ORIGINAL INVESTIGATION

Children with Attention-deficit/Hyperactivity Disorder Show an Altered Eye Movement Pattern during Reading

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SIGNIFICANCE: Attention-deficit/hyperactivity disorder (ADHD) is characterized by oculomotor abnormalities. However, the eye movement pattern of children with ADHD during reading has yet to be fully determined. This investigation provides novel insights into the altered eye movement pattern during oral reading of nonmedicated children with pure ADHD in comparison with age-matched controls.

PURPOSE: The purpose of this study was to objectively compare the eye movement pattern during oral reading in a group of nonmedicated children with pure ADHD and an age-matched control group.

METHODS: Forty-one children, 21 children with pure ADHD (9.3 ± 2.2 years, 15 boys) and 20 control children (9.3 ± 2.5 years, 10 boys), orally read a standardized text according to their age while the eye movement pattern was objectively recorded using the Visagraph Eye Movement recording system.

RESULTS: The Bayesian statistical analyses revealed that children with ADHD exhibited a significantly higher number of fixations (Bayes factor 10 [BF_{10}] = 3.39), regressions (BF_{10} = 9.97), saccades in return sweeps (BF_{10} = 4.63), and anomalies of fixations and regressions (BF_{10} = 3.66) compared with controls. In addition, children with ADHD significantly showed longer reading times (BF_{10} = 31.29), as well as lower reading rate (BF_{10} = 156.74) and grade-level equivalent (BF_{10} = 168.24) in comparison with controls.

CONCLUSIONS: Our data showed that the nonmedicated children with pure ADHD have an altered eye movement pattern during oral reading when compared with controls, which cannot be attributable to any comorbid condition. The present outcomes may help to understand the link between ADHD and reading performance and design the most pertinent strategies to enhance the reading skills of this population.

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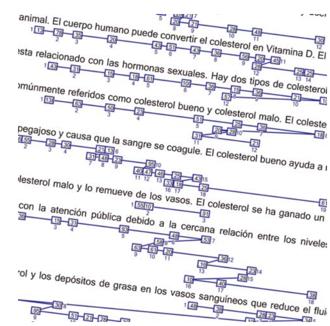

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Attention-deficit/hyperactivity disorder is an early-onset neurodevelopmental disorder characterized by impaired levels of inattention, hyperactivity, and impulsivity,[1] and its worldwide pooled prevalence is 5%.[2] Children and adolescents with attention-deficit/hyperactivity disorder have demonstrated academic underachievement in comparison with controls, with the severity of behavioral symptoms being negatively associated with school performance.[3] In this regard, a deficit in the development of executive functioning has been proposed as an explanatory model of attention-deficit/hyperactivity disorder,[4] and it seems to be a key factor for the academic underachievement.[5]

Attention-deficit/hyperactivity disorder has been commonly associated with learning disabilities[6] and particularly with reading disabilities.[7] Previous studies have stated that attention-deficit/hyperactivity disorder and reading disabilities show a comorbidity rate that ranges from 11 to 52%,[8] suggesting that attention-deficit/hyperactivity disorder symptoms have a negative impact on reading acquisition in childhood.[9] More specifically, it has been associated with a lower performance in decoding speed and text comprehension.[10] Also, eye-tracking studies have explored the specific aspects of oculomotor control on different behavioral tasks in individuals with attention-deficit/hyperactivity disorder, demonstrating the existence of abnormal eye movements (e.g., a reduced ability to suppress unwanted saccades and to control their fixation behavior voluntarily).[11,12]

A considerable number of competing explanations have been given to elucidate which causal mechanisms, at either the cognitive or biological levels, may be involved in the association between attention-deficit/hyperactivity disorder and reading disabilities.[13] A recent review of Hendren et al.[14] highlights the different areas of controversy within this comorbidity and provides directions for future research. The authors suggest that an interdisciplinary approach to this comorbid condition by mental health professionals and educators may help to develop treatment strategies to improve educational and health-related outcomes in this population.[14,15] There are studies that have reported that reading disabilities and attention-deficit/hyperactivity disorder have a common genetic etiology,[16] and relevantly, brain regions altered in attention-deficit/hyperactivity disorder (e.g., frontostriatal-cerebellar circuits) are also involved in the control of eye movements.[12] However, to date, there is no evidence whether the altered oculomotor pattern is due to a general oculomotor deficit or is secondary to a defect in the visual processing of linguistic material.[17] In addition, other authors have demonstrated that these oculomotor deficits were mostly linked to deficits in visual attention or an immaturity of the cortical areas controlling the fixation system[18] or even to an impaired or poor control of eye movements.[12] This relationship has been mainly explained by the inhibition deficits and the altered functioning of frontal lobe areas in children with attention-deficit/hyperactivity disorder.[19]

