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Title: Eye Movements during Sentence Processing in High-Functioning Autistic Children Compared to Neurotypical Peers: An Eye Tracking Study

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Abstract

Background: Autism spectrum disorder (ASD) is a neurodevelopmental disorder. The pattern of eye movements during reading can significantly impact reading quality. This study aimed to examine the eye movement patterns, which are essential for reading, in children with ASD as compared to their neurotypical peers.

Methods: This study focused on two crucial indicators that influence reading: eye fixation time and saccade movement. Comparison of parameters of saccade movements and eye fixation in a sentence reading task was done between two groups using an eye tracker device. autistic chidren (15 children, average age: 102.33months) and their neurotypical peers (17 children, average age: 101.69 months) participated in this study.

Results: The results showed that compared to their neurotypical peers, children with ASD have lower amplitude while reading sentences (P.Value : 0.02).These children used more number of fixations to read the words in the sentence (P.Value : 0.02). Comparing the total time spent to read a sentence between the two groups shows that autistic children need more time to read a sentence (P.Value : 0.02).

Discussion: these results suggest that low-level sensorimotor processes involved in generating accurate eye movements such as dorsal visual pathway and cerebellum can significantly impact the reading quality of children with ASD.

Keywords: High-functioning autism, Eye tracking, Reading, Eye movements, Saccadic eye movements, Sensory motor integration

Introduction

Autism spectrum disorders (ASD) are a collection of neurodevelopmental conditions characterized by impairments in social interaction, communication, repetitive behaviors, and limited interests. In 2021, the Centers for Disease Control and Prevention (CDC) reported that approximately 1 in 44 children in the United States is diagnosed with an autism spectrum disorder (ASD(Baio et al., 2018) .ASD is a lifelong condition, and individuals with ASD face significant challenges in all stages of development. Recent research has focused on the academic achievements of individuals with autism, particularly in the early years of education when acquiring reading, writing, and mathematics skills can be extremely challenging. These skills are crucial for social participation and achieving independence.

The CDC has stated that approximately 68% of school children with ASD exhibit cognitive abilities beyond the range of intellectual disability, meaning they have an IQ above 70(Seltzer, Shattuck, Abbeduto, & Greenberg, 2004). Despite having normal IQ ranges, these individuals often display limited verbal abilities at the sentence level. However, their academic and social outcomes are far from optimal. Many children with ASD, despite having an average IQ, show a discrepancy between their academic performance and achievement, which resembles specific learning disabilities. Notably, difficulties in reading comprehension and understanding written text have been a focal point, even when these students can read individual words proficiently(Huemer & Mann, 2010; Jones et al., 2009).

The "simple reading view"(Gough & Tunmer, 1986) proposes that skilled literacy relies on two closely interconnected processes: decoding or identifying individual words and engaging in language processes that construct meaningful text. Both processes are necessary for comprehension. Without adequate word-level reading skills, comprehension is likely to fail. However, skilled word-level reading in isolation does not guarantee understanding at the text level. Decoding and comprehension are believed to depend on underlying language skills. Consequently, there may be three potential subgroups that experience difficulties with reading comprehension: (a) individuals with strong decoding skills but poor oral language skills, (b)

individuals with strong oral language skills but deficits in decoding, and (c) individuals who struggle with both oral language and decoding(Catts, Hogan, & Fey, 2003) .

