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# Comparative analysis of prefrontal cortex oxygenation during cognitive tasks in typically developing vs. Autism Spectrum Disorder (ASD) preschoolers: A FNIRS-based study

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**Abstract**

Children diagnosed with Autism Spectrum Disorder (ASD) may face challenges in developing cognitive skills necessary for academic and social participation. This research report aims to assess and compare the cognitive capacities of children with Autism Spectrum Disorder (ASD) and Typically Developing (TD) children, particularly those who have participated in the ABLLS-R rehabilitation program. The research uses Functional Near-Infrared Spectroscopy (fNIRS) to assess brain activity, namely in the Prefrontal Cortex (PFC), during complex activities like puzzle-solving to identify cognitive differences between the two groups. Participants consisted of forty-eight preschool children, aged 4-7 years, chosen for their voluntary participation in this particular study. Participants were randomly divided into two different groups: a control group (Typically Developing, TD) as well as an experimental group (Autism Spectrum Disorder, ASD). Each child was exposed to a mental task that consisted of sorting, pairing, and moving puzzle pieces on top of a board. Meanwhile, the changes in their oxygenation were being tracked. Baseline task was completed. Intra-session variability was higher in the ASD group than that of the TD group. Ordinary least square regression did not show any statistically significant difference between the two groups. However, the result from the Mann-Whitney U test was statistically different between the two groups (U=606.5, p=0.0139). It appears that the use of Functional Near-Infrared Spectroscopy (fNIRS) can be considered as a method for the recording and assessment of cognitive functions in general, with specific use in autistic individuals. Indeed, this portable technology offers highly specific information on the changes of cerebral oxygenation, allowing a more rapid assessment of cognitive functions compared with laboratory-based technologies and allowing cognitive assessment of the person within their work or natural environment.

**Keywords:** Portable FNIRS, PFC, Oxygenation levels, Ecologically valid neuroimaging, Autism Spectrum Disorder (ASD), Puzzle-Solving task

## 1.Introduction

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by difficulties in social interaction, communication, and repetitive behaviors. To develop efficacious medicines and diagnostic instruments, it is imperative to understand the brain mechanisms that underlie these conditions. fNIRS has become an innovative way to study brain activity in people with ASD because it doesn't hurt, is easy to use outside of the lab, and can be moved around easily [1, 2]. Extensive studies on ASD brain activity have shown that cortical activation patterns differ from those in typically developing people. For example, children with ASD often produce altered hemodynamic responses at the prefrontal cortex (PFC) during social and cognitive tasks [3, 4].

Since the PFC serves a key role in executive function and social cognition, it is a key focus for exploring atypical neural processing in ASD.

### 1.1 Significance of FNIRS in studying autism

fNIRS can be used directly to measure the changes in cerebral blood oxygenation levels, that are associated with neural activity. Portable fNIRS devices can be used in indoor and naturalistic settings, making it invaluable in studying children with ASD, who may have difficulty remaining still or putting up with bulky equipment [2, 5]. Besides that, fNIRS is easy to use daily for studying young children and people with sensory sensitivity [6]. The high temporal resolution of fNIRS allows for real-time monitoring of brain activity during dynamic tasks [7, 8]. Another important point is that using non-invasive and more comfortable techniques, such as fNIRS, to scan people avoids the discomfort of being inside the scanner, which can be stressful for some [1, 4].

Recent research indicates that assessing the essential

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cognitive and executive functions required for school readiness (including working memory, cognitive flexibility, and planning) using fNIRS is a highly successful method [5, 9]. These roles form some of the elements within the comprehensive neurodevelopmental procedure, incorporating attention, reactivity, and cognitive perceptions [6, 7]. The use of fNIRS technology would be applicable for the analysis of the correlation that may link brain activity signals within the prefrontal cortical area with the processes associated with control functions as well as learning capabilities [10]. Emotion regulation, social interactions, and the entire class performance of students would also relate well with the mentioned control functions [8, 9]. By incorporating multiple aspects, such as fNIRS technology, within the formulation of estimations within treatment centers, a comprehensive viewpoint would be realized. [11, 12]. Table 1 provides a brief overview of current studies using fNIRS technology to assess the cognitive performance of preschool children.

