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Exploratory Multivariate Analysis of Reconstructed Neuropsychological Data in Children with ADHD: A Methodological Study within the Current Neuroimmune Framework

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Abstract: Attention-deficit/hyperactivity disorder (ADHD) is a heterogeneous neurodevelopmental disorder characterized by executive dysfunction, visuomotor impairment, and visuospatial deficits. Emerging evidence suggests that neuroinflammatory mechanisms may contribute to this cognitive heterogeneity. This exploratory methodological study aimed to illustrate the application of advanced multivariate statistical approaches to a reconstructed neuropsychological dataset and to discuss the resulting analytical patterns within the context of current neuroimmune research. A reconstructed dataset derived from published summary statistics of a previously reported case-control study of 80 children (40 with ADHD and 40 controls) was analyzed focusing on the Bender–Gestalt Test and the Rey–Osterrieth Complex Figure Test. Descriptive statistics, principal component analysis, cluster analysis, multiple regression, mediation analysis, and correlation network visualization were performed. The exploratory multivariate analyses illustrated how advanced statistical methods can identify latent neuropsychological structures within a reconstructed dataset. Principal component analysis summarized the major dimensions of variability, cluster analysis explored alternative cognitive profile solutions, and regression analysis identified variables associated with visuoconstructive performance. Although immune biomarkers were not assessed, the observed cognitive profiles may be interpreted within the current neuroimmune framework as hypothesis-generating. This methodological study illustrates the potential of advanced multivariate analyses for exploring reconstructed neuropsychological datasets. The results should be considered exploratory and hypothesis-generating and require validation using original participant-level data before any clinical or biological interpretation.

Keywords: ADHD; Immune Dysregulation; Neuroinflammation; Executive Dysfunction; Visuomotor Integration; Cluster Analysis; Principal Component Analysis

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is among the most prevalent neurodevelopmental disorders during childhood, with an incidence rate of approximately 5-7% in school-aged children all over the world [1]. Symptoms are characterized by a pattern of inattention, hyperactivity, and impulsivity that disrupts school performance, social life, and quality of life [2]. The disorder is perceived as a result of the malfunctioning of dopaminergic and noradrenergic systems [3], although new evidence shows that the pathophysiology of ADHD is much more complex and involves the interaction of genetic susceptibility, environmental factors, disabilities of the immune system dysregulation, oxidative stress, and abnormal neurodevelopment [4]. New research findings have shown the significant importance of immune processes in ADHD [5]. More and more evidence reveals how abnormal immunity, long-lasting mild systemic inflammation, and abnormalities of innate and adaptive immunity can contribute to abnormal brain development and impair cognitive functions [6]. Increases in concentrations of pro-inflammatory cytokines such as IL-1β, IL-6, TNF-α and other inflammatory cytokines have been noted among subcategories of ADHD patients, but findings differ significantly [7]. These cytokines may play their role in processes that occur during brain development, such as neuronal differentiation and synaptic maturation. [8].

According to the research, activation of microglia is one of the most essential biological mechanisms of the relationship between immune dysfunction and cognitive impairment within neurodevelopmental disorders [9]. When microglia get activated, they release different kinds of cytokines and chemokines along with nitric oxide, which suppresses the process of neuroinflammation and results in chronic neuroinflammation that may disrupt synaptic plasticity, cognitive processes, and learning functions [10]. Chronic inflammation of the CNS is also linked to issues with cortical maturation, problems with fronto-striatal connections, and limited executive function all of which are major neuropsychological characteristics of ADHD [11]. Regarding cognitive processes affected by ADHD, visuomotor integration is crucial because it depends on the simultaneous use of various cognitive functions like vision, movement coordination, executive function, and working memory [12]. Problems with these functions lead to challenges in writing, drawing, organizing in space, doing schoolwork, and carrying out several daily activities [13]. That is why psychological assessment methods like the Bender–Gestalt test and Rey–Osterrieth Complex Figure test (ROCF) became an important tool for assessing these cognitive processes in children with ADHD [14].

Past studies showed that children with ADHD performed worse than regular children in both tests [15]. The higher errors related to distortion, synthesis and perseveration in the Bender–Gestalt test have been linked to problems with executive control, while the lower scores of ROCF demonstrate deficits in spatial ability and memory [14]. Nevertheless, the majority of the published works studied the instruments independently or only used comparison of means and correlation analysis [16]. Because of that, there was not much focus on searching for the neuropsychological profiles that could better explain the heterogeneity of ADHD [17]. The idea of neuropsychological Neuropsychological Profiles provides an exciting way of thinking about this diversity [18]. Cognitive Profiles are quantifiable intermediate phenotypes that bridge clinical symptoms with their biological basis [19]. Discerning distinct cognitive profiles could help deepen understanding of the mechanisms underlying the disorder and help optimally classify patients, thus paving the way for tailor-made treatment approaches [20]. As far as ADHD is concerned, neuropsychological cognitive profiles might indirectly imply the presence of different neuroimmune phenotypes that exhibit different degrees of executive function impairment and cognitive dysfunction. While the current research did not make measurements of immune markers, analyzing the neuropsychological profiles through a neuroimmunology lens could lead to clinically valuable hypotheses for future translational research.