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Deans et al.[20] tested the eye movement pattern in children with attention-deficit/hyperactivity disorder and reading disabilities between the ages of 6 and 12 years while they read five sentences of first-grade reading level. They found that children with attention-deficit/hyperactivity disorder exhibited a slower reading time, longer fixation duration, and more atypical eye movements in comparison with the control group. However, the comparison between children with attention-deficit/hyperactivity disorder and reading disabilities yielded significant differences for the total reading time only, with children with attention-deficit/hyperactivity disorder reading slower than children with reading disabilities. In addition, Thaler et al.[21] compared the eye movement pattern in children with pure attention-deficit/hyperactivity disorder (i.e., free of any other comorbid condition), children with dyslexia, children with dyslexia and attention-deficit/hyperactivity disorder, and controls while reading single words, observing that children with attention-deficit/hyperactivity disorder and controls showed similar results in reading accuracy, reading times, number of fixations, and mean single-fixation duration. However, the use of brief texts and single words in these two studies may not be challenging enough because these tasks do not require high levels of concentration and sustained attention, and thus, possible attentional deficits may be irrelevant. Likewise, in Deans et al.,[20] 37% of children with attention-deficit/hyperactivity disorder were taking medication, whereas in Thaler et al.,[21] the number of children with attention-deficit/hyperactivity disorder under pharmacological treatment is not reported. This fact is of special relevance because the psychostimulants used for attention-deficit/hyperactivity disorder treatment act at the frontal area level, allowing for the reduction of the activity levels and increase of the capacity of attention,[22] which may have an impact of the eye movement pattern during reading. Indeed, previous studies have stated that medication should not be included when researching eye movement behavior to obtain data reflective of the true eye movement deficits in reading associated with attention-deficit/hyperactivity disorder.[23]

Because of limitations in these previous studies, we consider of interest to evaluate eye movements in nonmedicated children with pure attention-deficit/hyperactivity disorder during reading, to establish whether the altered oculomotor pattern observed in simple behavioral tasks with single-word reading[20,21] is also evident while reading a text with a level of difficulty adjusted to their reading skill. The assessment of reading performance with single words and short passages must not be considered interchangeably because they illustrate different aspects of the reading process.[24]

There are a few standardized tests that can be used to indirectly evaluate eye movements during nonreading tasks (e.g., Pierce Saccadic Test, the King-Devick Saccadic Test, and the Developmental Eye Movement Test), but the validity of these tests as indicators of the oculomotor behavior during reading is limited.[25–27] However, more detailed and valuable information on the reading process is gained by recording eye movement activity in real time.[28–30] The Visagraph Eye Movement recording system (Taylor Associates, New York, NY), which is based on the infrared limbal reflection technique,[31] has been identified as one clinical method that provides reliable and objective values in terms of quantitative eye movement data and reading speed.[32] This device records eye movements while the patient is reading a standardized text and displays data on the eye movement pattern during reading.

In view of the caveats found in the scientific literature about the use of inappropriate reading tasks (e.g., single words or texts not standardized by participants' age), as well as the lack of considering the presence of comorbidities or pharmacological treatments, the authors considered of relevance to test the following research questions: Can the diagnosis of attention-deficit/hyperactivity disorder in children be refined with objective eye movement testing? And more specifically, is there a difference among school-aged children with and without pure attention-deficit/hyperactivity disorder in their objective eye movements while reading aloud? Based on this, the main objective of the present study was to analyze the pattern of ocular movements while reading aloud a standardized text in nonmedicated children with attention-deficit/hyperactivity disorder, who were also free of any comorbidity, in comparison with an age-matched group of normally developing children. Based on the previous literature, we hypothesized that nonmedicated children with attention-deficit/hyperactivity disorder may present a lower oral reading performance in comparison with controls, which may be associated with an altered eye movement pattern.

METHODS

Participants and Ethical Approval

Fifty-eight children were recruited to participate in the present study (36 with attention-deficit/hyperactivity disorder and 22 controls). Children with attention-deficit/hyperactivity disorder were screened by their primary care pediatrician who referred them to the Neuropaediatric, Neuropsychology, and Early Intervention Unit of the San Cecilio University Hospital of Granada for subsequent monitoring and evaluation, to obtain a definitive diagnosis of the attention-deficit/hyperactivity disorder subtype and possible comorbidities. A thorough physical examination with a complete medical record based on the interviews to children and parents, as well as the information provided by teachers, was initially conducted. Attention-deficit/hyperactivity disorder diagnosis was performed by a clinical psychologist and neuropediatrician following the guidelines of the *Diagnostic and Statistical Manual of Mental Disorder* (Fifth Edition). In addition, a neuropsychological assessment was carried out to complement the diagnostic process and exclude comorbidities, which included the following questionnaires: the National Institute for Children's Health Quality Vanderbilt Parent Assessment Scale[33] and the National Institute for Children's Health Quality Vanderbilt Teacher Assessment Scale,[34] the Behavior Rating Inventory of Executive Functions–Parent Form,[35] the Wechsler Intelligence Scale for Children–Fourth Edition,[36] the Magallanes Scale of Visual Attention,[37] the Children's Depression Inventory,[38] and the Spence Children's Anxiety Scale.[39] Because of the lack of applicable data, no power calculations were performed. The sample size was based on a similar cohort where ocular movements were measured in children with attention-deficit/hyperactivity disorder while reading isolated words.[21]

The inclusion criteria imposed to participate in this study included no metabolic or endocrine disorders as well as other neurological diseases, which could justify the present symptoms. Specifically, all children must have a normal intelligence (intelligence quotient score >85 on the Wechsler Intelligence Scale for Children–Fourth Edition),[36] be free of any other medical or psychological condition, and not present learning disabilities, which were considered if scores were found to be in the impaired range of the multiple assessed areas (see pervious discussion). Also, preterm infants (i.e., infants born before 28 weeks' gestation) were excluded because they have demonstrated to have an increased risk of attention problems.[40] Lastly, to avoid contamination

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of the results by the effect of medication, none of children with attention-deficit/hyperactivity disorder selected for this study should ever have been treated with attention-deficit/hyperactivity disorder medication such as methylphenidate, orally administered melatonin, or any other treatment of attention-deficit/hyperactivity disorder that may disturb sleep or alter the metabolism.