**Table 1:** The key analytical results, number of participants, fNIRS device channels, and methodology of different research in cognitive task performance

| Study objective | Number of participants | fNIRS device channels. | Methodology | Key results |
|---|---|---|---|---|
| The effects of Animated Video Modeling (AVM) on cerebral function in children with ASD utilizing fNIRS[13]. | 30 children (15 ASD, 15 TD). | 63 channels. | fNIRS measured changes in Hb and $HbO_2$ levels between rest and visual stimulation. | ASD group showed reduced functional connectivity; AVM improved visual processing via increased occipital and parietal activation. |
| Using fNIRS data and Adaptive Time-Space Convolution Networks (ASGCNs) to classify ASD and TD children [14]. | 47 children (25 ASD, 22 TD). | 44 channels. | $HbO_2$, Hb, and HbT activation in bilateral frontotemporal cortices analyzed via sliding windows; ASGCN used for classification. | ASGCN model achieved 95.4% accuracy; left frontal lobe showed strongest ASD discrimination; inter-channel correlations enhanced accuracy. |
| To examine prefrontal cortex activity in children with ASD during cognitive tasks using fNIRS[15]. | 30 children (15 ASD, 15 TD). | 32 channels. | fNIRS measured prefrontal hemodynamic responses during verbal fluency and working memory tasks. | Weaker prefrontal activation in ASD children; correlated with poorer cognitive performance and executive dysfunction. |
| To investigate prefrontal cortex responses to social video stimuli in young children with ASD using fNIRS[16]. | 25 children (13 ASD, 12 TD). | 16 channels. | fNIRS recorded prefrontal activity while children viewed social vs. nonsocial videos to assess responses to social stimuli. | Reduced medial prefrontal activation to social stimuli in ASD, indicating neural basis for social processing deficits. |
| Our work | 84 children (42 ASD, 42 TD). | 2 channels | fNIRS measured cognitive activity in ASD children during matching and sorting puzzle tasks. | Significant TD, ASD difference ($p = 0.0139$, $U = 606.5$); fNIRS effectively assessed cognitive function in ASD children. |

Subsequent to the discussion on fNIRS and executive functions, it is also significant to underscore its role in assessing visuospatial task performance and developmental cognitive states. fNIRS has been used effectively to assess the brain activation in children during Mental Rotation Tasks (MRT)-one of the standard tests for measuring visuospatial ability. Increased activation in the dorsolateral prefrontal

cortex (dlPFC) corresponds to improved task performance, indicating a direct relationship between neural effort and cognitive output [17]. Furthermore, based on children's cognitive abilities, the task-specific processes in visuospatial working memory are revealed by the distinctive activation pattern identified by using fNIRS[18, 19].

Apart from task completion, cognitive development studies involving fNIRS technology confirm that task completion, age, and the activation of the prefrontal brain area show a positive correlation across different ages [20, 21]. Also, this technology provides valuable insights into cognitive states, effort, and levels of engagement within the process of learning, thus establishing the suitability of fNIRS technology for imaging cognitive and psychological interventions [22, 23].

## 2. Methodology

This research aims to comprehensively assess the cognitive abilities of children with autism spectrum disorder compared to their typically developing peers. Participants were selected to ensure a similarity in demographic characteristics and other relevant attributes. The type of cognitive test used and the data collection method (fNIRS) were described, followed by statistical analysis to obtain accurate and reliable data.

### 2.1 Criteria for participant selection

Children in educational environments need a number of executive functions, especially setting goals, committing to them, and controlling their emotions in order to achieve good performance at school. Sometimes these tasks are exhausting and difficult for children with limited cognitive abilities [1, 2]. Neurological maturation in the prefrontal cortex begins in early childhood (from 3 to 6 years old), and this cognitive development is very important in problem-solving and memory [24, 25].

Children with autism spectrum disorder often experience problems with cognitive flexibility, making it difficult for them to adapt to task modifications and solve problems efficiently [26, 27]. Detection of Autism Spectrum Disorder is essential in accelerating early intervene, which in turn improves the quality of life and rehabilitation process [28]. In its autism rehabilitation program, the Al-Sibtain Foundation in Iraq utilizes the ABLLS-R (Assessment of Basic Language and Learning Skills) program in assessing the rehabilitation process of children through their readiness to be merged into Mainstream schools [29]. The ABLLS-R approach includes 25 skill areas of ability, which cover a skill pool of 544 basic elements that must be acquired for a student to enhance their scholastic abilities [30]. In this regard, the children selected to participate in the experiment were those who passed through the ABLLS-R program. A cognitive assessment was carried out via the application of Functional Near-infrared Spectroscopy (fNIRS) technology, with their results contrasted with those of other children. [31].

