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Portable Functional Near-Infrared Spectroscopy for Neuroimaging of Prefrontal Activity in Preschool Children with Autism Spectrum Disorder

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ABSTRACT

Portable functional near-infrared spectroscopy (fNIRS) has emerged as a promising tool for investigating brain activity in naturalistic settings, particularly in populations that may experience discomfort in conventional laboratory environments. This study explores the feasibility of using a portable fNIRS system to measure prefrontal neural activity in preschool children with Autism Spectrum Disorder (ASD) during an ecologically valid cognitive task. A total of 84 children aged 4–7 years (42 diagnosed with ASD and 42 typically developing controls) participated in a graded puzzle-solving task designed to engage executive and working memory processes. Neural activity in the prefrontal cortex was recorded using a wireless low-channel fNIRS device positioned over the frontal poles. Statistical analyses revealed significantly higher and more variable prefrontal activation in children with ASD compared with typically developing peers, suggesting atypical neural processing during integrated cognitive demands. The results indicate that portable fNIRS can reliably capture meaningful neural activation patterns in real-world environments while reducing stress and improving compliance among young children. These findings highlight the potential of portable neuroimaging for studying early neurodevelopment in naturalistic contexts and suggest that fNIRS-based neural markers may complement behavioral assessments in autism research. Future work should employ higher-density systems, longitudinal designs, and multimodal neurophysiological measurements to further investigate developmental trajectories and intervention-related neural changes in ASD.

1. INTRODUCTION

Autism Spectrum Disorder (ASD) is a neurodevelopmental condition characterized by impairments in social interaction, communication, and repetitive behaviors. Understanding the neural mechanisms behind these symptoms is essential for improving diagnosis and intervention strategies.

Functional near-infrared spectroscopy (fNIRS) has become a promising tool for studying brain activity in ASD because it is non-invasive, portable, and suitable for use outside laboratory environments [1, 2].

Previous studies report differences in cortical activation between individuals with ASD and typically developing (TD) individuals. In particular, children with ASD often show altered hemodynamic responses in the prefrontal cortex (PFC) during social and cognitive tasks [3, 4].

Because the PFC is central to executive function and social cognition, it is frequently examined to understand atypical neural processing in ASD.

2. USING fNIRS TO INVESTIGATE NEURAL ACTIVITY IN ASD

fNIRS measures changes in cerebral blood oxygenation associated with neural activity. Its portability allows experiments in naturalistic environments, which is beneficial for studying children who may struggle to remain still or tolerate large imaging systems [2, 5].

The technique is also well suited for young participants and individuals with sensory sensitivities [6].

In addition, fNIRS provides high temporal resolution for monitoring brain responses during dynamic tasks [7, 8]. Unlike scanner-based imaging methods, it does not require participants to remain inside enclosed equipment, reducing stress during data collection [1, 4].

Table 1 summarizes key findings from fNIRS studies in autism, including affected brain functions, diagnostic sensitivity, and major conclusions [9-11].

3. fNIRS APPLICATIONS AND GAPS IN ASD RESEARCH

fNIRS has been largely used in ASD to identify possible biomarkers, for instance, deviant patterns of hemodynamic response during social and cognitive tasks [7, 12]. It also enables the investigation of functional connectivity and has been used to demonstrate abnormal patterns during working memory and social cognition tasks [13].

Additionally, it offers new perspectives and developmentally sensitive tools for understanding the maturation of ASD, by monitoring brain activity over time and its response to intervention [6, 14].

However, there are still some research gaps, although it has been widely studied. The majority of studies are cross-sectional rather than longitudinal, limiting insights into developmental trajectories [6, 13]. Task-specific effects complicate interpretation, as findings often remain confined to domains such as social cognition or working memory rather than reflecting broader functions [15].

Variability in ASD symptoms and severity further clouds the interpretation of these findings and underscores the importance of conducting studies with larger and more diverse samples [7, 12].

Three hypotheses consequently flow from this framework. First, brain activation patterns are different between people with and without ASD, particularly in the PFC in individuals who have ASD [3, 4]. Second, functional connectivity alterations, such as decreased intrahemispheric connectivity within the PFC [13], are observed.

Third, fNIRS indices (e.g., amplitude and laterality of hemodynamic response) have potential as biomarkers for ASD diagnosis and severity [7, 12].

Unlike most of the laboratory-based studies conducted in controlled, unfamiliar environments using a multi-channel fNIRS device, in this study, we used a portable low-channel system adapted to familiar settings. This reduces the anxiety of children with ASD and increases ecological validity.

