binocular vision is either delayed or reduced. Any deficiency in terms of vergence would thus provide a loose basis for focused attention interfering with the deployment of cognitive functions. The difference from the above pre–motor hypothesis is that the interference with the Stroop test is now at an advanced level, the attention level, which is a prerequisite for visual processing and subsequent cognition. This hypothesis calls for further research with objective measures on the angle of vergence, on the coordination of the saccades, and on the accommodative response during the interference phase of the Stroop test.

Correlation between NPA and Interference Effect

Monocular NPA represents the closest point that the subject can still see clearly using maximum accommodation. This measurement is carried out in real space, as opposed to fusion ranges, which use rotary prisms and induce a conflict between vergence and accommodation. During the fusion range test, the angle of vergence had to vary to maintain single vision, but the accommodative response had to stay stable to maintain clear vision. The results of the NPA are similar to those of the fusion range test when compared with the interference effect: the closer the target, indicating the existence of a higher accommodative amplitude, the weaker the interference effect in the Stroop test. This correlation confirms that convergence and accommodation are both linked to cognitive executive function, as measured by the Stroop test.

Visual Symptoms

The significant correlation between CISS score and Stroop IE in the entire group and in the SCI group and the significant difference found between symptomatic and nonsymptomatic

TABLE 7.

Mean values and SDs relative to vergence and accommodative functions, the reading tasks, and the Stroop test in the control group, the SCI group, and the SAE group

	Control group		SCI group		SAE group		Kruskal-Wallis test results	
	Mean value	SD	Mean value	SD	Mean value	SD	H (2, N = 36)	p
CISS	10.39	4.33	23.55	8	26.43	16.28	26.51*	<0.01*
NPC, cm	7.33	2.91	11.36	3.04	6.0	2.08	13.58*	<0.01*
Distance PH, PD	1.16	4.03	–1.77	2.16	–0.79	2.12	6.32*	0.04*
Distance TFV, PD	23.33	7.77	19	5.48	21	5.39	2.23	0.33
Distance NFV, PD	11.83	5.79	8.68	3.7	8.93	1.37	3.96	0.14
Distance PFV, PD	11.5	5.02	10.32	4.47	12.07	4.90	0.62	0.73
Near PH, PD	–0.5	3.15	–8.45	3.3	–3.14	3.19	20.82*	<0.01*
Near TFV, PD	39.22	9.97	27.81	6.48	34.71	5.77	10.77*	<0.01*
Near NFV, PD	15.67	5.16	7.09	3.76	10.71	5.16	15.26*	<0.01*
Near PFV, PD	23.56	6.75	20.73	6.76	24.00	3.23	2.66	0.26
NRA, D	1.93	0.36	1.59	0.55	1.64	0.32	4.38	0.11
PRA, D	2.54	1.33	3.34	1.69	2.29	1.05	2.24	0.33
Monocular NPA, D	11.09	2.76	8.56	2.2	10.74	1.22	7.48*	0.02*
Binocular NPA, D	12.96	2.69	10.28	2.99	13.41	1.54	6.61*	0.04*
Monocular accommodative facility, c./min	11.28	6.09	5.91	4.98	2.82	1.87	12.50*	<0.01*
Binocular accommodative facility, c./min	9.44	4.86	4.86	4.38	3.5	3.36	9.98*	<0.01*
Vergence facility, c./min	10.33	3.85	6.86	4.48	8.5	4.29	3.06	0.22
Reading speed *L'Alouette*	141.52	24.45	149.37	27.60	151.48	40.79	1.82	0.40
ER "Alouette" reading	12.22	9.01	9.64	5.43	16.14	8.05	3.21	0.20
Stroop reading speed	142.59	22.52	141.83	19.67	143.62	19.38	0.07	0.97
ER Stroop reading	0.22	0.43	0.27	0.65	0.14	0.38	0.19	0.91
Stroop IE	29.11	10.48	41.91	10.89	32	10.85	10.18*	<0.01*

The associated results of the nonparametric Kruskal-Wallis ANOVA between the three groups are shown (H and p value).

*Significant difference.

ANOVA, analysis of variance; CISS, Convergence Insufficiency Symptom Survey; ER, error rate; IE, interference effect; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; NRA, negative relative accommodation; PFV, positive fusional vergence; PH, phoria; PRA, positive relative accommodation; SAE, symptomatic accommodative excess; SCI, symptomatic convergence insufficiency; SD, standard deviation; TFV, total fusional vergence.

subjects in the entire sample suggest that the CISS score could be a good indicator in terms of cognitive executive function results: symptoms are negatively correlated to the Stroop interference performance. This has a clinical interest, especially for young students, revealing that every vision disorder that leads to symptoms in near vision should be managed, as inhibition measured with the Stroop test is linked with attention, memory, and comprehension in reading, even if the automatic reading skills at first appear to be correct. However, using another scale, like the College of Optometrists in Vision Development Quality of Life questionnaire,[67] would have been wise to compare these results with a more general grading scale of symptoms.