Visual function was evaluated by a board-certified optometrist to children with attention-deficit/hyperactivity disorder and controls, and the following inclusion criteria were also required: (1) no presence of any ocular disease, (2) no strabismus and/or amblyopia, (3) a best-corrected distance and near visual acuity ≤0.1 logMAR (6/7.5 Snellen) in each eye, (4) near stereoacuity of 50 seconds of arc or better measures with the Randot Stereotest (Stereo Optical Company, Chicago, IL) following the recommendations of Scheiman and Wick,[41] (5) uncorrected anisometropia <2.00, and (6) belonging to the asymptomatic group of Conlon et al.[42] and Convergence Insufficiency Symptoms Survey.[43] From the total of 36 patients, 21 (58.3%) were diagnosed as having pure attention-deficit/hyperactivity disorder, whereas 15 children with attention-deficit/hyperactivity disorder did not accomplish the inclusion criteria (5 children presented with amblyopia; 6, dyslexia; 1, amblyopia and low intelligence quotient; 1, dyslexia and amblyopia; and 2, low intelligence quotient). In the control group, two children presented with amblyopia and were also excluded from further analysis.

Finally, a total of 41 children took part in this study, 21 children with attention-deficit/hyperactivity disorder (mean ± SD age, 9.3 ± 2.2 years, 15 boys and 6 girls) and 20 control children (9.3 ± 2.5 years, 10 boys and 10 girls). Before the commencement of the study, parents or tutors received detailed instructions and signed an informed consent form. The study was approved by the local ethical committee of biomedical research of the University of Granada (institutional review board approval: 546/CEIH/2018) and adhered to the guidelines of the Declaration of Helsinki.

Procedures

Upon arrival to the laboratory, all children underwent an optometric examination, which included: (*a*) direct ophthalmoscopy to detect any ocular pathology; (*b*) cover test to determine the presence of ocular deviation; (*c*) monocular and binocular distance visual acuity (5 m) using the logarithmic letters chart test with the Bailey-Lovie design in a computerized monitor (POLA VistaVision; DMD Med Tech SRL, Torino, Italy), as well as monocular and binocular near visual acuity (40 cm) using a near test with logarithmic letters and the Bailey-Lovie design; and (*d*) objective noncycloplegic ocular refraction using the Grand Seiko WAM-5500 autorefractor in static mode (Grand Seiko Co. Ltd., Hiroshima, Japan). Participant's spherical equivalent of each eye was calculated as the mean value of three consecutive measurements: (*e*) monocular and binocular noncycloplegic subjective refraction or overrefraction was measured considering an end point criterion of maximum plus consistent with best vision; (*f*) overrefraction through +2.00-D fogging lenses using the WAM-5500 open-field autorefractor was measured to discard the presence of latent hyperopia[44]; (*g*) static near stereoacuity was measured to 40 cm using the Randot Stereotest Circle (Stereo Optical Company, Chicago, IL); and (*h*) the Mallet near-unit disparity test was used to measure lateral fixation disparity.[45] Participants were compensated with their ocular refraction if needed, and the trial frame was adjusted for their interpupillary distance and pupil heights to avoid prismatic effects. After 5 minutes of wearing the optical correction, visual acuity was again evaluated, and we ensured that subjects felt comfortable with their new correction, and it was used during experimental session (two children in each group required a new optical correction).[46]

Eye Movements Assessment in Reading

The Visagraph system was used to obtain the objective assessment of the eye movement pattern during reading.[47] Following the procedures described in the Visagraph user's manual, the comprehension passages were long texts composed of a series of sentences of different levels in accordance with children's age, within a range of length and legibility (according to INFLESZ scale[48]) from 67 to 123 words and from 90.6 to 62.6, respectively. During the reading task, the Visagraph records eye movements at a frequency of 60 Hz and automatically computes various reading performance measures such as the following: (*a*) the visual coordination, ocular motility, and precision in tracking; (*b*) perceptual development that tests the accuracy in visual discrimination and word recognition automaticity; and (*c*) information processing competence that shows efficiency in the use of short-term memory and language experience. Participants were comfortably seated at 40 cm from the reading text, which was positioned below the subject's horizontal line of sight and placed on a 30° slant board. All measures were performed under constant photopic illumination conditions (142 ± 3 lux, as measured in the corneal plane; Illuminance meter, T-10; Konica Minolta Inc., Tokyo, Japan) and in an isolated room to avoid any possible distraction or noise. Proper positioning of the Visagraph goggles was obtained for each child. When the child was wearing eyeglasses (five in the group of children with attention-deficit/hyperactivity disorder and six in the control group), the Visagraph was carefully adjusted based on the manufacturer's instructions, and we checked that traces of the two eyes on the screen were valid recordings.[47]

Following the instructions of the Visagraph system and aiming to control for the confounding effect of reading level, all children performed a comprehension test before the commencement of the Visagraph assessment to adjust text difficulty with child's knowledge. After reading the corresponding text, children had to correctly answer 7 of 10 true/false comprehension questions. When they did not achieve seven correct answers, another text of an easier comprehension level was chosen, and the procedure was repeated until achieving a minimum of seven correct answers. This allowed us to ensure that text complexity was individually adjusted, and the child was attentively reading the text for comprehension.