Recent fNIRS studies in preschool children are summarized in Table 2, suggesting that the environmental context may have a significant impact on these neural activation responses (e.g., familiar rehab centers vs. novel labs) [16, 17].

Table 1. Summary of fNIRS findings in autism

Brain Region	Diagnostic Accuracy	Key Findings
Bilateral Temporal Lobes	AUC[a] > 0.8 for >1.5 min	HbO/Hb[b] coupling serves as a characteristic feature for ASD [9].
Multiple Brain Channels	97.2% accuracy	Dynamic connections between specific channels impact ASD classification [8].
Left Frontal Lobe	95.4% accuracy	The left frontal lobe shows the highest classification effect; correlations between channels [10].
Inferior Frontal Gyrus	96.8% accuracy	Weaker resting-state connectivity in ASD; visualizable brain connectivity networks [7].
Right Prefrontal Lobe	93.33% accuracy	Higher MSE[c] values in ASD; effective for inhibitory control task-based classification [11].

Note: [a]AUC: Area Under the Curve, [b]Hb/HbO: Hemoglobin/Oxygenated Hemoglobin, [c]MSE: Mean Squared Error; [d]fNIRS: functional near-infrared spectroscopy. [c]ASD: Autism Spectrum Disorder.

Table 2. Summary of recent studies in preschoolers using fNIRS devices

Study Objective	Number of Participants	fNIRS Device Channels	Methodology	Key Results
Deception Detection in Preschoolers [18]	89 children	23 channels	fNIRS during a deception task assessing prefrontal cortex activation	Deception engages the right VLPFC[a] and right temporoparietal junction, plus the frontopolar cortex and bilateral DLPFC[b].
Ecological fNIRS in Mobile Children [19]	39 children	48 channels	fNIRS during computerized and immersive virtual reality tasks; superficial signal regression (SSR) applied	SSR enhanced mapping of functional brain activity, more so during dynamic VR tasks.
Social Development in Preschoolers Using fNIRS and Virtual Reality [20]	37 children	48 channels	Wearable fNIRS in CAVE[c] for realistic social environments	Showing proof of combining fNIRS with a VR[d] to examine social development in naturalistic contexts.
Syntactic Development in Preschoolers [21]	67 children	48 channels	fNIRS in language tasks that tap syntax, semantics, and working memory	Relations among syntax, semantics, working memory, and early neural patterns may predict later language development.
Our work	84 children	2 channels	The puzzle task is used to assess the engagement of multiple neural activities: visual perception, spatial reasoning, and working memory.	The portable fNIRS was effective in measuring the differences in brain functioning in real-life settings and exploring the dispersed and high PFC activation patterns in children with ASD

Note: [a]VLPFC: Ventrolateral Prefrontal Cortex, [b]DLPFC: Dorsolateral Prefrontal Cortex, [c]CAVE: Cave Automatic Virtual Environment, [d]VR: Virtual Reality. [c]ASD: Autism Spectrum Disorder.

4. METHODOLOGY

The methodology provides a systematic examination of cognitive abilities in children with ASD compared to TD children. It outlines the task, targeted brain area, inclusion criteria for participant selection, and data collection procedures. Participants were purposively selected to reflect a broad sociodemographic spectrum. The fNIRS device used for data recording is also described, ensuring accuracy and reliability in measurements.

Task Description and Cortical Brain Regions of Interest

In this study, we used a task-based design approach to observe neural activity changes in preschoolers. In this research paper, we consider the puzzle-solving task for the evaluation of neural activity. This task is especially appropriate for preschool-aged children as it appeals to multiple developmental domains and represents an integrated cognitive challenge. Specifically:

- Cognitive Processes: To solve puzzles, children need multiple functions that are essential for how children interact with their environment. These skills encompass visual perception, e.g., identifying shapes, colors, and patterns, spatial reasoning (comprehension of how the specific pieces fit together spatially), sustained attention (perseverance and concentration over prolonged time periods), and problem-solving abilities (recognizing mismatches, generating appropriate solutions) [22, 23].
- Working Memory: Engaging in a puzzle task also demands significant use of working memory. Children must temporarily store and manipulate relevant information, such as remembering the shape of a target space, recalling previously viewed or attempted puzzle pieces, and mentally rotating pieces to assess potential fits [24].