The Relationship with Vergence Dysfunction

To the best of our knowledge, this is the first time a significant inferiority on executive functions as measured in the interference phase of the Stroop test has been found in symptomatic subjects with CI (SCI) compared with nonsymptomatic subjects with normal binocular vision (control group). Interestingly, no significant difference was found between the control group and the symptomatic subjects showing AE (SAE) in terms of Stroop test results. The CISS score appeared to be a good indicator of cognitive executive function, but the results reveal that a vergence problem like CI tends to have a higher effect on cognitive executive function than an accommodative problem like AE.

This has clinical implications and opens frontiers between the clinical practices of optometry, ophthalmology, and neuropsychology. First of all, it provides ergonomic and clinical indications for managing vergence problems to maintain optimal cognitive functions. Second, the Stroop test is also usually used to diagnose dyslexia or ADHD in children. We suggest that vergence and accommodative functions have to be evaluated systematically because low vergence capabilities can reduce the quality of visual processing and the quality of focused attention and thereby interfere with cognitive executive functions.

Why Isn't Reading Affected?

Mild significant correlations were found between optometric results and reading speed or error rate during the reading tasks in some groups, but not in the entire sample. Moreover, significant correlations between reading speed and optometric results only concerned one of the two reading tests ("Alouette" or Stroop reading task) and not both at the same time, as did error rate. Finally, comparisons between the three major groups did not show any significant differences in terms of reading speed or error rate. During the reading test *L'Alouette* or the color reading task of the Stroop test, no comprehension or memorization was demanded. Therefore, these two tasks were less cognitive demanding than the Stroop interference task. Consequently, we can suggest that vergence dysfunctions can lead to problems when the cognitive demand is higher than for simple automatic reading tasks.

Optometry Testing and the Weight of Meeting Sheard's Criterion

Throughout the optometric testing procedure, we used about 20 different tests to evaluate accommodative function, binocular function, and their synergy. Yet, the results indicate that only a few of them are important relative to cognitive executive function: vergence ranges, monocular accommodative ranges, NPC, and phorias. These tests are necessary to detect the basic dysfunctions and show the quality of the response in convergence, divergence, and accommodation. Moreover, meeting Sheard's criterion at near distance seemed to be a good indicator in terms of the results of the interference phase of the Stroop test. This physiological measurement, calculated by linking phoria to the fusion ranges and basically reflecting the comfort in sustained vision tasks, is also closely linked with cognitive executive functions. This strengthens the overall message of this study: both the quality of vergence and accommodation are linked with cognitive executive functions.

TABLE 8.

Nonparametric Mann-Whitney U test results for comparison between the control group, the SCI group, and the SAE group to confirm the nonparametric Kruskal-Wallis ANOVA test results

Test	Groups	Mann-Whitney U test result	p
CISS	SCI vs. control	0.00	<0.01*
	SCI vs. SAE	30.0	0.44
	SAE vs. control	0.00	<0.01*
NPC	SCI vs. control	30.5	<0.01*
	SCI vs. SAE	4.00	<0.01*
	SAE vs. control	46.5	0.32
Distance phoria	SCI vs. control	45.0	0.02*
	SCI vs. SAE	30.5	0.47
	SAE vs. control	41.5	0.19
Near phoria	SCI vs. control	4.5	<0.01*
	SCI vs. SAE	6.0	<0.01*
	SAE vs. control	35.5	0.09
Near TFV	SCI vs. control	31.0	<0.01*
	SCI vs. SAE	14.5	0.03*
	SAE vs. control	44.0	0.25
Near NFV	SCI vs. control	16.5	<0.01*
	SCI vs. SAE	18.0	0.06
	SAE vs. control	32.5	0.06
Monocular NPA	SCI vs. control	43.5	0.01*
	SCI vs. SAE	15	0.03*
	SAE vs. control	53.5	0.57
Monocular accommodative facility	SCI vs. control	48.5	0.02*
	SCI vs. SAE	26.0	0.26
	SAE vs. control	8.5	<0.01*
Binocular accommodative facility	SCI vs. control	47.0	0.02*
	SCI vs. SAE	36.5	0.86
	SAE vs. control	16.5	<0.01*
Stroop IE	SCI vs. control	23.5	<0.01*
	SCI vs. SAE	23.5	0.17
	SAE vs. control	56.5	0.69

*Significant difference.