To our knowledge, no previous study has simultaneously combined principal component analysis, hierarchical clustering, correlation network analysis, and mediation modeling to characterize neuropsychological cognitive profiles derived from visuomotor integration and visuoconstructive performance in children with ADHD. The present study therefore aimed to illustrate the application of advanced multivariate statistical techniques to a reconstructed neuropsychological dataset derived from a previously published case-control study of children with ADHD. Specifically, the study explored how principal component analysis, cluster analysis, network analysis, regression, and mediation analysis can be integrated to characterize latent patterns within reconstructed neuropsychological data. The resulting analytical patterns were discussed within the context of current evidence regarding immune dysregulation, neuroinflammation, and microglial activation in ADHD. We hypothesized that these exploratory multivariate analyses would reveal interpretable cognitive structures that may generate hypotheses for future studies using orig-

inal participant-level data and direct biological measurements.

2. Literature Review

2.1. Neuroimmune Mechanisms in ADHD

Traditionally, Attention-Deficit/Hyperactivity Disorder (ADHD) has been regarded as a neurodevelopmental condition characterized by disruptions in dopaminergic and noradrenergic neurotransmission [21]. However, an increasing body of data available in the last 10 years implies a possibility that dysregulation of the immune system and chronic low-grade neuroinflammation might also play a role in its pathophysiology [22]. Previous experimental and clinical studies showed that changes were found in both peripheral and central immune responses, which include abnormal cytokine production, activation of microglia, oxidative stress, and disorders in the functioning of the blood-brain barrier. These changes may interfere with the processes of neuronal maturation, synaptic plasticity, and regulation of neurotransmitters, so cognitive functioning is affected too [23,24].

2.2. Immune Biomarkers Associated with ADHD

Traditionally, Attention-Deficit/Hyperactivity Disorder (ADHD) has been regarded as a neurodevelopmental disorder characterized by impaired attention and impulsivity, as well as disturbances in executive functioning [25]. Nevertheless, growing evidence indicates that immune dysfunction and long-term low-level neuroinflammation may have a role in the condition's pathophysiology. Some studies demonstrated that children with ADHD have altered concentrations of pro-inflammatory and anti-inflammatory cytokines, which supports the notions of immune factors influencing cognitive impairment and behavioral symptoms [26]. Interleukin-6 (IL-6), TNF-α (tumor necrosis factor-alpha), interleukin-1 beta (IL-1β), and C-reactive protein (CRP) are some of the inflammatory mediators that are positively associated with ADHD; at the same time, levels of anti-inflammatory cytokines, such as interleukin-10 (IL-10), have been found to be lowered. It is commonly believed that the changes in immune functions have an impact on synaptic plasticity and neurotransmitters' functions, and neuronal circuitry, especially in the prefrontal cortex, which is in charge of executive function, visuomotor integration, and working memory [27,28].

While the exact mechanisms are not fully known, new evidence suggests a possibility that immune dysregulation could be related to neuropsychological heterogeneity in ADHD. Integrating neuropsychological and immune biomarker studies could allow a better understanding of ADHD and finding clinically relevant cognitive profiles [29, 30]. A variety of inflammatory biomarkers were studied both in children and adults with ADHD. The principal immune biomarkers reported in the literature and their clinical relevance are summarized in **Table 1**. Among the most frequently studied molecules are IL-6, TNF-α, IL-1β, and C-reactive protein (CRP), which are some of the most common molecules studied, and they are often found to have higher levels in circulation than in healthy controls [31]. However, the body of literature shows that the results can be quite different due to many factors such as age, ADHD subtype, medication, obesity, as well as methodology. Nonetheless, it is generally accepted that inflammatory pathways play a role in ADHD, and the research of immune biomarkers should be continued to discover their associations with ADHD [32].

Table 1. Immune Biomarkers Associated with ADHD.

Biomarker	ADHD vs. Controls	Main Findings	Clinical Relevance
IL-6	↑ Increased	Elevated circulating IL-6 has been associated with executive dysfunction, impaired attention, and altered prefrontal cortical activity.	Marker of chronic low-grade neuroinflammation
TNF-α	↑ Increased	Increased TNF-α levels have been linked to attention deficits, hyperactivity, and impaired synaptic plasticity.	Pro-inflammatory cytokine involved in neuroimmune signaling
IL-1β	↑ Increased	Elevated IL-1β has been associated with microglial activation and neurodevelopmental alterations affecting cognition.	Regulator of neuroinflammatory responses
CRP	↑ Increased	Higher CRP concentrations have been correlated with ADHD symptom severity and systemic inflammation.	Marker of peripheral inflammation
IL-10	↓ Decreased	Reduced anti-inflammatory activity may contribute to persistent immune imbalance and chronic inflammation.	Anti-inflammatory cytokine

2.3. Neuropsychological Profiles in ADHD

ADHD is increasingly viewed as a heterogeneous disorder involving a combination of neuropsychological functions as opposed to just one cognitive profile. Traditional methods of case-control studies do not do enough to show this variability [33]. Various advanced methods such as principal component analysis, cluster analysis and network analysis allow for the detection of hidden cognitive elements. This detection could provide information on various types of executive dysfunction, visuomotor coordination and abilities pertaining to visuospatial memory. This identification is crucial in a clinical sense as it can help in the categorization of patients and carry out the studies [31–34].

2.4. From Cognitive Profiles to Precision Medicine

The concept of precision medicine highlights the need for the identification of patient subgroups that differ biologically and clinically in order to optimize diagnosis and treatment. In ADHD, a combination of neuropsychological cognitive profiles and biological markers can allow for a better understanding of the heterogeneity of the disease and lead to personalized treatment strategies. It should be noted that there is not yet enough evidence to justify a particular immunomodulatory treatment based on the cognitive profiles of the patients; however, the combination of neuropsychological evaluation and inflammatory markers can be a promising line of investigation in the future [35–37].