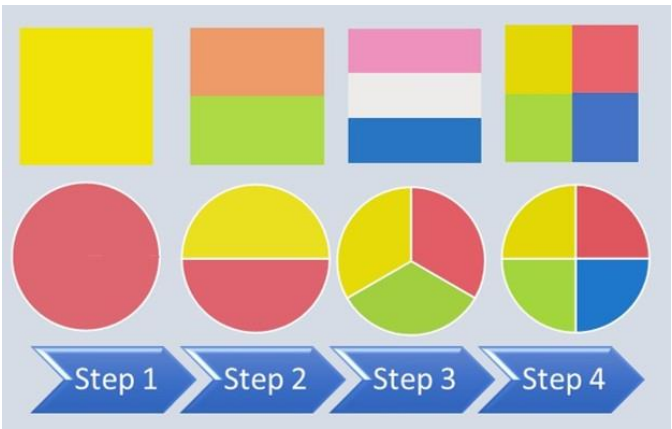

Figure 1. Graded puzzle task demonstrating the experimental setup, simulating the original wooden design using MS PowerPoint

Both groups had been asked to solve a cognitive task involving a matching and sorting puzzle. Puzzles have been recognized as valuable tools for enhancing cognitive development in individuals with autism and other developmental disabilities [25]. Creativity and innovative thinking require restructuring of the cognitive schema, and it is boosted by using puzzle games [26]. The puzzle reveals the participant's ability to enhance problem-solving abilities by requiring critical and strategic thinking, thereby improving cognitive flexibility, planning skills, and working memory [27]. Furthermore, puzzles foster visual perception through tasks involving discrimination, spatial reasoning, and pattern recognition, which are foundational for various academic and life skills [28]. The manipulation of puzzle pieces also refines fine motor control and coordination [29]. Finally, the inherent demands of completing puzzles cultivate sustained attention and focus, crucial for learning and other cognitive tasks [27].

Participants solved puzzles of progressively increasing complexity (see Figure 1 for a representation of the original wooden design rendered in MS PowerPoint). The task involved matching shapes and colors, with pieces provided randomly, one at a time, to encourage focused engagement at each difficulty level. This graded complexity is anticipated to elicit varying PFC neural activity, reflecting neuroplasticity in participants.

In preschoolers, the PFC has been a focal region of interest in fNIRS studies of preschoolers, given its role in executive functions. Research has consistently shown that PFC activation increases with age, particularly during tasks requiring inhibitory control and working memory [30, 31]. This region was selected because fNIRS is widely used to monitor cognitive functions by measuring hemodynamic changes in the cerebral cortex, as illustrated in Figure 2 [32]. Table 3 shows the prime targets in the PFC, their involvement in higher cognitive processes, and their superficial location, making them accessible to fNIRS.

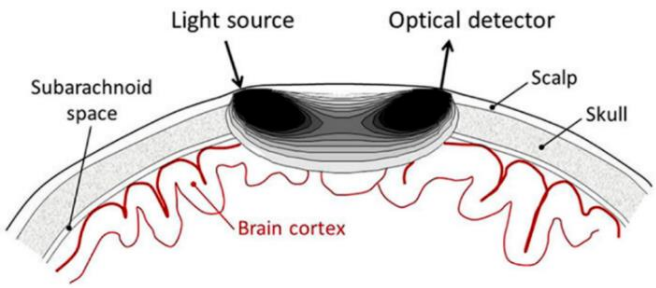

Figure 2. Schematic of the optical path (banana-shaped signal) of the fNIRS system [32]
Note: fNIRS = functional near-infrared spectroscopy.

Table 3. Key fNIRS findings observed cognitive and developmental activation patterns in prefrontal and orbitofrontal cortices

Brain Region	Key Findings
Prefrontal Cortex [30, 31]	Increased activation with age during executive tasks.
Left [a]OFC [33]	Activation correlated with inhibitory control and stress responses.
Right PFC [31, 34]	Bilateral activation patterns emerge during toddlerhood.
Orbital Frontal Cortex [33]	Activation linked to goal-directed behavior and inhibitory control.

Note: [a]OFC: Orbitofrontal Cortex

4.1 Participant selection, demographics, and eligibility criteria

This study included 84 preschoolers, aged 4 to 7, equally divided into control and experimental groups. The control group consisted of TD children with no neurodevelopmental conditions, while the experimental group included children diagnosed with ASD, without co-occurring conditions. All participants were eligible for mainstream school and had neither prior medication use nor history of medication.