The Visagraph analysis program directly provides a wide range of reading-related parameters such as the number of fixations and regressions per 100 words, the return sweep saccades (slightly oblique saccadic eye movement that reflect the shift the eyes make from the end of one line to the beginning of the next line of text), the average duration of fixations (time interval that the eye pauses or remains fixated on a word), and the reading rate (number of words read per minute). The reading program software also infers the grade-level equivalent (reading eye movement efficiency), which is calculated by using a relative efficiency formula [Reading rate/(fixations per 100 words + regression per 100 words)], and then this value is converted to a grade-level equivalent score using normative values provided by Taylor,[47] ranging from 1 to 18. This last value indicates whether performance is below average for their age or school grade level. The Visagraph software also calculates

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the ratio between regressions and fixations, which is defined as the percentage of the number of fixations by the number of regressions performed. The number of fixation and regression anomalies, as well as the combination of both, is also provided by the reading program software. In the fixation anomalies, one eye moves forward to correctly perform the fixation, and the other does not perform a correct movement, whereas in the regression anomalies, one eye does not perform correctly the regression movement. Also, the Visagraph provides the anomalies of both (fixation and regression), with this value indicating that both eyes are moving in the opposite direction. Lastly, the spent reading time is the amount of time in seconds that the child needs to read the text.

Experimental Design and Statistical Analysis

A between-group design was used to test the eye movement pattern and efficiency in reading between a group of nonmedicated children with pure attention-deficit/hyperactivity disorder and an age-matched control group. The group (attention-deficit/hyperactivity disorder vs. control) was the only between-subject factor, and all the parameters given by the Visagraph software were considered as the dependent variables.

Bayesian statistic was used given its advantages over classical "frequentist" statistics.[49] Notably, the Bayesian framework permits a consistent determination of whether nonsignificant results confirm the null hypothesis, or whether data are just insensitive by the interpretation of the Bayes factor. In this study, we considered that the null and alternative hypotheses were nested because of the lack of previous data, and thus, an objective prior was used for all the analyses.[50]

Bayesian *t* tests for independent samples, considering a default Cauchy prior width of $r = 0.707$, were individually carried out for all the parameters tested to assess the differences between groups (attention-deficit/hyperactivity disorder vs. control). Here, we used Bayes factor 10, which considers the alternative hypothesis against the null hypothesis, and we followed the recommendations given by Wetzels et al.[51] about the evidence categories for Bayes factor. Therefore, Bayes factor 10 values of 3 or more and 0.33 or less were considered for accepting the alternative and null hypothesis, respectively. Values between 3 and 1/3 were considered insensitive for accepting any of the two hypotheses.[49] It should be noted that the Bayesian statistic is comparative in nature, and therefore, the Bayes factor 10 should be interpreted as a ratio that reveals the amount of evidence in favor of the alternative or null hypothesis.[50] In addition, the effect sizes (Cohen *d*) were calculated and interpreted as negligible (<0.2), small (0.2 to 0.5), moderate (0.5 to 0.8), and large (≥0.8) based on recommendations of Cohen.[52] Statistical analyses were performed using the JASP statistics package (version 0.8.5.1; JASP Team, Amsterdam, The Netherlands).

RESULTS

First, we confirmed that there were no significant differences in age and optometric clinical measures between groups (Bayes factor 10 <3 in all cases). Participants' characteristics and clinical measures are reported in Table 1.

Table 2 shows descriptive values (mean ± SD), as well as statistical indices (Bayes factor 10 and Cohen *d*) from the comparison between groups (attention-deficit/hyperactivity disorder vs. control). The interpretation of the Bayes factor 10 permitted us to accept the alternative hypothesis (significant changes) for the number of fixations and regressions per 100 words, reading rate, grade-level equivalent, the relation between anomalies of fixations and regressions, and saccades in return sweeps (Bayes factor 10 >3 in all cases; Fig. 1). For its part, the null hypothesis was confirmed for the percentage of the relationship between regression and fixation (Bayes factor 10 = 0.34; effect size, 0.15) and, as expected, for the grade level of text, which is based on the age of participants (Bayes factor 10 = 0.32; effect size, −0.09). Data from the fixation duration, anomalies of fixations and regressions, and percentage of correct answers were insensitive for accepting the null or alternative hypothesis (Bayes factor 10 between 0.33 and 3 in all cases). On the other hand, spent reading time in children with attention-deficit/hyperactivity disorder was significantly higher in comparison with control children (Bayes factor 10 = 31.29; effect size, 1.11). No significant differences were found for text comprehension between children with attention-deficit/hyperactivity disorder and controls (percent of correct answers, 79.1 ± 23.4 and 81.5 ± 14.2, respectively; Bayes factor 10 = 0.44).

DISCUSSION

The present study aimed to compare the eye movement pattern during oral reading between nonmedicated children with pure attention-deficit/hyperactivity disorder and an age-matched control group. Our data demonstrated that the Visagraph Eye Movement recording system could be a good objective eye movement testing to refine attention-deficit/hyperactivity disorder diagnosis. For the primary outcomes of the Visagraph, children with attention-deficit/hyperactivity disorder showed a greater number of fixations and regressions, as well as a lower reading rate (words per minute). Also, for the measures derived from the reading program software, children with attention-deficit/hyperactivity disorder had more saccades in return sweeps and anomalies of fixations and regressions, whereas they exhibited a worse grade-level equivalent when compared with controls (Bayes factor 10 >3 in all cases). These findings show that nonmedicated children with pure attention-deficit/hyperactivity disorder present a deficient eye movement pattern during oral reading associated with a worse level of reading skill.