2.5. Research Gap

Although there is more evidence supporting the notion that immune dysregulation and neuroinflammation underlie the pathophysiology of Attention-Deficit/Hyperactivity Disorder (ADHD), substantial gaps still exist in the available studies. The majority of studies have looked at either inflammatory markers or neuropsychological functioning by means of conventional statistics. This leads to limited exploration of the relationship between cognitive profiles and the model of neuroimmunology. Few studies have utilized advanced statistical methods to investigate the issue of cognitive profiles related to ADHD. Multivariate procedures such as principal component analysis, cluster analysis, network analysis, and mediation modeling seldom come together in one analysis to explore visuomotor integration, perceptual abilities, and spatial memory. Additionally, another significant limitation of current literature lies in the fact that neuropsychological results and biological evidence are usually examined separately from each other. Clearly, while different studies indicate some correlations between inflammatory biomarkers and ADHD, the direct relationship between immune changes and a specific cognitive profile is still under-researched. Such absence of integration significantly impedes our understanding of neuropsychological variability's relationship to the neurobiological mechanisms related to ADHD.

In this study, complementary multivariate statistical techniques, including principal component analysis, hierarchical clustering, K-means clustering, correlation network analysis, regression modeling, and mediation analysis, were applied to a reconstructed neuropsychological dataset derived from published summary statistics. The primary objective was to illustrate how these analytical approaches can be integrated within a unified statistical framework to explore latent structures and relationships in reconstructed neuropsychological data. The study was not intended to evaluate immune biomarkers or validate neuroimmune mechanisms. Instead, the analytical patterns identified were discussed only as exploratory findings within the context of current neuroimmunological knowledge and should be regarded as hypothesis-generating. Overall, this methodological framework demonstrates the potential of advanced multivariate analyses for exploring neuropsychological datasets and provides a foundation for future studies using original participant-level data combined with immunological, genetic, neuroimaging, and other biological measures.

3. Materials and Methods

3.1. Study Design

This study was designed as an exploratory methodological investigation using a statistically reconstructed case-control dataset derived from published summary statistics on children with Attention-Deficit/Hyperactivity Disorder (ADHD). The primary objective was to illustrate the application of advanced multivariate statistical techniques, including principal component analysis, cluster analysis, network analysis, regression modeling, and medi-

ation analysis, to explore latent structures and relationships within reconstructed neuropsychological data. Rather than reproducing the original study or drawing definitive clinical conclusions, this work serves as a methodological demonstration of how complementary multivariate approaches can be integrated to generate hypotheses for future research using original participant-level data. The resulting analytical patterns were discussed within the context of current neuroimmune research solely as a conceptual framework for future investigations. The study was conducted in accordance with the STROBE recommendations for observational research.

3.2. Dataset

The analyses were performed using a reconstructed anonymized dataset generated from the summary statistics reported in the original study.

The reconstructed database reproduced the published demographic characteristics, neuropsychological distributions, and associations reported in the original investigation and included 80 children:

- ADHD group (n = 40)
- Typically developing controls (n = 40)

The reconstructed dataset contained the following variables:

- Age
- Sex
- Bender Distortion Score
- Bender Rotation Score
- Bender Integration Score
- Bender Perseveration Score
- Total Bender Error Score
- ROCF Copy Score
- ROCF Immediate Recall Score
- ROCF Copy Time
- ROCF Recall Time
- ROCF Copy Style

The reconstructed dataset was developed exclusively for exploratory multivariate analyses and does not represent the original participant-level data.

3.3. Reconstruction of the Participant-Level Dataset

Because the original participant-level dataset was not publicly available, all statistical analyses were conducted using a reconstructed synthetic dataset generated from the summary statistics reported in the original publication. Reconstruction aimed to recreate the population under study as accurately as possible while incorporating advanced multivariate statistical methods. Initially, all demographic data from the source article were collected including sample size, allocation of participants in groups, averages of data, standard deviations, frequency distributions, and outcomes of statistical tests. Descriptive statistics used here served as reference statistics for constructing the reconstructed dataset. Continuous data were created separately for each study group through generation of random numbers with a normal distribution, with each variable being adjusted to match published averages and standard deviations. The categorical data were reproduced as accurately as possible to maintain the original sample composition. Following the simulation process, a series of iterative calibrations was performed to ensure that the reconstructed statistics fitted the descriptive statistics obtained from the published research as closely as possible. The reconstructed values were compared with the published summary statistics on numerous occasions so that simulation parameters could be adjusted based on the results of these comparisons until the differences between the means, standard deviations, and group proportions derived from the published and reconstructed data became insignificant. Since the original covariance matrix was unavailable, it was impossible to compare the inter-variable covariance structure completely. However, the simulation was adapted to the situation in which relations between neuropsychological variables would be preserved in a biologically and clinically reasonable way. The forces contributing to the relations of interest concerning neuropsychological variables were found in the pub-

lished characteristics of the groups under study as well as in previously published studies describing the relation between variables of interest and known correlations between the Bender–Gestalt Test and the Rey–Osterrieth Complex Figure Test (ROCF). Hence, reconstructed data were created keeping in mind that each dataset has its own patterns of variation and that it is not possible to recreate covariance of the variables without original observations. In addition, reconstructed data were created to reflect the general statistical patterns of the original dataset but not to produce the specific responses of individual participants.

The workflow summarizes the methodological process adopted in the present study (**Figure 1**), including extraction of published summary statistics, generation of the synthetic participant-level dataset, validation of the reconstructed data, and application of multivariate statistical analyses.