### 2.2 Demographics, group composition, and eligibility

Subjects were 84 preschool children, subsequently separated equally between control and experiment groups, aged 4–7 years. Review of their health history was undertaken, excluding all participants then taking medication or otherwise existing with other forms of neurological disorders

### 2.3 Measurements and data collection procedures

Considering the existing evidence that puzzles positively contribute to the cognitive development of autistic as well as developmentally delayed children [32,39], both sets of children were required to solve a cognitive puzzle, which involved matching the color and shape of pieces that relate to different geometric figures.

This type of cognitive test works to enhance cognitive flexibility, problem-solving ability, visual perception, fine motor skills, and sustained attention [33, 34, 35, 36]. The puzzle's complexity increases through four stages, requiring participants to align colors and shapes, as illustrated in Figure 1.

Different puzzle pieces were randomly distributed to participants to foster interaction across various cognitive levels. Changes in participants' prefrontal cortex oxygenation were accurately recorded and stored for later analysis.


**Figure 1.** Ordinal transition in solving the cognitive puzzle

Changes in oxygen levels and blood flow in the prefrontal cortex were recorded using a 33 Hz dual-channel fNIRS headband manufactured by Mendi INNOVATIONS AB, along with acquisition software developed by the same company. This technique gave real-time input on brain activity while the task was going on. A acquisition software turned brain activity into scores [37]. There was a separate test for each participant. The changes in oxygen levels during the task were recorded and statistically analyzed.

## 3. Results

Data were collected from both generally developing youngsters and those with autism during the puzzle assessment. The variations in oxygen concentration were analyzed for statistical and linear relationships. The outcomes of these analyses are presented below.

Figure 2 illustrates the histogram for typically developing children, with a right-skewed distribution. This indicates that a limited number of elevated oxygenation levels skew the average to the right. Likewise, the histogram for individuals with autism, illustrated in Figure 3, exhibits a right-skewed distribution, but with a reduced number of extreme values. The skewness coefficient for the typical group is 2.02, and for the autism group, it is also 2.02, so reinforcing the right-skewness. The typical group's kurtosis is 5.53, whereas the autism group's kurtosis is 5.17, signifying variations in the peakedness of their distributions.

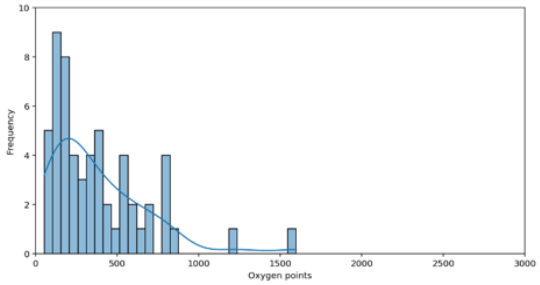


**Figure 2:** Histogram illustrating the distribution of oxygenation points within the TD group

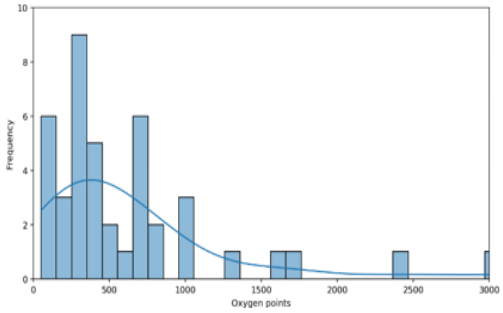


**Figure 3:** Histogram illustrating the distribution of oxygenation points within the ASD group

Both histograms demonstrate a right-skewness, where a few larger values shift the average to the right. The central tendency of the autism group's histogram appears slightly higher compared to the typical group, as the data are more concentrated around higher values. Both histograms exhibit outliers on the right side, suggesting the presence of extreme data points in both groups. The central tendency and dispersion measures for both groups are summarized in Table 2.

**Table 2.** Measurements of central tendency and variability

| **Central Tendency** | | |
|---|---|---|
| | **Normal children** | **Individuals with autism** |
| Mean | 357 | 632 |
| Median | 263 | 430 |
| Mode | 54 | 51 |
| Dispersion | | |
| | Normal children | Individuals with autism |
| Standard deviation | 295 | 623 |
| Variance | 87188 | 387771 |
| Range | 1544 | 3021 |

Confidence Intervals (CI) for the means were computed for both groups: the 95% CI for the TD group is (268.70, 445.16), and for the ASD group, it is (446.19, 818.34). Figure 4 provides a comparison examination of oxygen level distributions between the normal and autism populations through the use of boxplots. The Interquartile Range (IQR) separates each cohort, and a line shows the median inside the box. Outliers are intentionally excluded, but the whiskers show the extreme values as separate points.