The assessment of eye movements may disclose some cues from the pathophysiology of attention-deficit/hyperactivity disorder. Generally, eye movement researchers focus their attention on the analysis of executive functions on attention-deficit/hyperactivity disorder to verify the hypothesis that the motor system, controlled by the prefrontal area, is altered in attention-deficit/hyperactivity disorder. Notably, fixations are strongly related to direction of attention in reading,[53] and the use of excessive fixations and regressions for word recognition results in a reduction of reading speed and performance.[54] As reading skill increases, natural development of eye movements implies a decrease in the number of fixations and regressions. These reading skills are related to the developmental stage, and normative reading values are attributed according to age.[17] Based on the fact that task complexity affects the oculomotor behavior, both experimental groups were age matched, and also reading complexity was individually adjusted for each child, depending on their reading level. Several studies have shown that subjects with attention-deficit/hyperactivity disorder present an abnormal oculomotor behavior, which has been associated with deficits in the inhibitory mechanisms involved in the saccades and fixations control during highly simplified visual tasks.[11,12,23] Indeed, psychophysical and imaging studies support the idea that the shifts in attention are usually reflected in the pattern of ocular fixations.[55] As indicated by Rayner,[17] attentional movements and saccades are

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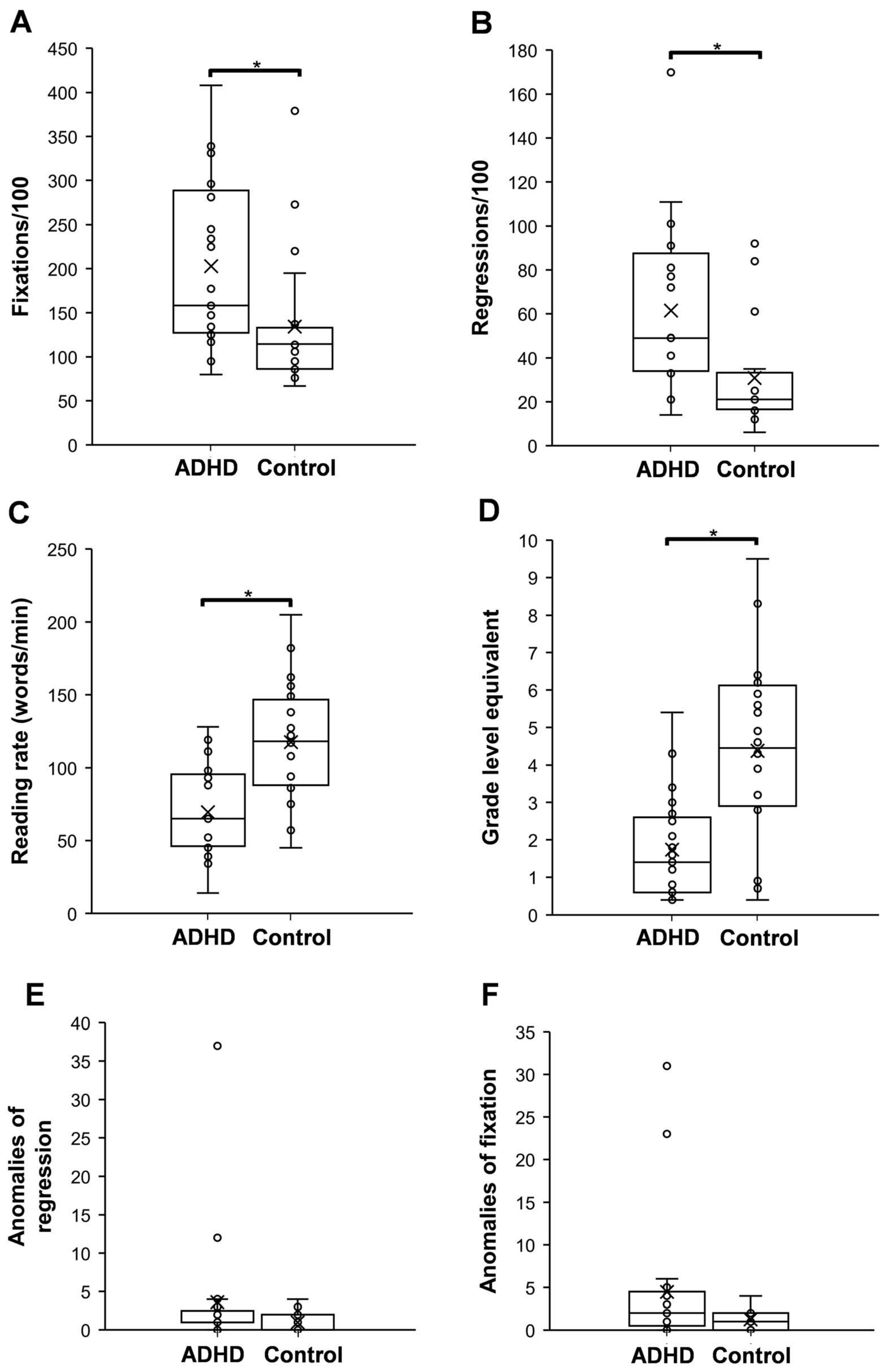

FIGURE 1. Scatterplot and boxplot of the eye movement and reading efficiency parameters for the attention-deficit/hyperactivity disorder (ADHD) and control groups. (A) Number of fixations per 100 words. (B) Number of regressions per 100 words. (C) Reading rate (number of words per minute). (D) Grade-level equivalent (reading eye movement efficiency). (E) Number of regression anomalies. (F) Number of fixation anomalies. (G) Number of fixations and regressions anomalies. (H) Fixations duration. (I) Relation between regressions and fixation. (J) Number of saccades in return sweeps. Spent reading time (K) and grade level (L) of text. *Acceptance of the alternative hypothesis (Bayes factor 10 > 3). The whiskers represent the interquartile range, and horizontal lines indicate the median value.