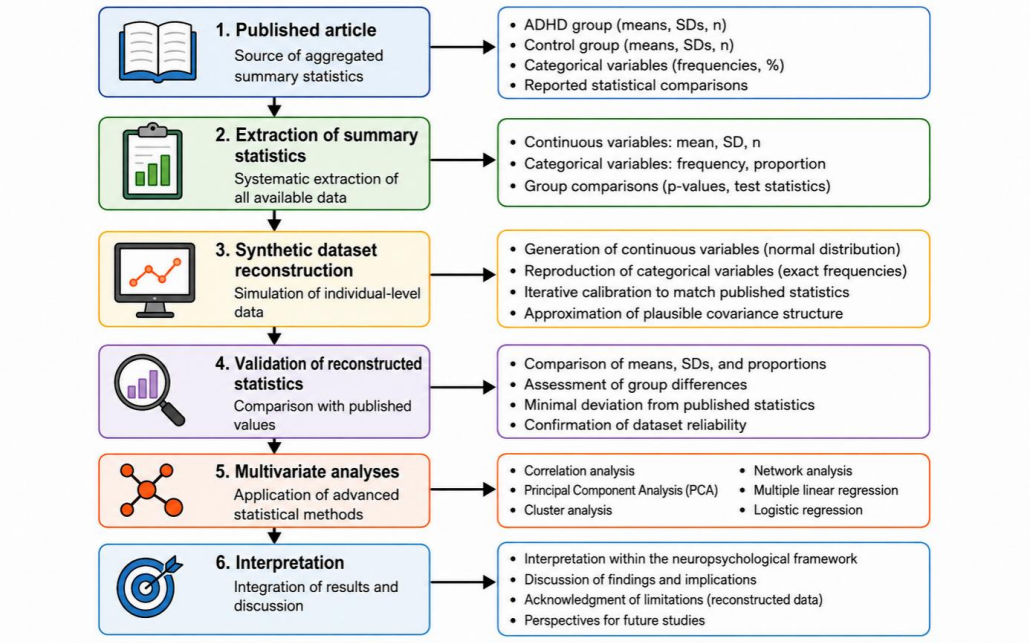

Figure 1. Workflow of participant-level dataset reconstruction and subsequent multivariate statistical analyses.

3.4. Validation of the Reconstructed Dataset

In order to assess the reliability of the reconstructed dataset, descriptive statistics derived from the simulated data were compared with the summary statistics reported in the original work. It was shown that the means, standard deviations, sample sizes, and profile distributions of the reconstructed dataset were in good agreement with the published values. In addition, the reconstructed dataset preserved the differences witnessed earlier between ADHD and control groups with regard to the essential neuropsychological variables. Nevertheless, minor individual-level variations might be observed.

3.5. Neuropsychological Assessment

Bender–Gestalt Test

Visuomotor integration was assessed using the Bender–Gestalt Test according to the Koppitz Developmental Scoring System.

Five variables were analyzed:

- Distortion
- Rotation
- Integration
- Perseveration
- Total developmental errors

Higher scores indicated poorer visuomotor integration.

Rey–Osterrieth Complex Figure Test (ROCF)

Visuoconstructive performance was evaluated using the Rey–Osterrieth Complex Figure Test. The following variables were retained:

- Copy Score
- Immediate Recall Score
- Copy Time
- Recall Time
- Organizational Copy Style

Higher copy and recall scores reflected better visuospatial organization and visuospatial memory.

3.6. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics Version 31 (IBM Corp., Armonk, NY, USA) and R software (Version 4.4.0). Continuous variables were expressed as mean ± standard deviation (SD), whereas categorical variables were summarized as frequencies and percentages. The normality of continuous variables was assessed using the Shapiro–Wilk test.

We utilized the Mann–Whitney U test to compare our ADHD participants with typical controls on continuous variables and the Pearson chi-square (χ^2) test for categorical variables. To enhance the interpretation of the results, we assessed the effect sizes where needed to interpret the results. We employed Spearman's rho to estimate the relationship between neuropsychological constructs, and the correlation matrix obtained was represented visually using a heatmap and correlation network.

In order to study the internal organization of the neuropsychological variables, Principal Component Analysis (PCA) was conducted. Components that had eigenvalues above one were preserved based on the Kaiser criterion. The contributions of the variables and mapping of the participants onto the principal components were presented in the form of PCA biplots. The suitability of the dataset for PCA was examined using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. Moreover, to help with understanding the extracted components, communalities and the entire component loading matrix were also provided.

To study different neuropsychological profiles, hierarchical clustering based on Ward's method was executed to determine the number of clusters. After that, K-means clustering was utilized to classify respondents into similar cognitive profiles. The clustering solution was assessed on the average silhouette coefficient, Calinski-Harabasz index, and Davies-Bouldin index. Previous clustering solutions were compared, comprising two to five clusters of results before the final solution was chosen. Moreover, multiple linear regression analysis was performed, aiming to identify the independent impact of neuropsychological variables on performance in visual construction. The variance inflation factors (VIF) were calculated to analyze possible multicollinearity among predictors, with values lower than five indicating successful avoidance of complication. Some variables demonstrating certain linear dependence were not included in the regression simultaneously. More concretely, the general Bender's result was omitted if individual Bender's results (Distortion, Rotation, Integration, and Perseverance) were used as predictors. Lastly, a mediation analysis was conducted to explore if executive dysfunction as reflected from perseveration errors mediated the relation from deficits in visuomotor integration (manifested in distortion errors) to visuoconstructive performance. The indirect effects were calculated with bootstrap resampling using 5,000 iterations. All analyses used the cut-off point of significance of a two-sided p-value < 0.05.