Children who experience cognitive delays often have difficulty in the classroom, especially with executive skills or high-level cognitive functions that are required for goal-setting, task focus, and emotional regulation [35]. Given that children diagnosed with ASD typically demonstrate cognitive impairments, particularly in cognitive flexibility [36, 37]. The study was approved by the relevant ethics committee, conducted in compliance with the ethical principles of the 1964 Declaration of Helsinki and its subsequent amendments, and all participants provided informed consent prior to inclusion.

Participants were recruited from four specialized autism treatment centers in Iraq, which uses the ABLLS-R for monitoring of performance and defining educational goals regarding mainstream school integration (Al-Sibtain Academy) [38].

4.2 Measurements and data collection procedures

Neural activity was recorded using a wireless, wearable fNIRS headband (MENDI Innovations AB, Sweden), designed for portable and naturalistic neuroimaging applications. The device employs a continuous-wave fNIRS configuration and consists of three optodes forming two measurement channels, positioned bilaterally over the frontal poles (Brodmann area 10) to capture prefrontal cortex activity in the left and right hemispheres [39]. The system utilizes dual near-infrared wavelengths in the range commonly used for cerebral hemodynamic monitoring (approximately 730-850 nm), enabling differential sensitivity to oxygenated (HbO) and deoxygenated hemoglobin (HbR). The source-detector separation is fixed at a short-to-moderate distance (approximately 3 cm), optimized for sampling superficial cortical tissue while maintaining signal quality in pediatric populations. Data were acquired at a sampling rate of 33 Hz, allowing adequate temporal resolution for task-related hemodynamic changes. Raw optical signals are internally processed using proprietary signal-processing algorithms provided by the manufacturer [32]. These include basic preprocessing steps such as motion artifact mitigation, temporal filtering to attenuate physiological noise (e.g., cardiac and respiratory components), and normalization procedures. The processed output is expressed as unitless neural activity scores, which reflect relative changes in prefrontal hemodynamic activity rather than absolute chromophore concentration values. While this limits direct comparison with conventional multi-channel research-grade fNIRS systems, the approach has been validated for tracking relative cognitive engagement and workload in mobile and real-world settings. The headband was adjusted individually to ensure stable optode-scalp contact and minimal movement during task performance. Its lightweight and non-invasive design allowed children to complete the cognitive task comfortably in familiar environments, thereby reducing stress-related confounds and supporting ecologically valid data acquisition [40].

5. RESULTS AND DISCUSSION

The results from analyzing data from the TD and ASD groups are statistically analyzed using descriptive and inferential methods. The results are depicted with histograms, pair plot-scatter matrices, and cumulative distribution functions (CDFs) to emphasize the differences in data distributions as well as data. Statistical tests confirmed the individual differences in PFC activation between the ASD and TD children.

5.1 Descriptive statistics

The descriptive statistics are summarized in Table 4. The results revealed that the ASD group exhibits significantly higher mean and greater dispersion than the TD group, indicating considerable differences in neural activity patterns. Both groups display right-skewed distributions, with skewness values of 1.72 (TD) and 2.52 (ASD). Kurtosis was also higher for ASD (6.22 vs. 3.88), higher frequency of extreme values.

Table 4. Summary of descriptive statistics

Group	Mean	Standard Deviation (SD)	25th Percentile	50th Percentile	75th Percentile	Minimum	Maximum
TD Children	10.09	6.09	6	9	12.5	3	34
Children with ASD	21.28	21.41	10.5	14	21.5	3	102

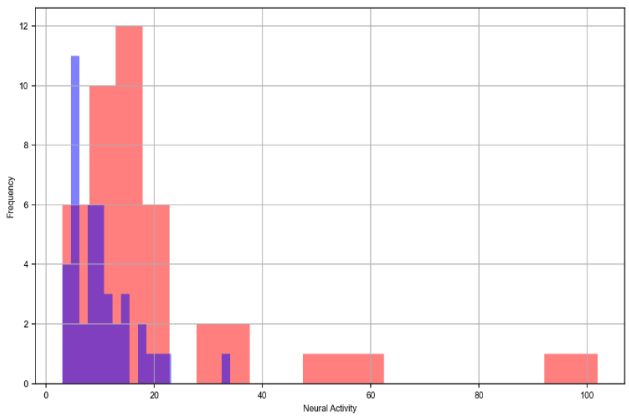

Figure 3. Histograms of data distribution for TD and ASD groups
Note: TD = Typically developing; ASD = Autism Spectrum Disorder.