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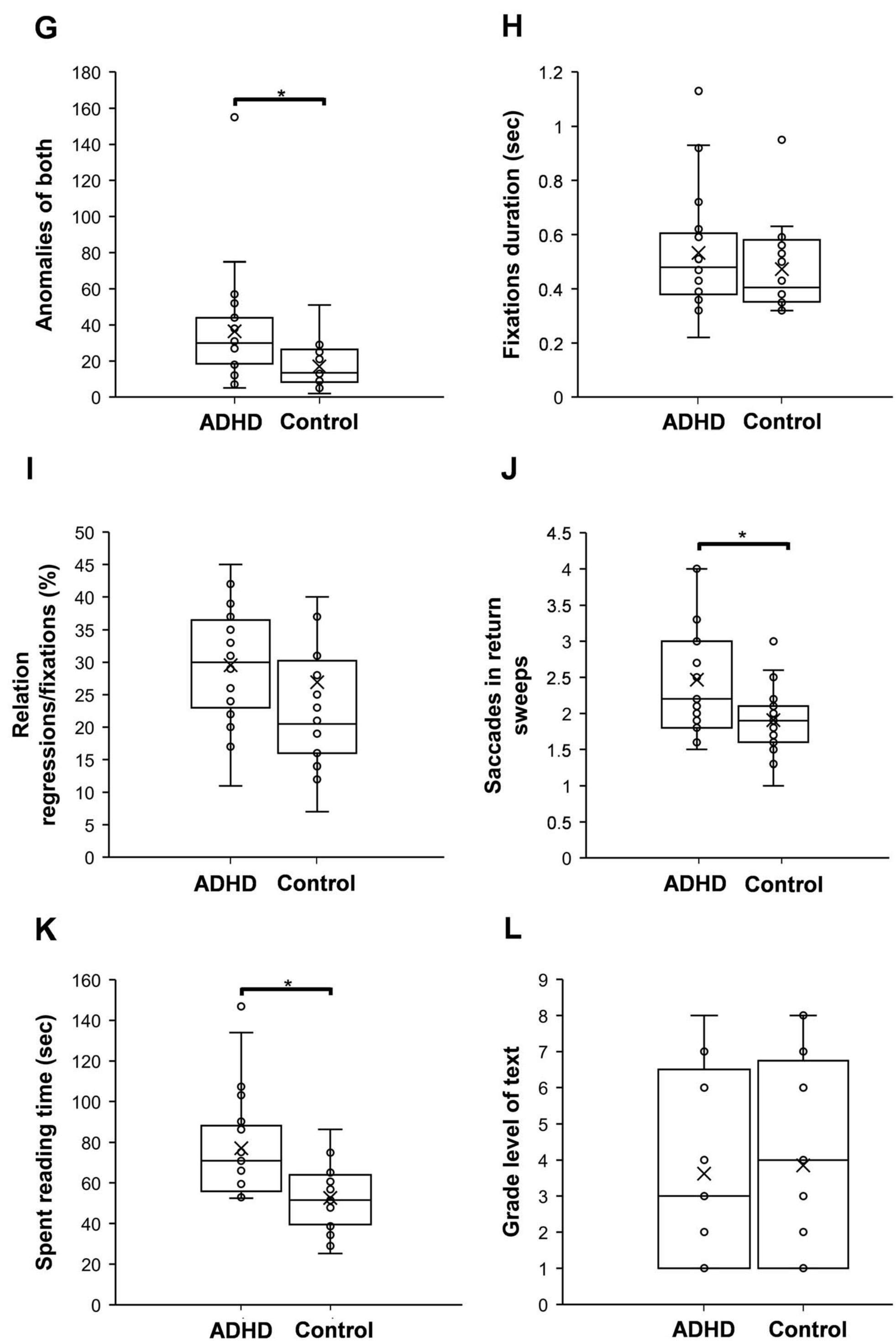

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TABLE 1. Descriptive characteristics and optometric clinical measures for the ADHD and control groups

	ADHD (n = 21), mean ± SD	Control (n = 20), mean ± SD	BF_{10}	ES (90% CI)
Age (y)	9.3 ± 2.2	9.3 ± 2.5	0.31	0.01 (–0.50 to 0.53)
Sex (% female)	28.6	50.0	—	—
Ocular refraction, right eye (SE; D)	0.35 ± 0.81	0.07 ± 0.48	0.64	0.43 (–0.09 to 0.95)
Ocular refraction, left eye (SE; D)	0.52 ± 1.01	0.19 ± 0.44	0.62	0.42 (–0.11 to 0.93)
Distance-corrected VA (logMAR)	–0.13 ± 0.25	–0.11 ± 0.06	0.31	–0.08 (–0.59 to 0.43)
Near-corrected VA (logMAR)	0.01 ± 0.03	0.01 ± 0.02	0.00	–0.17 (–0.70 to 0.36)
Distance horizontal phoria to 5 m (Δ)	0.55 ± 2.20	0.15 ± 0.46	0.39	0.25 (–0.27 to 0.76)
Near horizontal phoria to 0.4 m (Δ)	–1.26 ± 2.08	–0.38 ± 1.82	0.70	–0.45 (–0.97 to 0.71)
Horizontal fixation disparity (Δ)	–0.10 ± 0.91	–0.10 ± 1.17	0.31	0.00 (–0.53 to 0.52)
Stereopsis (seconds of arc)	35.7 ± 21.4	34.3 ± 14.4	0.31	0.08 (–0.44 to 0.59)

ADHD = attention-deficit/hyperactivity disorder; BF_{10} = Bayes factor 10; CI = confidence interval; D = diopter; ES = effect size (Cohen *d*); MAR = minimum angle of resolution; SE = spherical equivalent, VA = visual acuity; Δ = prism diopter.

closely coupled in tasks requiring complex information processing such as reading.