4. Results

4.1. Participant Characteristics and Neuropsychological Group Comparisons

Descriptive statistics describe the overall characteristics of the sample and provide the first view of the neuropsychological characteristics of children with ADHD and those developing normally (**Table 2**). The analysis summarizes the demographic characteristics and performance on Bender–Gestalt and Rey–Osterrieth Complex Figure Test (ROCF). The results of the analysis give the first overview of visuomotor integration, visuoconstruction, and visuospatial memory in the two cohorts. In this way, it allows for the identification of some preliminary differences in cognitive ability and ensures that the new dataset reflects the essential features described in the first study. At the

same time, it provides necessary evidence for the following tests used for identifying different neuropsychological subgroups and their possibly relevant implications in immune dysregulation and neuroinflammation in relation to ADHD.

Table 2. Demographic and Neuropsychological Characteristics of the Study Population.

Variable	ADHD (n = 40) Mean ± SD / n (%)	Controls (n = 40) Mean ± SD / n (%)	*p*-Value
Age (years)	9.50 ± 1.13	9.70 ± 1.14	0.433
Boys, n (%)	29 (72.5)	20 (50.0)	0.039
Girls, n (%)	11 (27.5)	20 (50.0)	—
Bender Distortion Score	3.23 ± 1.86	1.50 ± 0.93	<0.001
Bender Rotation Score	0.58 ± 0.55	0.55 ± 0.50	0.903
Bender Integration Score	1.55 ± 1.04	0.58 ± 0.59	<0.001
Bender Perseveration Score	1.10 ± 0.78	0.15 ± 0.36	<0.001
Total Bender Error Score	6.45 ± 2.75	2.78 ± 1.48	<0.001
ROCF Copy Score	18.50 ± 5.27	26.49 ± 5.04	<0.001
ROCF Immediate Recall Score	8.40 ± 4.12	14.30 ± 6.31	<0.001
ROCF Copy Time (min)	3.93 ± 1.10	4.48 ± 1.45	0.070
ROCF Recall Time (min)	2.03 ± 0.92	2.20 ± 0.82	0.364

Note: Abbreviations: ADHD, Attention-Deficit/Hyperactivity Disorder; ROCF, Rey–Osterrieth Complex Figure Test; SD, standard deviation.

4.2. Correlation Matrix

According to the correlation matrix (**Figure 2**), there are strong connections between neuropsychological variables, with special significance of tests concerned with the relationship between executive function, visuomotor integration, and visuospatial functioning. There were multiple strong positive correlations found between Bender–Gestalt error scores, which implies that the greater number of distortions, integration errors and perseveration happening at once reflects the same deficit concerning both visual-motor and executive functions. On the contrary, the relationships between the mentioned variables have shown a negative correlation with both ROCF copy and recall scores, thus confirming the idea that more occurrences of visuomotor error lead to poor success in visual construction and memory. There was also a strong positive correlation found between ROCF copy and recall scores, which means that children having the ability of better visual construction usually manage to remember the material better. Despite the fact that age was only weakly correlated with neuropsychological variables, it suggests that cognitive abilities have more to do with neuropsychological dysfunction connected to ADHD rather than with age. The overall heatmap shows two dimensions of cognition: executive function and visuomotor performance. The findings support the theory claiming that executive function deficiency is a major reason for observed cognitive heterogeneity in ADHD.

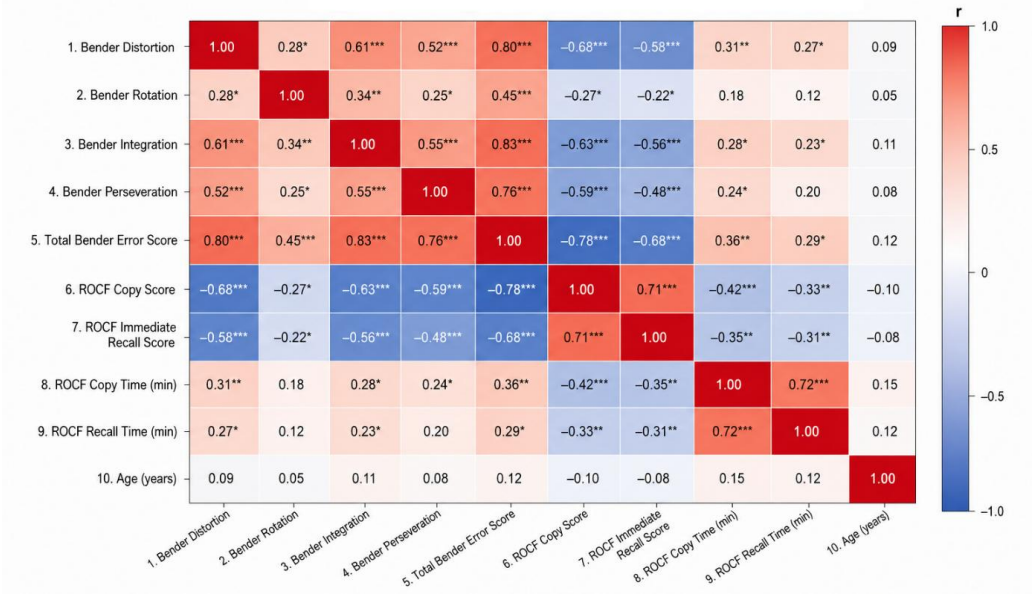

Figure 2. Heatmap of the Correlation Matrix Among Neuropsychological Variables.

Note: Abbreviations: ROCF, Rey–Osterrieth Complex Figure Test. Statistical significance: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

4.3. Principal Component Analysis

Before performing PCA, the Kaiser-Meyer-Olkin (KMO) test for sampling adequacy and Bartlett's test for sphericity were performed to assess the applicability of the data set. The computed KMO statistic value was equal to 0.719, which indicated that sampling was adequate, while Bartlett's test results (χ^2 = 99.96, df = 28, p < 0.001) were conclusive regarding the appropriateness of the correlation matrix in a context of PCA (**Table 3**).