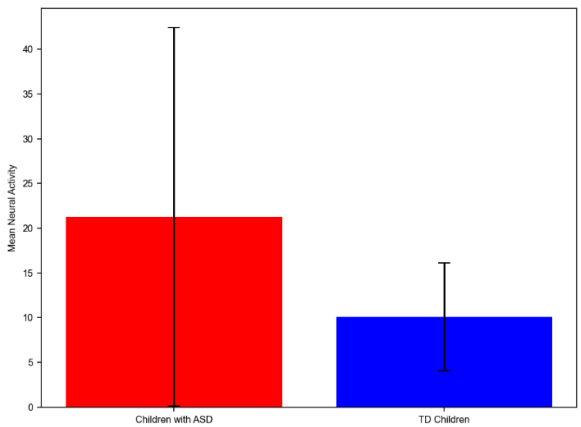

Figure 4. Bar plot comparing the mean values of neural activity in the PFC for TD and ASD groups
Note: TD = Typically developing; ASD = Autism Spectrum Disorder.

Figure 3 illustrates a broader distribution marked by extreme outliers for the ASD group, while the TD group has a more uniform distribution. Figure 4 highlights a higher proportion of mean values in ASD, and Figure 5 (scatter matrix) shows a wider spanning range. The larger spread in the ASD was further emphasized in Figure 6 (CFD).

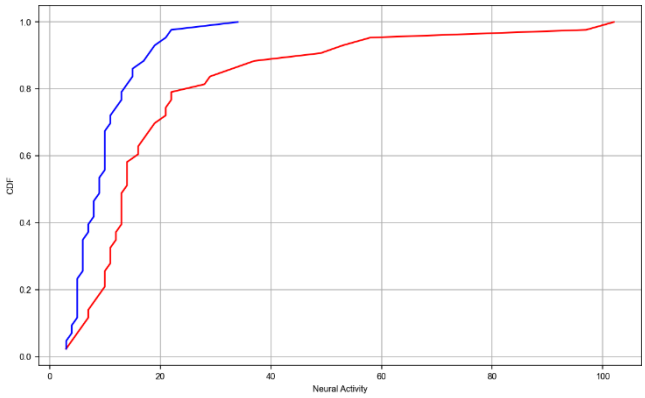

Figure 5. Scatter plot comparing data points between TD and ASD groups
Note: TD = Typically developing; ASD = Autism Spectrum Disorder.

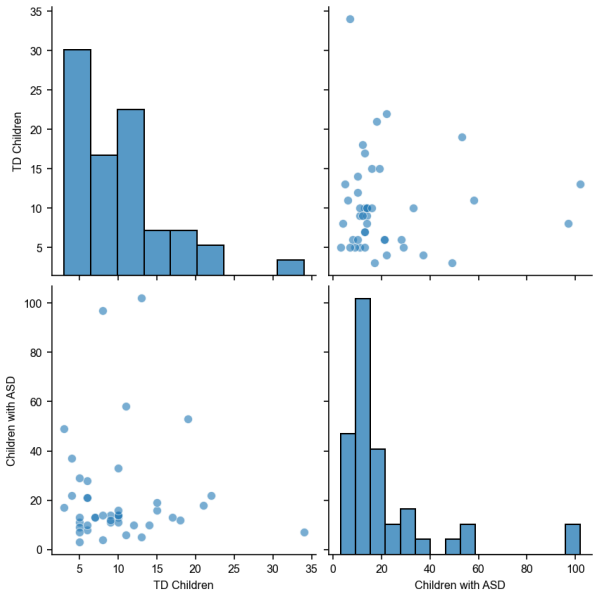

Figure 6. CDF comparing the neural activity of TD and ASD groups
Note: CDF = cumulative distribution function; TD = Typically developing; ASD = Autism Spectrum Disorder.

5.2 Inferential statistical analysis

Due to violations of normality (Shapiro-Wilk test: $p < 0.001$ for both groups) and homogeneity of variances (Levene's test: $p = 0.017$), a non-parametric Mann-Whitney U test was performed [41]. The test revealed that the ASD group exhibited significantly higher neural activity (Median = 14.0, IQR = 11.0) than the TD group (Median = 9.0, IQR = 6.5; U = 1367.0, $p = 0.00013$). To quantify the shift between groups, the Hodges–Lehmann median difference was calculated as 6.0 with a 95% confidence interval of [3.0, 8.0]. The effect size, measured by the Rank-Biserial Correlation, was 0.48 (95% CI: [0.26, 0.68]), demonstrating a meaningful and statistically significant difference between the groups. Since a single between-group comparison was performed for only one outcome variable, neural activity, no multiple-comparison correction was required.