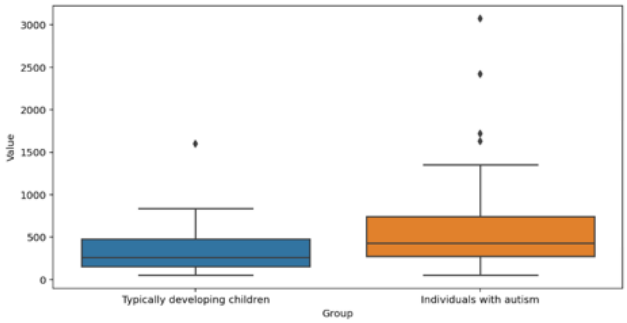


**Figure 4:** A boxplot showing the oxygenation levels in the TD group compared to the ASD group

The results in Table 2 and the boxplot in Figure 4 show that the median for the typical group is lower than the median for the autism group. This means that the typical group has a lower central tendency. Additionally, the interquartile range for the standard cohort is diminished, signifying that the data points exhibit lower variability around the median. There are outliers in both categories, but they are far more obvious in the usual group. The right skewness seen in both histograms is verified by the fact that the whiskers go to the right for both groups. We used bootstrapping to find the median confidence intervals because it is a non-parametric method. The 95% confidence interval for the TD group's median is (178.5, 379.5), while for the ASD group, it is (320.5, 674.5). This shows that the two groups are very different from one other.

Additional statistical analyses were performed to determine if there is a big difference between the averages of the control group and those who have autism. Although t-tests and OLS regression were used, the Mann-Whitney U Test was a better fit for the data and the hypotheses being tested, especially since the data did not follow a normal distribution. Initially, Ordinary Least Squares regression was considered for assessing potential linear correlations among the variables; however, due to the non-normal distribution of the data, it was ultimately regarded as less suitable for this analysis. The Mann-Whitney U test showed a big difference between the distributions of normally developing children and those with autism spectrum disorder. The p-value was 0.0139, which is less than 0.05. The U-statistic value of 606.5 supports the idea of a statistically significant difference between the control and experimental groups. This difference is clearly demonstrated by the Cohen effect of -2.46, confirming that the gap between the two groups is substantial, statistically significant, and realistic.

## 5. Discussion and Conclusions

This research investigated as well as compared the cognitive capabilities of two different groups of preschoolers: typically developing children, as well as those with Autism Spectrum Disorder (ASD) that was identified, through the use of functional near-infrared spectroscopy (fNIRS). The results of this study show that the method used is an important, promising tool for cognitive functions assessment, as well as demonstrating the effect of rehabilitation measures on children with Autism Spectrum Disorder, thus enabling sound decisions on children's enrollment in conventional schools.

The results show that children with Autism Spectrum Disorder (ASD) required more cognitive effort for puzzle-solving, as shown through higher cerebral oxyhemoglobin saturation compared with their peers (as seen in figures 2 & 3). Distributions for both were right-skewed, with greater skewness in the autistic group, which was more concentrated on the higher side.

Although there was a similarity in terms of skewness, central tendency, and cognitive engagement, the result of the Mann-Whitney U test indicated a difference between the two groups.

Although there is a difference in the baseline distribution of the two groups based on the linear correlation, the p-values of 0.0139 ($p < 0.05$) show that there is significance between the two groups. This is supported by the results from the Mann-Whitney U test, as there was a difference in the

distribution of values in the two groups.

The marked variance in classification was confirmed by the U-statistic of 606.5. This is true even though t-tests and ordinary least squares regression studies suggest that there may not be a strong predictive or correlational relationship.

Based on the research findings, fNIRS technology is a promising tool; however, it requires further advanced studies and research to assess cognitive development across different age groups, and particularly in children. This technology can be integrated with other portable technologies, such as skin conductivity meters, leading to the development of hybrid systems that may improve the assessment of cognitive performance and enhancing our understanding of their developmental paths.

## 6. Author contribution statements

The authors contributed to the manuscript in the following steps: Mahir Rahman Al-Hajaj conceived the presented idea. Ahmet Reşit Kavsaoğlu developed the theory and performed the review. Ahmet Hayrettin Yuzer verified the integrity of the data and encouraged Mahir Rahman Al-Hajaj to investigate TD and ASD participants and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

## 7. Ethics committee approval and conflict of interest statement

### 7.1 Ethical statement:

The Non-Interventional Clinical Research Ethics Committee at Karabuk University has approved this study to be ethically appropriate (Number: E-77192459-050.99-186801 21.11.2022, Subject: Decision No. 2022/1159).

### 7.2 Conflict of interest

The authors declare that they have no conflict of interest. "There is no conflict of interest with any person/institution in the article prepared."

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