Most previous studies on reading in children with ASD have focused on a specific subgroup characterized by the ability to decode words but difficulty comprehending written text, often referred to as hyperlexia(Newman et al., 2007) .These studies have specifically examined inconsistencies in reading comprehension and decoding ability within average samples(Jones et al., 2009). Children with ASD are often reported to have advanced word-reading abilities at an early age(Grigorenko, Klin, & Volkmar, 2003). However, these early developments may be hindered by long-term deficits in word reading and reading comprehension(Nation & Snowling, 1999). In a study exploring reading profiles in ASD, Nation, Clarke, Wright, and Williams (2006) discovered that many children with ASD struggled with both decoding and comprehension. Around 65% of the cohort exhibited poor reading comprehension, often alongside poor word-level reading skills. Notably, the most significant finding of Nation et al.'s (2006) study was the substantial variation observed, with a wide range of performance levels seen across most reading and reading-related measures. However, the extent of this discrepancy varies widely, possibly due to the specific characteristics of the individuals being studied(Saldaña & Frith, 2007) (Newman et al., 2007) (Ricketts, Jones, Happé, & Charman, 2013) (Nation, Clarke, Wright, & Williams, 2006) (Jones et al., 2009).

Eye movements play a crucial role in the process of reading, consisting of three primary components: saccade, fixation, and regression. During fixations, new information is encoded as vision is suppressed during saccades. Although the size of saccades and the duration of fixations may vary, this pattern of eye movements remains consistent across various visual-cognitive tasks, driven by the same neural circuitry. As visual limitations heavily influence eye movement behavior, it is unsurprising that general similarities are observed. In reading, linguistic factors such as word frequency, predictability, and syntactic complexity impact moment-to-moment eye movements.(Rayner, 1978, 2009) . Despite the association between eye movement patterns and reading skills(Irwin, 2004), eye movements are seldom considered the root cause of reading difficulties. Research on eye movements ranges from perceptual issues to theoretical and computational models of eye movement control during reading. One crucial question is whether

eye movements in reading are governed by low-level motor strategies or influenced by cognitive processes in real-time. (Reichle, Pollatsek, Fisher, & Rayner, 1998).

While some studies have explored eye movement characteristics in individuals with autism spectrum disorder (ASD), they primarily utilized stimuli with limited content, such as solely faces(Arkush, Smith-Collins, Fiorentini, & Skuse, 2013; Harms, Martin, & Wallace, 2010) , and few open datasets are available. Eye-tracking research has also examined attention shifting and disengagement in ASD, with recent research (Manyakov et al., 2018)documenting fewer shifts and longer disengagement time in response to pictures considered of high interest (e.g., trains, cars) in adolescents and adults with ASD—a finding consistent with earlier work linking atypical shifting and disengagement to circumscribed interests in children with ASD(Sasson, Elison, Turner-Brown, Dichter, & Bodfish, 2011) .

 The cause of reading comprehension problems in people with autism spectrum disorder (ASD) is debatable. have investigated the ability of autistic children to adapt reading strategies based on different reading goals using eye-tracking technology. The effect of reading purposefulness on number of fixations (Micai, Vulchanova, & Saldaña, 2021) (Drysdale, Furlonger, Anderson, & Moore, 2022), duration of fixations, number of forward fixations, length of forward saccade was reported(Micai et al., 2021). (Micai, Joseph, Vulchanova, & Saldaña, 2017). Interestingly, more fixations were observed for the purposeful reading of the text compared to the entertainment-only condition in the control group(Micai et al., 2021) . children with HFASD are able to make the necessary inferences to understand reading. Eye movement data showed that children with HFASD spent more time fixating on the text, had more fixations overall, and made more regressions during reading (i.e., moving backward through the text) than neurotypical peers (Sansosti, Was, Rawson, & Remaklus, 2013).

Nonetheless, studies indicate that individuals with ASD exhibit differences in decoding written language and lexical acquisition, yet they can read words within sentences. The question remains as to whether the delayed semantic processing and comprehension of sentences in individuals with ASD are attributable to higher-level language learning phenomena or if lower-level sensorimotor skills when extracting visual information from written language contribute to the

performance disparities and subsequent linguistic processing slowness. Consequently, this study aims to investigate the eye movement characteristics and lower sensory motor skills employed while reading sentences in children with autism.