6. CONCLUSIONS

The key finding is that children with ASD revealed significantly greater neural response and variability in the PFC. This indicates that the children with ASD require a higher cognitive load to complete the task, potentially reflecting reduced efficient neural processing, consistent with the heterogeneity of ASD, where individuals rely on different neural strategies.

The use of portable fNIRS in naturalistic settings supported a more ecologically valid measurement of brain activity, as it minimized the anxiety induced by traditional lab-based setups. The Mendi headband's unitless scores, while limiting direct cross-study comparisons, proved practical for real-world cognitive assessment. These results indicate the promise of portable fNIRS for accessible and ecologically valid ASD research.

The use of a two-channel device with limited spatial resolution restricts the ability to investigate the functional connectivity of the PFC with other brain regions. This limitation should be overcome in future research by adopting higher-density arrays of fNIRS devices, and multi-modal approaches, like combining fNIRS with eye-tracking or behavioral coding.

Furthermore, as this was a cross-sectional design, longitudinal studies are needed to underscoring the developmental progress in ASD neural activity. Overall, this study provides a practical approach for developing the accessibility and ecological validity of portable neuroimaging as a tool for determining objective biomarkers and for more individualized and impactful interventions.

REFERENCES

[1] Conti, E., Scaffei, E., Bosetti, C., Marchi, V., et al. (2022). Looking for "fNIRS signature" in autism spectrum: A systematic review starting from preschoolers. Frontiers in Neuroscience, 16: 785993. https://doi.org/10.3389/fnins.2022.785993

[2] Yamamuro, K. (2022). Near-infrared spectroscopy in child and adolescent neurodevelopmental disorders. Psychiatry and Clinical Neurosciences Reports, 1(4): e59. https://doi.org/10.1002/pcn5.59

[3] Su, W.C., Culotta, M., Mueller, J., Tsuzuki, D., Bhat, A.N. (2023). Autism-related differences in cortical activation when observing, producing, and imitating communicative gestures: An fNIRS study. Brain Sciences, 13(9): 1284. https://doi.org/10.3390/brainsci13091284

[4] Barreto, C., Curtin, A., Topoglu, Y., Day-Watkins, J., et al. (2024). Prefrontal cortex responses to social video stimuli in young children with and without autism spectrum disorder. Brain Sciences, 14(5): 503. https://doi.org/10.3390/brainsci14050503

[5] Mazzoni, A., Grove, R., Eapen, V., Lenroot, R.K., Bruggemann, J. (2019). The promise of functional near-infrared spectroscopy in autism research: What do we know and where do we go? Social Neuroscience, 14(5):