In this particular case, when comparing the reading skills of nonmedicated children with pure attention-deficit/hyperactivity disorder and a control group with the same age range, we found a higher number of fixations and regressions in the first group, indicating a reading development below age-related normative values and a pattern of declining reading efficiency in children with attention-deficit/hyperactivity disorder. In this regard, a higher number of ocular regressions and fixations have been linked to reading processing difficulty and comprehension in the scientific literature.[56] Relevantly, our results seem to be in accordance with these findings because the number of fixations showed a negative correlation with the reading rate and grade-level equivalent ($r = –0.65$ and $r = –0.76$, respectively), the number of regressions was negatively associated with the reading rate and grade-level equivalent ($r = –0.69$ and $r = –0.75$, respectively). There was also a negative relationship of spent reading time with the reading rate and grade-level equivalent ($r = –0.53$ and $r = –0.38$, respectively). The spent reading time showed a modest positive association with number of fixations ($r = 0.20$), regressions ($r = 0.31$), saccades in return sweeps ($r = 0.50$), and the anomalies of fixations and regressions ($r = 0.49$; Bayes factor 10 >3 in all cases). Taken together, the present findings indicate that a worse reading efficiency is linked with a poor eye movement pattern.

There is evidence of a bidirectional relationship between reading fluency and comprehension, with a poor reading fluency constituting a major barrier to reading comprehension.[57] As stated previously, children with attention-deficit/hyperactivity disorder needed more time than did controls to complete the reading task, suggesting that slow readers may require a high mental effort on decoding and word recognition. Cognitive resources are limited for reading understanding, and thus, slow readers find more difficulties to retain long and complicated sentences.[58] Previous studies that focused on the association between attention-deficit/hyperactivity disorder and reading comprehension have reported controversial

TABLE 2. Descriptive (mean ± SD) and statistical values of reading-related parameters for the ADHD and control groups

Reading-related parameters	ADHD (n = 21), mean ± SD	Control (n = 20), mean ± SD	BF_{10}	ES (90% CI)
Fixations/100	203 ± 96	134 ± 78	3.39*	0.78 (0.24 to 1.31)
Regressions/100	61.5 ± 38.1	30.9 ± 24.3	9.97*	0.95 (0.40 to 1.49)
Fixations duration (s)	0.53 ± 0.22	0.47 ± 0.16	0.45	0.31 (–0.21 to 0.82)
Reading rate (words/min)	69.4 ± 30.7	117.5 ± 41.9	156.74*	–1.32 (–1.88 to –0.74)
Grade-level equivalent	1.74 ± 1.39	4.38 ± 2.48	168.24*	–1.32 (–1.89 to –0.75)
Relation regressions/fixations (%)	29.5 ± 8.7	26.9 ± 23.0	0.34	0.15 (–0.36 to 0.67)
Anomalies of fixation	4.48 ± 7.80	1.25 ± 1.07	1.14	0.57 (0.04 to 1.09)
Anomalies of regression	3.62 ± 8.07	1.00 ± 1.34	0.69	0.45 (–0.08 to 0.97)
Anomalies of both	36.5 ± 32.1	17.0 ± 11.9	3.66*	0.80 (0.26 to 1.33)
Correct answers (%)	79.1 ± 23.4	81.5 ± 14.2	0.44	–0.12 (–0.64 to 0.39)
Grade level of text	3.62 ± 2.54	3.85 ± 2.66	0.32	–0.09 (–0.60 to 0.43)
Saccades in return sweeps	2.47 ± 0.77	1.91 ± 0.47	4.63*	0.88 (0.31 to 1.44)
Spent reading time (s)	77.1 ± 26.3	52.7 ± 16.1	31.29*	1.11 (0.55 to 1.66)

"Anomalies of both" refers to anomalies of fixations and regressions. *The alternative hypothesis is accepted ($BF_{10} > 3$). ADHD = attention-deficit/hyperactivity disorder; BF_{10} = Bayesian factor 10; CI = confidence interval; ES = effect size (Cohen *d*); n = number of participants.

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findings,[7] and most of them agree that working memory deficits, which are typical among children with attention-deficit/hyperactivity disorder, are tightly linked to poor reading comprehension.[7,16,59] Although it was beyond the aims of this study, no significant differences between groups were found for reading comprehension because this variable was used to guarantee an adequate comprehension of the text. Of note, we found a lower grade-level equivalent in children with attention-deficit/hyperactivity disorder in comparison with the control group. Indeed, the control group showed a grade-level equivalent score according to their age (4.38 ± 2.48; note that, in relation to the average age of both groups, they were in fourth grade); however, grade-level equivalent was 60.3% lower for the children with attention-deficit/hyperactivity disorder (1.74 ± 1.39) in relation to the control group. This could lead to considerably lower academic achievements because children who continually struggle with text tend to become frustrated and avoid reading.[60]

Longer fixations are characteristic of less skillful readers and reflect, for example, less familiarity with vocabulary and an inability to use textual context.[61] In the current study, no significant difference for fixations duration between groups was obtained, and therefore, it could indicate that the slower reading rates (less words per minute) found in children with attention-deficit/hyperactivity disorder were due to the higher number of fixations, regressions, and saccades in return sweeps, instead of being due to longer fixations. Fixation duration has shown to be linked to attentional and behavioral control,[62] and the similar results found for this parameter in children with attention-deficit/hyperactivity disorder and controls during oral reading may vary with silent reading because this modality (silent reading) could be less engaging and is associated with faster reading and poorer comprehension.[20,63] Based on our findings, the greater number of anomalies of fixations and regressions found in children with attention-deficit/hyperactivity disorder in comparison with controls might explain in part the differences found between groups. Furthermore, there are other possible causes that should be taken into account. For example, binocular vision anomalies (e.g., convergence insufficiency) may provoke reading impairments, although visual therapy permits to improve vergence and reading performance.[64] Future studies are required to elucidate the possible association between binocular vision anomalies and altered eye movement pattern on children with attention-deficit/hyperactivity disorder, as well as the effects of visual therapy on the oculomotor behavior during reading and its impact on academic performance.