ANOVA, analysis of variance; CISS, Convergence Insufficiency Symptom Survey; IE, interference effect; NFV, negative fusional vergence; NPA, near point of accommodation; NPC, near point of convergence; SAE, symptomatic accommodative excess; SCI, symptomatic convergence insufficiency; TFV, total fusional vergence.

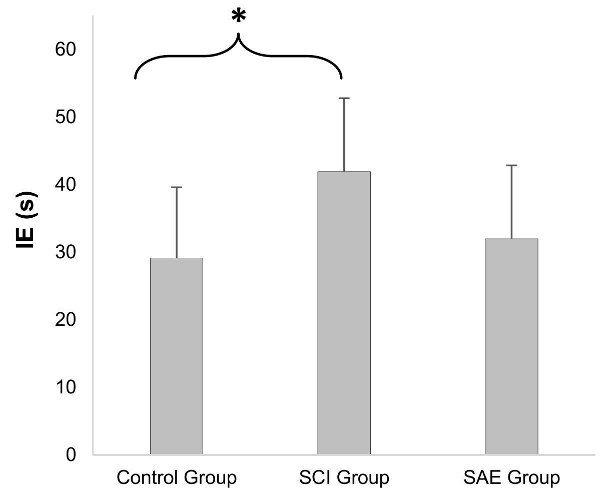

FIGURE 6.

Mean values and standard deviations concerning interference effect (IE) in seconds (s) in the control group (N = 18), in the symptomatic convergence insufficiency group (SCI Group, N = 11), and in the symptomatic accommodative excess group (SAE Group, N = 7).

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REFERENCES

1. Ciuffreda KJ. The scientific basis for and efficacy of optometric vision therapy in nonstrabismic accommodative and vergence disorders. Optometry 2002;73:735–62.
2. Borsting E, Rouse MW, Deland PN, Hovett S, Kimura D, Park M, Stephens B. Association of symptoms and convergence and accommodative insufficiency in school-age children. Optometry 2003;74:25–34.
3. Shin HS, Park SC, Park CM. Relationship between accommodative and vergence dysfunctions and academic achievement for primary school children. Ophthalmic Physiol Opt 2009;29:615–24.
4. Hoffman LG. Incidence of vision difficulties in children with learning disabilities. J Am Optom Assoc 1980;51:447–51.
5. Garzia R. The relationship between visual efficiency problem and learning. In: Scheiman M, ed. Optometric Management of Learning Related Vision Problems. St. Louis: Mosby; 1994:153–75.
6. Castanes MS. Major review: the underutilization of vision screening (for amblyopia, optical anomalies and strabismus) among preschool age children. Binocul Vis Strabismus Q 2003;18:217–32.