505-518. https://doi.org/10.1080/17470919.2018.1497701
[6] Su, W.C., Colacot, R., Ahmed, N., Nguyen, T., George, T., Gandjbakhche, A. (2023). The use of functional near-infrared spectroscopy in tracking neurodevelopmental trajectories in infants and children with or without developmental disorders: A systematic review. Frontiers in Psychiatry, 14: 1210000. https://doi.org/10.3389/fpsyt.2023.1210000
[7] Rohilla, S., Jadeja, M., Pilli, E.S., Vyas, P., Gehlot, P. (2025). CC-GCN: A novel graph-based approach for identification and detection of autism spectrum disorder. Multimedia Tools and Applications, 84(22): 25287-25308. https://doi.org/10.1007/s11042-024-20111-3
[8] Wu, T.X., Yin, X., Xu, L.Y., Yu, J. (2024). Using dynamic spatio-temporal graph pooling network for identifying autism spectrum disorders in spontaneous functional infrared spectral sequence signals. Journal of Neuroscience Methods, 409: 110157. https://doi.org/10.1016/j.jneumeth.2024.110157
[9] Lin, F. (2024). Acquisition time for resting-state HbO/Hb coupling measured by functional near-infrared spectroscopy in assessing autism. Journal of Biophotonics, 17(11): e202400150. https://doi.org/10.1002/jbio.202400150
[10] Zhang, H.R., Xu, L.Y., Yu, J., Li, J., Wang, J.H. (2023). Identification of autism spectrum disorder based on functional near-infrared spectroscopy using adaptive spatiotemporal graph convolution network. Frontiers in Neuroscience, 17: 1132231. https://doi.org/10.3389/fnins.2023.1132231
[11] Yu, G.Y., Ta, N., Wang, H.A., Liu, F.L., Dong, Y.H., Yu, D.C. (2023). Identifying autistic children using multi-scale entropies of right prefrontal oxy-hemoglobin signals. In 2023 Cross Strait Radio Science and Wireless Technology Conference (CSRSWTC), Guilin, China, pp. 1-3. https://doi.org/10.1109/CSRSWTC60855.2023.10427207
[12] Scaffei, E., Mazziotti, R., Conti, E., Costanzo, V., et al. (2023). A potential biomarker of brain activity in autism spectrum disorders: A pilot fNIRS study in female preschoolers. Brain Sciences, 13(6): 951. https://doi.org/10.3390/brainsci13060951
[13] Han, Y.M.Y., Chan, M.C., Chan, M.M.Y., Yeung, M.K., Chan, A.S. (2022). Effects of working memory load on frontal connectivity in children with autism spectrum disorder: A fNIRS study. Scientific Reports, 12: 1522. https://doi.org/10.1038/s41598-022-05432-3
[14] Wan, L., Li, Y.H., Zhu, G., Yang, D.L., Li, F.L., Wang, W., Chen, J., Yang, G., Li, R.H. (2024). Multimodal investigation of dynamic brain network alterations in autism spectrum disorder: Linking connectivity dynamics to symptoms and developmental trajectories. NeuroImage, 302: 120895. https://doi.org/10.1016/j.neuroimage.2024.120895
[15] Li, Y., Ma, S., Zhang, X., Gao, L. (2024). ASD and ADHD: Divergent activating patterns of prefrontal cortex in executive function tasks? Journal of Psychiatric Research, 172: 187-196. https://doi.org/10.1016/j.jpsychires.2024.02.012
[16] Zhu, H.L., Fan, Y.B., Guo, H., Huang, D., He, S.L. (2014). Reduced interhemispheric functional connectivity of children with autism spectrum disorder: Evidence from functional near-infrared spectroscopy studies. Biomedical Optics Express, 5(4): 1262-1274. https://doi.org/10.1364/boe.5.001262
[17] Sun, W.T., Wu, X.Y., Zhang, T.Z., Lin, F., Sun, H.W., Li, J. (2021). Narrowband resting-state fNIRS functional connectivity in autism spectrum disorder. Frontiers in Human Neuroscience, 15: 643410. https://doi.org/10.3389/fnhum.2021.643410
[18] Dai, M., Gao, Y., Hu, X.T., Fu, G.Y., Hu, Z.S., Sai, L.Y. (2024). Preschoolers' deception related to prefrontal cortex activation: An fNIRS study. NeuroImage, 298: 120795. https://doi.org/10.1016/j.neuroimage.2024.120795
[19] Pinti, P., Dina, L.M., Smith, T. (2024). Ecological fNIRS in mobile children: Using short separation channels to correct for systemic contamination during naturalistic neuroimaging. bioRxiv. https://doi.org/10.1101/2024.06.02.596560
[20] Bulgarelli, C., Pinti, P., Aburumman, N., Jones, E.J.H. (2023). Combining wearable fNIRS and immersive virtual reality to study preschoolers' social development: A proof-of-principle study on preschoolers' social preference. Oxford Open Neuroscience, 2: 1-15. https://doi.org/10.1093/oons/kvad012
[21] Yan, D.S., Fang, T.F., He, W., Xu, M. (2025). Syntactic development and its interplay with word processing and working memory in preschoolers' brain: An fNIRS longitudinal study. NeuroImage, 305: 120987. https://doi.org/10.1016/j.neuroimage.2024.120987
[22] Nazilah, M.B., Rahmah, M.F., Aliza, N., Salianty, S. (2022). The use of educational puzzle games for the development of cognitive abilities of children aged 5–6 years. GENIUS: Indonesian Journal of Early Childhood Education, 3(2): 151-162. https://doi.org/10.35719/gns.v3i2.102
[23] Mulyana, A., Nurcahyani, N. (2022). The effect of the puzzle playing method on improving the cognitive development of children aged 4–6 years. KnE Life Sciences, 7(2): 542-548. https://doi.org/10.18502/kls.v7i2.10354
[24] Fanari, R., Meloni, C., Massidda, D. (2019). Visual and spatial working memory abilities predict early math skills: A longitudinal study. Frontiers in Psychology, 10: 2460. https://doi.org/10.3389/fpsyg.2019.02460
[25] Atherton, G., Cross, L. (2021). The use of analog and digital games for autism interventions. Frontiers in Psychology, 12: 669734. https://doi.org/10.3389/fpsyg.2021.669734
[26] Öllinger, M., Szathmáry, E., Fedor, A. (2023). Search and insight processes in card sorting games. Frontiers in Psychology, 14: 1118976. https://doi.org/10.3389/fpsyg.2023.1118976
[27] Weng, T.S. (2022). Enhancing problem-solving ability through a puzzle-type logical thinking game. Scientific Programming, 2022(1): 7481798. https://doi.org/10.1155/2022/7481798
[28] Ratri, M.M., Wardhani, P., Triyani, I. (2023). The influence of Borneo puzzle game based on education game towards the concentration level of children with attention deficit hyperactivity disorder (ADHD) in the extraordinary school of Pontianak City. Jurnal Kesehatan Manarang, 9(2): 112-120. https://doi.org/10.33490/jkm.v9i2.722
[29] Aral, N., Gursoy, F., Yasar, M.C. (2012). An