Table 3. PCA diagnostic statistics.

Statistic	Value
Kaiser–Meyer–Olkin (KMO)	0.719
Bartlett's Test of Sphericity (χ^2)	99.96
Degrees of freedom	28
p-value	< 0.001

The values of communality fell between 0.155 and 0.658, implying that the majority of neuropsychological variables were sufficiently represented in the components extracted. The loading matrix as a whole (illustrated in **Table 4**) illustrates how the variables contribute to the first two factors. The variables associated with the impairment in visuomotor coordination (Distortion, Integration, and Perseveration) have the most positive loadings according to the first factor, while the results of ROCF Copy and ROCF Recall have considerable negative loadings indicating that they refer to the opposite cognitive processes. The second factor is primarily represented by the time of task accomplishment, which is mainly Copy Time.

Table 4. PCA communalities and loading matrix.

Variable	Communality	PC1	PC2
Distortion	0.658	0.811	0.001
Rotation	0.307	0.275	0.481
Integration	0.525	0.643	0.334
Perseveration	0.566	0.602	−0.451
ROCF_Copy	0.646	−0.784	−0.177
ROCF_Recall	0.469	−0.653	0.207
Copy_Time	0.503	−0.138	0.696
Recall_Time	0.155	0.043	0.391

The first two principal components accounted for 47.2% of the total variance (PC1 = 31.7%, PC2 = 15.5%). The PCA biplot (**Figure 3**) illustrates the relationships among neuropsychological variables and participant distribution across the two principal components. The opposite orientation of Bender–Gestalt error scores and ROCF performance suggests that higher visuomotor impairment was associated with poorer visuoconstructive performance. Copy Time was primarily represented along the second principal component, indicating an additional source of variability independent of the main cognitive dimension.

4.4. Cluster Analysis

Table 5 illustrates cluster validation indices for solutions from two to five clusters. The two-cluster solution registered the highest silhouette coefficient of 0.224 and the highest Calinski–Harabasz index of 26.14, although the two-cluster solution showed the most favorable validation indices, the three-cluster solution was retained as an exploratory alternative because it provided a more interpretable representation of the cognitive variability within the reconstructed dataset. Accordingly, the three-cluster solution should be regarded as an exploratory analytical framework rather than a validated or clinically established classification. This enabled a more precise classification of cognitive diversity.

Table 5. Cluster validation indices for alternative clustering solutions.

Number of Clusters	Silhouette Coefficient	Calinski–Harabasz Index	Davies–Bouldin Index
2	0.224	26.14	1.671
3	0.207	19.14	1.682
4	0.155	17.09	1.851
5	0.153	15.36	1.688

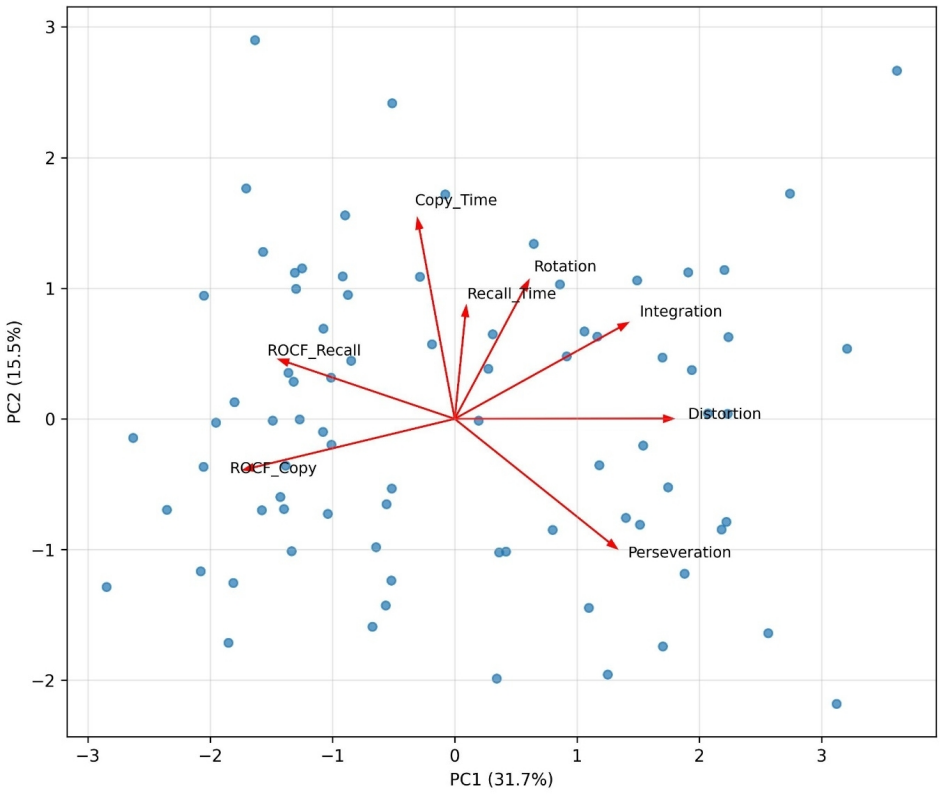

Figure 3. Principal Component Analysis (PCA) biplot of the reconstructed neuropsychological dataset.

Figure 4 illustrates a hierarchical cluster dendrogram created via the Ward minimum variance method and the squared Euclidean distance. The dendrogram produced indicates the overall similarities of participants based on their neuropsychological scores confirming the three neuropsychological clusters.