Method

Participants

The researcher recruited a group of children diagnosed with high-functioning autism disorder (n=15) with an average age of 102.3 months. Diagnosis was conducted by a child and adolescent psychiatrist using the DSM-V diagnostic criteria. In addition to the psychiatrist's opinion, the Garez 3 scale has been used to diagnose autism. In this scale, scoring 50 to 70 is mild autism or level 1. In the articles, high functioning autism is used as equivalent to level 1 autism. control group of typically developing children (n=17) from primary schools, with an average age of 101.10 months, participated in the study. The control group had no recorded developmental disorders according to their health records. Written consent was obtained from both the participants and their parents for their involvement in the study. Parents were asked to rate their child's behavior using the Gilliam Autism Rating Scale. It is important to note that the autistic children did not take any medication during the study.

Procedure

The research involved a two-hour session during which the Wechsler IQ test was administered. On a separate day, the children were present to record their eye movements. The children with autism, along with their neurotypical peers, had recently entered public schools after completing six years of education. One of the criteria for entry into the study was that none of the children had repeated any academic classes. This was crucial to minimize any potential learning effects on the task. The autistic children were referred to the researcher from General Hospitals in Tehran.

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Measures

The Gilliam Autism Rating Scale, Third Edition (GARS-3)

Gilliam developed the GARS-3 scale by extracting questions from the DSM V diagnostic criteria and the American Autism Association definition (Gilliam, 2014). The aim was to create a tool with high validity and content. The scale consists of 56 questions, rated on a four-point Likert scale ranging from 0 to 3. The GARS-3 includes six subscales: Repetitive/restrictive behaviors, social communication, social interaction, emotional responses, maladaptive speech, and cognitive style. In this study, we utilized the standardized Iranian version of the GARS-3 scale.(Minaei & Nazeri, 2018)

The GARS-3 scale was administered to all participants in the research. Individuals with autism who scored between 50 and 70 were diagnosed with ASD-level 1 autism, as shown in table 1 and table 2. None of the autistic children were prescribed medication.

Wechsler Intelligence Scale for Children (WISC IV)

An expert psychologist administered the Wechsler Intelligence Scale for Children (WISC) to both groups. Autistic children who achieved a score higher than 90 on the Wechsler intelligence test were eligible to participate in the study. The standardized Iranian version of the test was used (table 1 -2). We have used the standardized version of this test in Iran(Abedi, Sadeghi, & Rabiei, 2015)

Task

The task consisted of 40 sentences, with 12 sentences containing 8 words, 15 sentences containing 7 words, 9 sentences containing 6 words, and 4 sentences containing 5 words. These sentences were displayed on a monitor screen and were selected from the reading skills book used in the second year of primary school. The selected words had a high frequency of occurrence as they were taken from the second-grade Persian reading book.

Only nouns and verbs were included among the selected words to ensure control over the semantic load and objectivity. Iranian linguistics and speech therapy experts were consulted to

determine the objectivity of the words, using a 5-point Likert scale. Words with a score of more than 2.5 on the scale were agreed upon for use. Subsequently, 130 neurotypical children aged 8 to 10 years were asked to rate these words based on their degree of objectivity. From the initial pool of 280 words, 160 words with objectivity scores above 2.5 were selected to form the sentences. These sentences were well-known and had low emotional value.

During the experiment, the participants' left eye was tracked using a remote monocular eye-tracker (Segal Tracker iSaw, FARMED, Tehran, Iran) with a sampling frequency of 500 Hz. The stimulus presentation was regulated using the Psychopy framework. The stimuli were displayed on a screen measuring 57 by 43.1 cm, positioned 55 cm in front of the participant, and had a screen resolution of 1920 by 1080 pixels. This setup resulted in a viewing angle of 0.031 degrees for the screen's pixels.

The task consisted of 40 trials, where the participants were required to read the sentences aloud. After each sentence, the examiner pressed the space button to display the next sentence. If the participants became tired during the trials, the task was temporarily paused and then resumed after a break. Both groups of participants in the research performed the task under the same physical conditions.