7. Maples WC. Visual factors that significantly impact academic performance. Optometry 2003;74:35–49.
8. Vaughn W, Maples WC, Hoenes R. The association between vision quality of life and academics as measured by the College of Optometrists in Vision Development Quality of Life questionnaire. Optometry 2006;77:116–23.
9. Grisham D, Powers M, Riles P. Visual skills of poor readers in high school. Optometry 2007;78:542–9.
10. Kedzia B, Tondel G, Pieczyrak D, Maples WC. Accommodative facility test results and academic success in Polish second graders. J Am Optom Assoc 1999;70:110–6.
11. Kiely PM, Crewther SG, Crewther DP. Is there an association between functional vision and learning to read? Clin Exp Optom 2001;84:346–53.
12. Blika S. Ophthalmological findings in pupils of a primary school with particular reference to reading difficulties. Acta Ophthalmol (Copenh) 1982;60:927–34.
13. Eames TH. Low fusion convergence as a factor in reading disability. Am J Ophthalmol 1934;17:709–10.
14. Park G, Burri C. The relationship of various eye conditions and reading achievement. J Ed Psychol 1943;34:290–9.
15. Palomo-Alvarez C, Puell MC. Binocular function in school children with reading difficulties. Graefes Arch Clin Exp Ophthalmol 2010; 248:885–92.
16. Hokoda SC. General binocular dysfunctions in an urban optometry clinic. J Am Optom Assoc 1985;56:560–2.
17. Lara F, Cacho P, García A, Megías R. General binocular disorders: prevalence in a clinic population. Ophthalmic Physiol Opt 2001; 21:70–4.
18. Porcar E, Martinez-Palomera A. Prevalence of general binocular dysfunctions in a population of university students. Optom Vis Sci 1997;74:111–3.
19. Cooper J, Duckman R. Convergence insufficiency: incidence, diagnosis, and treatment. J Am Optom Assoc 1978;49:673–80.
20. Kent PR, Steeve JH. Convergence insufficiency, incidence among military personnel and relief by orthoptic methods. Mil Surg 1953; 112:202–5.
21. Norn MS. Convergence insufficiency—incidence in ophthalmic practice. Results of orthoptic treatment. Acta Ophthalmol 1966;44: 132–8.
22. Duane A. A new classification of motor anomalies of the eye based upon physiological principles. Ann Ophthalmol Otolaryngol 1886; 247–60.
23. Bucci MP, Kapoula Z, Bui-Quoc E, Bouet A, Wiener-Vacher S. Saccades and vergence performance in a population of children with vertigo and clinically assessed abnormal vergence capabilities. PLoS One 2011;6:e23125.
24. Gaertner C, Bucci MP, Ajrezo L, Wiener-Vacher S. Binocular coordination of saccades during reading in children with clinically assessed poor vergence capabilities. Vision Res 2013;87:22–9.
25. Alvarez TL, Kim EH. Analysis of saccades and peak velocity to symmetrical convergence stimuli: binocularly normal controls compared to convergence insufficiency patients. Invest Ophthalmol Vis Sci 2013;54:4122–35.
26. Alvarez TL, Jaswal R, Gohel S, Biswal BB. Functional activity within the frontal eye fields, posterior parietal cortex, and cerebellar vermis significantly correlates to symmetrical vergence peak velocity: an ROI-based, fMRI study of vergence training. Front Integr Neurosci 2014;8:50.
27. White JW, Brown HW. Occurrence of vertical anomalies associated with convergent and divergent anomalies—a clinical study. Arch Ophthalmol 1939;21:999–1009.
28. Borsting E, Rouse M, Chu R. Measuring ADHD behaviors in children with symptomatic accommodative dysfunction or convergence insufficiency: a preliminary study. Optometry 2005;76:588–92.
29. Protopapas A, Archonti A, Skaloumbakas C. Reading ability is negatively related to Stroop interference. Cogn Psychol 2007;54:251–82.
30. Stroop JR. Studies of interference in serial verbal reactions. J Exp Psychol 1935;18:643–62.
31. MacLeod CM. Half a century of research on the Stroop effect: an integrative review. Psychol Bull 1991;109:163–203.
32. Cain K. Individual differences in children's memory and reading comprehension: an investigation of semantic and inhibitory deficits. Memory 2006;14:553–69.
33. Ikeda Y, Okuzumi H, Kokubun M. Stroop/reverse-Stroop interference in typical development and its relation to symptoms of ADHD. Res Dev Disabil 2013;34:2391–8.
34. Rizzolatti G, Riggio L, Dascola I, Umiltá C. Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. Neuropsychologia 1987;25:31–40.
35. Rouse M, Borsting E, Mitchell GL, Cotter SA, Kulp M, Scheiman M, Barnhardt C, Bade A, Yamada T; Convergence Insufficiency Treatment Trial (CITT) Investigator Group. Validity of the convergence insufficiency symptom survey: a confirmatory study. Optom Vis Sci 2009;86:357–63.
36. Goss DA. Ocular Accommodation, Convergence, and Fixation Disparity: A Manual of Clinical Analysis, 2nd ed. Newton, MA: Butterworth-Heinemann; 1995.
37. Sheard C. Zones of ocular comfort. Am J Optom 1930;7:9–25.
38. Gall R, Wick B, Bedell H. Vergence facility: establishing clinical utility. Optom Vis Sci 1998;75:731–42.
39. Buzzelli AR. Vergence facility: developmental trends in a school age population. Am J Optom Physiol Opt 1986;63:351–5.
40. Pellizzer S, Siderov J. Assessment of vergence facility in a sample of older adults with presbyopia. Optom Vis Sci 1998;75:817–21.
41. Morgan MW. Analysis of clinical data. Am J Optom Arch Am Acad Optom 1944;21:477–91.
42. Scheiman M, Wick B. Clinical Management of Binocular Vision: Heterophoric, Accommodative and Eye Movement Disorders, Philadelphia: Lippincott Williams and Wilkins; 2002.
43. Lefavrais P. *Test de l'Alouette*, 2nd ed. Paris: Editions du Centre de Psychologie Appliquée; 1967.
44. Debray P, Debray Q, Binoche T, Nebout MC. An advance in leximetry: proportional assessment of the Alouette test. Rev Neuropsychiatr Infant 1972;20:725–32.
45. Kapoula Z, Lê TT, Bonnet A, Bourtoire P, Demule E, Fauvel C, Quilicci C, Yang Q. Poor Stroop performances in 15-year-old dyslexic teenagers. Exp Brain Res 2010;203:419–25.
46. Jensen AR, Rohwer WD, Jr. The Stroop color-word test: a review. Acta Psychol (Amst) 1966;25:36–93.
47. Stuss DT, Floden D, Alexander MP, Levine B, Katz D. Stroop performance in focal lesion patients: dissociation of processes and frontal lobe lesion location. Neuropsychologia 2001;39:771–86.
48. Sheedy JE, Saladin JJ. Association of symptoms with measures of oculomotor deficiencies. Am J Optom Physiol Opt 1978;55:670–6.
49. Mays LE. Neural control of vergence eye movements: convergence and divergence neurons in midbrain. J Neurophysiol 1984;51:1091–108.
50. Judge SJ, Cumming BG. Neurons in the monkey midbrain with activity related to vergence eye movement and accommodation. J Neurophysiol 1986;55:915–30.