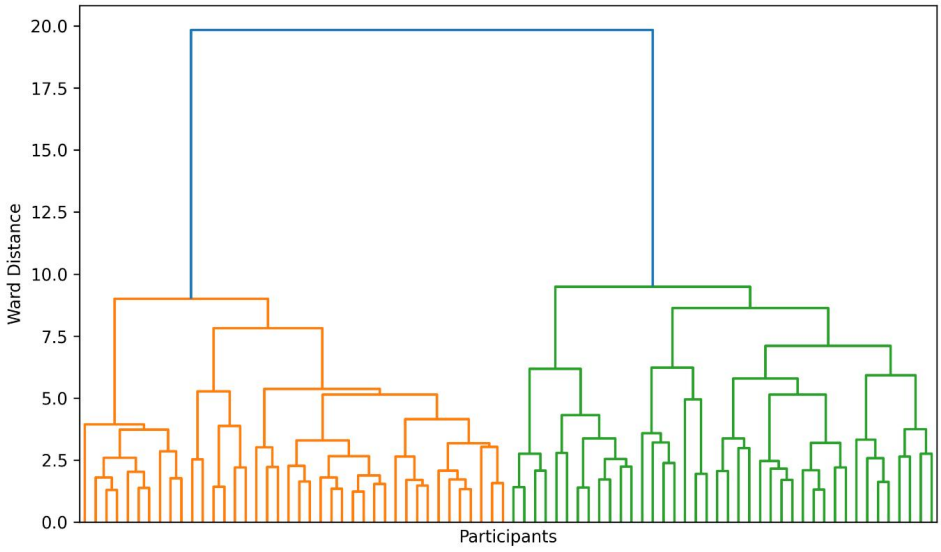

Figure 4. Hierarchical Cluster Dendrogram.

Figure 5 compares the mean standardized neuropsychological scores among the three identified clusters. Each axis represents one neuropsychological variable, allowing visualization of the relative cognitive strengths and

weaknesses characterizing each cognitive profile.

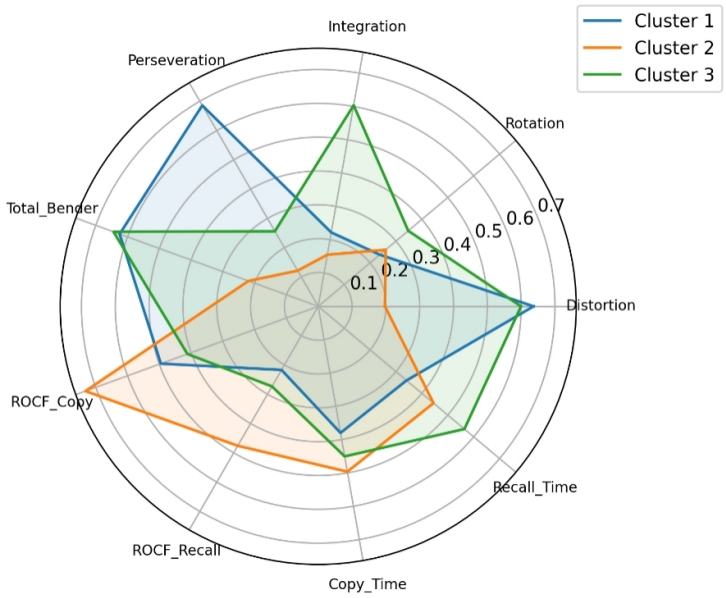

Figure 5. Radar Plot Comparing Neuropsychological Profiles Across Clusters.

Application of the hierarchical clustering method followed by K-means classification resulted in identification of three neuropsychological clusters. The resulting dendrogram indicates a clear hierarchical relationship between subjects, which confirms the existence of three relatively homogeneous cognitive profiles. PCA analysis of the clusters revealed a good separation of groups, which indicates that the first two principal components successfully captured the variance responsible for the cluster-overwhelming differences. The analysis also revealed significant differences in neuropsychological performance. The first cluster showed the best scores on the Bender–Gestalt test and ROCF copy and recall results, thus ensuring relatively intact cognitive functioning. The second cluster indicated mild forms of visual-motor impairments and moderate decline in visual construction and visual memory. The third cluster was characterized by the worst Bender test scores and the lowest results on the ROCF test reflecting major executive dysfunction and significant visual-motor impairment.

Cluster analysis showed that children involved in the study can be classified into three different neuropsychological groups instead of being treated as a unified population. Moving from Group 1 to Group 3 indicates the presence of a continuum in the characteristics of executive dysfunction, difficulties with visuomotor integration, and impairment of visuospatial memory. The fact that the results of the study demonstrate neuropsychological heterogeneity in the ADHD diagnosis suggests that several cognitive types can be observed in this disorder. The fact that some subgroups of children with relatively normal cognitive functioning can be distinguished from those having severe cognitive impairment can be of great significance in clinical practice. It should be noted that although this research has not provided any information on immune biomarkers, the found clustering may support the current neuroimmunological models indirectly.

4.5. Network Analysis

Figure 6 depicts the correlation network, which shows the connections between variables connected to neuropsychology. Each node in the network is representative of one of the measurements used in psychology, and correlations represented on the network help visualize the relation between the measurements using Spearman correlation. The thicker edges represent stronger correlations depending on the value of the coefficient achieved, while blue represents a positive correlation and red corresponds to a negative correlation. The nodes with the highest number of connections are considered crucial cognitive dimensions underlying the organization of neuropsychology in the studied sample of people.