Results

In this research, the data were first analyzed descriptively; Categorical variables were reported as frequency and percentage, and quantitative variables that had normal distribution were reported with mean and standard deviation, and quantitative variables that had skewed distribution were reported with median and interquartile range (IQR). Then the distribution of quantitative variables was measured with the Shapiro-Wilk test. Independent Samples T-test was used for analytical analysis of variables that had normal distribution and Mann-Whitney test was used for variables that did not follow normal distribution. We used spss software, version 27.0.1

Pearson's correlation test was used to correlate quantitative variables. The analysis was done with SPSS software and the significance level was considered to be 0.05 in all tests.

The duration of eye fixation in children diagnosed with ASD (Mean = 98.38) was found to be longer compared to typically developing peers (Mean = 162.0), although this disparity did not reach statistical significance. The findings indicate that, on average, children with ASD exhibited a significantly higher number of eye fixations while reading sentences when compared to their neurotypical counterparts (Table 3).

In terms of eye movement, children with ASD demonstrated a higher rate of saccadic movements (Mean = 3.71) compared to their neurotypical peers (Mean = 2.90), but this difference was not statistically significant. However, the amplitude of saccadic movements was significantly greater in autistic children than in their neurotypical peers (refer to table4). These results suggest that individuals with autism display a higher frequency of saccades with smaller amplitudes during sentence reading, while their neurotypical peers exhibit a lower frequency of saccades with larger amplitudes. These findings imply that children with ASD may generate saccades in order to correct their eye fixation points and compensate for inaccuracies in estimating the location where their eyes will land (ocular fixation point).

In addition, the average time required to read a single sentence was compared between the two groups, revealing a statistically significant difference whereby children with ASD spent more time reading compared to their neurotypical peers. (Refer to table3).

Table 1: Descriptive characteristics of the study sample		
Variable	Autism (n=16)	TD (n=17)
	Mean ±SD	Mean ±SD
Gender (Male)*	12(80%)	12(75%)
Age(month)	102.33±5.589	101.69±4.586
Restricted repetitive	47.67±3.086	34.56±2.394
Social interaction	51.33±4.923	26.75±1.915
Social communication	58.40±2.501	38.06±2.016
Emotional responses	49.93±4.183	53.50±74.325
Cognitive style	57.13±7.726	39.13±4.938
Maladaptive speech	56.27±2.658	39.38±1.500
Total GARS score	59.20±5.102	28.44±1.750
NON-verbal Weschler test	106.47±8.543	104.56±7.806
Verbal Weschler test	94.40±8.365	102.19±7.521
Total. Weschler test	100.87±8.814	104.00±7.257
* Frequency (Percentage)		

Table 2: Statistical comparison of total GARS score, verbal, Nonverbal and Total Weschler scores neurotypical groups (Mann-Whitney)			
Variable	Autism Mean ±SD	TD Mean ±SD	P-Value
Total GARS[1]	59.20± 5.102	28.44± 1.750	<0.001
verbal	94.40±8.365	102.19±7.521	0.011
Non verbal	106.47±0.522	104.56±7.806	0.522
Total Weschler	100.87± 8.814	104.00± 7.257	0.288

Table 3: Statistical comparison of fixation duration, time spent and number of fixation ASD and neurotypical groups (Mann-Whitney)					
Variable	Autism		TD		P-Value
	Mean ±SD	Median ±IQR	Mean ±SD	Median ±IQR	
Fixation duration	98.388± 51.471	78.499± 86.378	164.081± 323.370	68.213± 58.258	0.470
Time spent	8.085± 4.509	7.298± 4.918	5.888± 3.531	4.745± 1.721	0.033
Number of fixations	29.560± 19.017	26.650± 34.300	16.022± 14.556	11.837± 10.287	0.024

Table 4: Statistical comparison of saccade amplitude and saccade rate in ASD and neurotypical groups (T-test)			
Variable	Autism Mean ±SD	TD Mean ±SD	P-Value
Saccade Rate	3.716±1.757	2.922±1.098	0.139
Saccade Amplitude	3.637±1.721	4.959±1.806	0.046