investigation of the effect of puzzle design on children's development areas. Procedia: Social and Behavioral Sciences, 51: 228-233. https://doi.org/10.1016/j.sbspro.2012.08.150

[30] Smith, E., Anderson, A., Thurm, A., Shaw, P., Maeda, M., Chowdhry, F., Chernomordik, V., Gandjbakhche, A. (2017). Prefrontal activation during executive tasks emerges over early childhood: Evidence from functional near-infrared spectroscopy. Developmental Neuropsychology, 42(4): 253-264. https://doi.org/10.1080/87565641.2017.1318391

[31] Fiske, A., Mortimer, A., Collins-Jones, L., de Klerk, C.C.J.M., Gattas, S.U., Dvergsdal, H., Scerif, G., Holmboe, K. (2025). Inhibitory control development from infancy to early childhood: A longitudinal fNIRS study. Developmental Cognitive Neuroscience, 73: 101557. https://doi.org/10.1016/j.dcn.2025.101557

[32] Quaresima, V., Ferrari, M. (2019). A mini-review on functional near-infrared spectroscopy (fNIRS): Where do we stand, and where should we go? Photonics, 6(3): 87. https://doi.org/10.3390/photonics6030087

[33] Ramacciotti, M.C.C., Soares Junior, R.D.S., Sato, J.R., Gualtieri, M. (2024). Left OFC activation in functional near-infrared spectroscopy during an inhibitory control task in an early years sample: Integrating stress responses with cognitive function and brain activation. Developmental Neuroscience, 47(2): 81-97. https://doi.org/10.1159/000539023

[34] Fiske, A., Collins-Jones, L., de Klerk, C., Lui, K.Y.K., et al. (2024). The neural correlates of response inhibition across the transition from infancy to toddlerhood: An fNIRS study. Imaging Neuroscience, 2: 1-21. https://doi.org/10.1162/imag_a_00206

[35] Wang, Z.L., Wang, L.M. (2015). Cognitive development: Child education. In International Encyclopedia of the Social & Behavioral Sciences (Second Edition), pp. 38-42. https://doi.org/10.1016/B978-0-08-097086-8.92007-5

[36] Deák, G.O., Wiseheart, M. (2015). Cognitive flexibility in young children: General or task-specific capacity? Journal of Experimental Child Psychology, 138: 31-53. https://doi.org/10.1016/j.jecp.2015.04.003

[37] Lage, C., Smith, E.S., Lawson, R.P. (2024). A meta-analysis of cognitive flexibility in autism spectrum disorder. Neuroscience & Biobehavioral Reviews, 157: 105511. https://doi.org/10.1016/j.neubiorev.2023.105511

[38] Partington, J.W., Bailey, A., Partington, S.W. (2018). A pilot study on patterns of skill development of neurotypical children as measured by the ABLLS-R: Implications for educational programming for children with autism. International Journal of Contemporary Education, 1(2): 70-85. https://doi.org/10.11114/ijce.v1i2.3619

[39] Kroger, J., Kim, C. (2022). Frontopolar cortex specializes for manipulation of structured information. Frontiers in Systems Neuroscience, 16: 788395. https://doi.org/10.3389/fnsys.2022.788395

[40] Boere, K., Hecker, K., Krigolson, O.E. (2024). Validation of a mobile fNIRS device for measuring working memory load in the prefrontal cortex. International Journal of Psychophysiology, 195: 112275. https://doi.org/10.1016/j.ijpsycho.2023.112275

[41] Gerald, B., Patson, T.F. (2021). Parametric and nonparametric tests: A brief review. International Journal of Statistics and Applications, 7(3): 78-82. https://doi.org/10.11648/j.ijsd.20210703.12