Reading requires the integration of a significant number of brain networks, including the visuomotor, memory, and attentional systems.[65] Accurate eye movements are needed for reading, and they are highly dependent on neural maturity.[66] Most studies on brain function and anatomy have found that children with attention-deficit/hyperactivity disorder present a reduced volume of the prefrontal cortex in relation to controls,[67] which is an area specially involved in the attentional process and eye movement control.[12] Future studies are required to elucidate not only the functional relationship between attention and ocular movement control but also the functional connection between the frontal and occipital cortices (visual processing area) in these patients, which has been shown to be altered in attention-deficit/hyperactivity disorder.[68]

Limitations and Future Research

Here, we compared the eye movement pattern during oral reading between nonmedicated children with pure attention-deficit/hyperactivity disorder and an age-matched control group with the use of the Visagraph Eye Movement recording system. However, the results of this study should be considered with caution in light of some potential limitations. The main limitation of the present study is that we did not obtain basic eye movement measurements such as fixation, prosaccades, antisaccades, and pursuits, which would permit to ascertain whether the altered eye movement pattern observed in children with pure attention-deficit/hyperactivity disorder is due to alterations in the mechanisms of eye movement control or delays in reading acquisition. Also, the differences observed in gaze behavior could be explained by the reading skill differences. The inclusion of a control group matched in reading level with the attention-deficit/hyperactivity disorder group may be of interest in this regard. Another possible limitation is that we used relatively short sentences and passages to assess the reading fluency, and therefore, the predictors of fluency could be different if longer texts are used. In addition, we did not carry out a previous control on the vocabulary level or working memory capacity for each child, and it would allow us to obtain a solid conclusion in parameters such as reading comprehension. In this study, we used fogging lenses to discard the presence of latent hyperopia instead of cycloplegic refraction, and it may be considered as a limitation of this study. There are multiple neurocognitive skills that are known to be associated with attention-deficit/hyperactivity disorder (e.g., cognitive flexibility, sustained attention, response inhibition, working memory, etc.), and thus, we consider of interest to assess whether deficits in these neurocognitive skills may be associated with reading performance and oculomotor behavior during reading.[13] Lastly, to control the attention of the children, all of them read aloud the passages, and therefore, the reading aloud could have influenced in the reading efficiency of one or both groups because it has been demonstrated that as children generally read aloud, because of the additional articulatory demands between eye and voice, the reading speed is slower,[69] and this fact could mask the differences in fixation duration between groups. The ability to verbalize visual information (i.e., rapid automated naming) has demonstrated to be deficient in children with attention-deficit/hyperactivity disorder,[70,71] and thus, future studies should consider to control this factor. It should be noted that our data cannot definitively determine the causal directionality between an altered eye movement pattern and reading performance in children nonmedicated with pure attention-deficit/hyperactivity disorder. Children with attention-deficit/hyperactivity disorder may present a slower reading development that would be explained by a different pattern of eye movements or vice versa. Future longitudinal studies would be of vital importance to determine the association between attention-deficit/hyperactivity disorder and low reading efficiency, as well as the most appropriate management (e.g., medication, neurofeedback, visual therapy, physical activity, etc.) to reduce the undesirable effects of attention-deficit/hyperactivity disorder (e.g., symptoms, poor reading skills, academic underachievement, etc.). Importantly, there is recent evidence on the positive effect of methylphenidate on eye movement behavior in children with attention-deficit/hyperactivity disorder because its administration is linked with improvements in the functioning of the frontal lobe, which permits a better consistency of motor responses and oculomotor performance.[23,72] Here, we controlled this effect by considering only nonmedicated children with attention-deficit/hyperactivity disorder, and future studies should explore the influence of attention-deficit/hyperactivity disorder medication (i.e., methylphenidate) on the eye movement pattern

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during reading in children with pure attention-deficit/hyperactivity disorder. Also, in the same area, neurofeedback and physical activity have been incorporated as possible strategies to mitigate the symptoms and improve behavioral and cognitive performance of attention-deficit/hyperactivity disorder,[73] and their possible benefits on eye movement in attention-deficit/hyperactivity disorder remain unknown. Future research is also guaranteed in this regard. Lastly, we consider that the evaluation of the eye movement pattern during reading by the incorporation of the Visagraph Eye Movement recording system in clinical settings could help in the diagnosis of attention-deficit/hyperactivity disorder or other neuropsychological conditions (e.g., dyslexia).

CONCLUSIONS

Our data indicate that nonmedicated children with pure attention-deficit/hyperactivity disorder present an altered eye movement pattern (more fixations, regressions, saccades in return sweeps, and anomalies of fixations and regressions) during oral reading in comparison with a control group. Accordingly, children with attention-deficit/hyperactivity disorder demonstrated worse reading efficiency and spent more time to complete the reading task. The present findings have potential impacts on the association between attention-deficit/hyperactivity disorder and reading performance, which could have a direct influence on the academic achievement of children with attention-deficit/hyperactivity disorder. The Visagraph Eye Movement recording system is a useful tool to assess the eye movement pattern during reading in the clinical practice. Future studies should address which are the most appropriate strategies (e.g., medication, visual therapy, biofeedback, physical activity, etc.) to improve the eye movement pattern in attention-deficit/hyperactivity disorder, aiming to reduce the adverse consequences of poor reading performance on academic achievements in this population.

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