Discussion & Implications

Children with Autism Spectrum Disorder (ASD) exhibit increased fixation of the eyes. Specifically, their eyes pause on the text for longer durations, accompanied by numerous saccades with smaller amplitudes compared to their neurotypical counterparts. The results of the present study indicate that when reading sentences, autistic children display a greater number of eye fixations than their neurotypical peers, although the duration of each fixation does not differ significantly. The increased occurrence of saccades during sentence reading could be attributed to difficulties in identifying the next fixation point on the subsequent word within the sentence. Saccadic endpoint variability is often attributed to neural noise during sensorimotor processing. Saccadic amplitude refers to the distance covered by the eye between two fixation points, where the eyes

typically land near the intended target. These findings suggest that individuals with autism experience computational errors in generating saccadic movements during reading, potentially stemming from impairments in sensorimotor and perceptual processing.

Research has demonstrated that individuals with autism display atypical visual scanning patterns when observing faces and engaging in social interactions.(Klin, Jones, Schultz, Volkmar, & Cohen, 2002) They also exhibit abnormalities in sensorimotor control of eye movements when presented with simple visual stimuli, such as illuminated dots on a black screen(Y Takarae, Minshew, Luna, & Sweeney, 2004) (Yukari Takarae, Minshew, Luna, & Sweeney, 2007) and demonstrated smaller saccadic amplitudes inface perception task(Van der Donck et al., 2021). they also decreased saccade duration and and amplitude which is independent of human video content (Bast et al., 2021).When making rapid shifts in eye gaze (saccades), individuals with ASD exhibit reduced accuracy(Beth P Johnson et al., 2012; Jones et al., 2009; Mercadante, Macedo, Baptista, Paula, & Schwartzman, 2006) and increased trial-to-trial variability in saccade accuracy (18, 20(Rosenhall, Johansson, & Gillberg, 1988)

Eye movement data is an exceptionally reliable and valuable source for inferring the moment-to-moment processing of words and larger sections of text. While it may appear that our eyes move slowly across the screen while reading, the act of reading actually consists of a series of saccades, where the eyes jump from one point to another, and fixations, where the eyes remain relatively still (Rayner, 1998).

The difference in parameters of eye movements while reading sentences in the study groups can be explained by two dysfunctions of brain processing: dysfunction of the cerebellum and dysfunction of the dorsal visual pathway.

The cerebellum plays a crucial role in the precise and adaptable control of eye movements(Ramat, Leigh, Zee, & Optican, 2007). Individuals with cerebellar disorders exhibit a wide range of eye movement abnormalities, including saccadic intrusions and oscillations, fixation nystagmus, and slow refixation saccades.

 reading necessitates eye fixation to acquire visual information from words. To read a sentence, one's eyes must systematically move from one word to the next. The saccadic movement must

be executed with precision to direct the eye to the correct position on the next word and in the right direction within the sentence. Accurate visual information from the "where" pathway of vision is essential for moving in the correct direction. Multiple studies have reported dysfunctions in this pathway among individuals with autism(Chung & Son, 2020; Hay, Dutton, Biggar, Ibrahim, & Assheton, 2020; Kana et al., 2013) (Simmons et al., 2009). The dorsal pathway of the visual system plays a vital role in guiding movements and developing the spatial visual network(Righi & Vettel, 2011). It appears that when children with autism spectrum disorder (ASD) begin reading a sentence, they struggle to perceive the direction of the line's continuation and direct their eye movements accordingly. Sequentially reading words in the correct direction to comprehend the sentence becomes a process of trial and error, leading to slower reading speed. To execute the saccadic movement, parameters such as speed and movement accuracy are required. These parameters are determined within the neural network, where the cerebellum plays a significant role. Even if the location of the next eye fixation is determined correctly, if the saccadic movement is either too short or too long, it needs to be corrected.