51. Leigh RG, Zee DS. The Neurology of Eye Movements, 4th ed. New York: Oxford University Press; 2006.
52. Milham MP, Banich MT, Claus ED, Cohen NJ. Practice-related effects demonstrate complementary roles of anterior cingulate and prefrontal cortices in attentional control. Neuroimage 2003;18:483–93.
53. Aron AR. The neural basis of inhibition in cognitive control. Neuroscientist 2007;13:214–28.
54. Wang L, Liu X, Guise KG, Knight RT, Ghajar J, Fan J. Effective connectivity of the fronto-parietal network during attentional control. J Cogn Neurosci 2010;22:543–53.
55. Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. Annu Rev Neurosci 2001;24:167–202.
56. Brass M, Derrfuss J, Forstmann B, von Cramon DY. The role of the inferior frontal junction area in cognitive control. Trends Cogn Sci 2005;9:314–6.
57. Botvinick MM, Cohen JD, Carter CS. Conflict monitoring and anterior cingulate cortex: an update. Trends Cogn Sci 2004;8:539–46.
58. Coulthard EJ, Nachev P, Husain M. Control over conflict during movement preparation: role of posterior parietal cortex. Neuron 2008;58:144–57.
59. Nachev P, Kennard C, Husain M. Functional role of the supplementary and pre-supplementary motor areas. Nat Rev Neurosci 2008;9:856–69.
60. Banich MT, Milham MP, Atchley RA, Cohen NJ, Webb A, Wszalek T, Kramer AF, Liang Z, Barad V, Gullett D, Shah C, Brown C. Prefrontal regions play a predominant role in imposing an attentional "set": evidence from fMRI. Brain Res Cogn Brain Res 2000;10:1–9.
61. Banich MT, Milham MP, Atchley R, Cohen NJ, Webb A, Wszalek T, Kramer AF, Liang ZP, Wright A, Shenker J, Magin R. fMRI studies of Stroop tasks reveal unique roles of anterior and posterior brain systems in attentional selection. J Cogn Neurosci 2000; 12:988–1000.
62. Banich MT, Milham MP, Jacobson BL, Webb A, Wszalek T, Cohen NJ, Kramer AF. Attentional selection and the processing of task-irrelevant information: insights from fMRI examinations of the Stroop task. Prog Brain Res 2001;134:459–70.
63. Milham MP, Banich MT, Webb A, Barad V, Cohen NJ, Wszalek T, Kramer AF. The relative involvement of anterior cingulate and prefrontal cortex in attentional control depends on nature of conflict. Brain Res Cogn Brain Res 2001;12:467–73.
64. Milham MP, Erickson KI, Banich MT, Kramer AF, Webb A, Wszalek T, Cohen NJ. Attentional control in the aging brain: insights from an fMRI study of the stroop task. Brain Cogn 2002; 49:277–96.
65. Barch DM, Braver TS, Akbudak E, Conturo T, Ollinger J, Snyder A. Anterior cingulate cortex and response conflict: effects of response modality and processing domain. Cereb Cortex 2001;11:837–48.
66. Mohanty A, Engels AS, Herrington JD, Heller W, Ho MH, Banich MT, Webb AG, Warren SL, Miller GA. Differential engagement of anterior cingulate cortex subdivisions for cognitive and emotional function. Psychophysiology 2007;44:343–51.
67. Maples WC. Test-retest reliability of the College of Optometrists in Vision Development Quality of Life Outcomes Assessment short form. J Optom Vis Dev 2002;33:126–34.

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