Saccade dysmetria in individuals with Autism Spectrum Disorder (ASD) is characterized by increased variability in saccade errors without a corresponding change in mean saccade gain(Barash et al., 1999) A meta-analysis conducted by Johnson et al. confirmed the presence of saccade dysmetria in ASD, as indicated by greater variability in saccade errors. This dysmetria is typically observed when there is disruption in the pathway between the cerebellar vermis-fastigial nuclei pathway and the brain stem premotor nuclei, which impairs the ability to recalibrate and reduce saccadic inaccuracies over time(Golla et al., 2008) (Barash et al., 1999; Scudder, 2002). Notably, both Johnson et al. (2013) (Beth Patricia Johnson, Rinehart, White, Millist, & Fielding, 2013) and Mosconi et al. (2013)(Beth Patricia Johnson et al., 2013) discovered that individuals with ASD had impaired correction of systematic errors in saccade amplitude, induced by classic saccade adaptation paradigms. The pattern of saccade dysmetria in ASD and the impaired ability to correct saccadic errors align with reported morphological abnormalities in the cerebellar vermis(D'Mello, Crocetti, Mostofsky, & Stoodley, 2015; Hashimoto, Tayama, Miyazaki, Murakawa, & Kuroda, 1993; McKinney et al., 2022) (Crucitti, Hyde, Enticott, & Stokes, 2020; Laidi et al., 2017) (Courchesne, Yeung-Courchesne, Hesselink, & Jernigan, 1988);(Stoodley,

2012), deep cerebellar nuclei(Bauman, 1996; Courchesne et al., 1988), and brainstem in ASD(Hashimoto et al., 1993) (Courchesne et al., 1988). Moreover, fMRI evidence indicates reduced cerebellar activation during visually guided saccades in individuals with ASD(Yukari Takarae et al., 2007).

Although the rate of saccades and duration of eye fixations in autistic children do not show statistically significant differences, difficulties in accurately estimating the next fixation point in a sentence hinder proper lexical acquisition. Consequently, the child must readjust the fixation point and repeat the lexical access process, leading to increased overall reading time. These findings suggest that in order to enhance reading skills in individuals with autism, sensory and motor activities should be considered in addition to language parameters. Sensorimotor activities have the potential to modify sensory inputs in autism, and exercises that stimulate the motor functions of the cerebellum may aid in improving the acquisition of visual information from words. By enabling the brain to receive accurate visual information, it is anticipated that semantic and linguistic processing will become more efficient.

In addition to sensorimotor activities, it is recommended that neurovisual rehabilitation targeting the enhancement of the dorsal visual pathway and improvement of saccades should be considered for preschool-aged children with autism as part of their rehabilitation program.

limitation

The primary constraint lies in the persistent sensory processing difficulties experienced by children with autism spectrum disorder (ASD), prompting the exploration of potential strategies to address this issue. One such strategy involved adjusting the lighting and sound within the room, as well as modifying the texture of the fabric on the chin rest, while also taking into consideration the rest periods between trials.

Our study aimed to examine eye movements during sentence reading in 8-9-year-old children with ASD and their neurotypical counterparts. To extend the applicability of our findings, it is imperative to conduct further investigations encompassing diverse age groups.

Suggestions for Future Research

In this investigation, we scrutinized the eye movement patterns during sentence reading in both autistic children and neurotypical peers. The results demonstrated that although the increased fixation duration and number of saccades in autistic children did not exhibit statistical significance when compared to those of typically developing children, the overall time taken to read a sentence was significantly longer for autistic children. We propose that forthcoming studies on sentence reading should explore eye movement patterns under time-constrained conditions and consider the average reading time of neurotypical children.

To elucidate the cognitive mechanisms that underlie these disparities, it is crucial to examine the synchronization between brain waves and eye movements. Additionally, it is worth exploring whether these differences persist in autistic individuals as they grow older and their reading skills advance. Consequently, replicating the study with a broader age range would yield intriguing insights.

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Conflict of Interest

 The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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