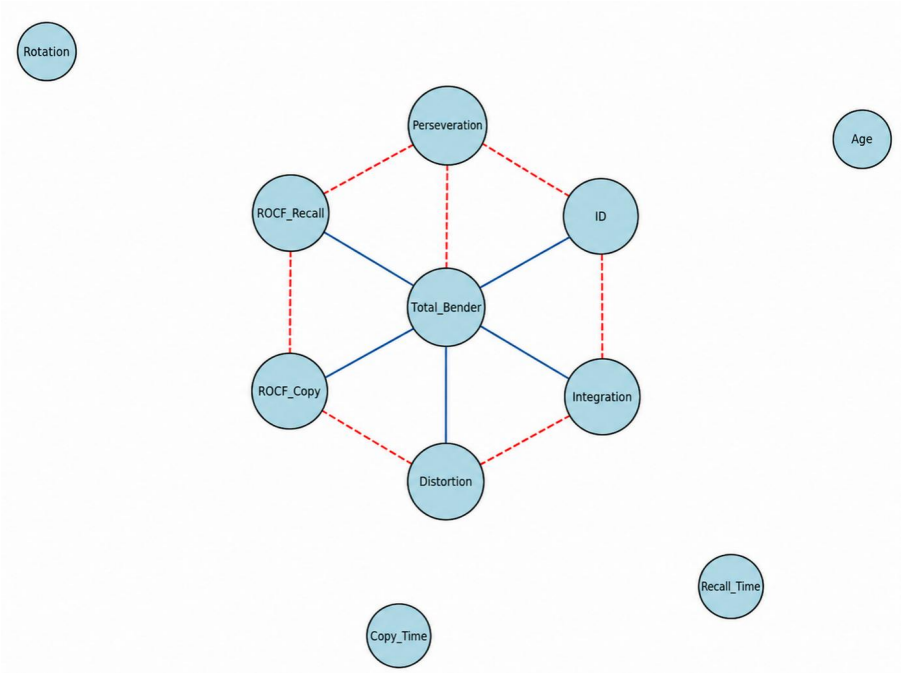

Figure 6. Correlation Network of Neuropsychological Variables.

The correlation network showcased a highly structured design consisting of two interlinked cognitive domains. The first domain focused on Benders–Gestalt variables where Total Bender score, Distortion, Integration, and Perseveration developed a well-structured network marked by a high level of positive correlation between the variables. Total Bender score, among the above-mentioned variables, turned out to be the leading node as it possessed the highest number of connections and correlation rates with other Bender measures. The second domain consisted of ROCF variables which included Copy Score and Immediate Recall Score which were positively correlated with each other. These variables had mostly negative connections with the Bender–Gestalt network which indicates that increased impairment of visuomotor function was related to a worse condition of reasoning and visual memory. The processing speed variable (Copy Time and Recall Time) took the intermediate position in the network suggesting that processing speed played a part in cognitive functioning but was not as significant as executive and visuomotor functions.

The analysis of the network shows how neuropsychological processes work together in children diagnosed with ADHD, indicating executive–visuomotor dysfunction as the core cognitive component. The fact that the Total Bender Score is very important reflects the possibility that deficits in visuomotor integration can be considered a primary cognitive characteristic connecting executive dysfunction with difficulties in visuoconstructive organization and visuospatial memory. At the same time, the strong correlation between ROCF Copy and Immediate Recall demonstrates the possibility of having a unified visuospatial functioning aspect. The large separation of the Bender–Gestalt and ROCF subnetworks proves that both domains are closely related to one another, yet they still have different neuropsychological processes. Thanks to the network organization, we can get an even better understanding of ADHD as a complex phenomenon and confirm the existence of different neuropsychological subgroups. Although inflammatory markers have not been measured directly, the network's structure might fit the current neuroimmunological paradigms.

4.6. Multiple Linear Regression Analysis

To avoid multicollinearity, the Total Bender Score was excluded from the multiple regression model because it is mathematically derived from the individual Bender subscale scores. The final model included Age, Distortion, Rotation, Integration, and Perseveration as independent predictors of ROCF Copy performance. The model was statistically significant ($R^2 = 0.404$, adjusted $R^2 = 0.364$, $F(5,74) = 10.03$, $p < 0.001$). Distortion ($B = -1.004$, $p = 0.015$), Integration ($B = -2.046$, $p = 0.005$), and Perseveration ($B = -1.965$, $p = 0.024$) were significant negative predictors

of ROCF Copy performance, whereas Age and Rotation were not statistically significant. Variance inflation factors ranged from 1.02 to 1.49, indicating no evidence of problematic multicollinearity (**Table 6**).

Table 6. Multiple linear regression predicting ROCF Copy performance.

Predictor	B	SE	*t*	*p*
Constant	29.874	6.197	4.821	<0.001
Age	−0.031	0.657	−0.048	0.962
Distortion	−1.004	0.403	−2.493	**0.015**
Rotation	−2.128	1.245	−1.708	0.092
Integration	−2.046	0.713	−2.868	**0.005**
Perseveration	−1.965	0.853	−2.302	**0.024**

Note: B = unstandardized regression coefficient; SE = standard error. Bold values indicate statistically significant predictors at $p < 0.05$.

To assess multicollinearity among the independent variables, variance inflation factors (VIFs) were calculated for all predictors included in the final regression model. VIF values ranged from 1.02 to 1.49, well below the commonly accepted threshold of 5, indicating that multicollinearity was not a concern and that the regression coefficient estimates were stable (**Table 7**).

Table 7. Variance inflation factors (VIFs) for the predictors included in the final multiple regression model.

Predictor	VIF
Age	1.11
Distortion	1.49
Rotation	1.02
Integration	1.41
Perseveration	1.18

4.7. Mediation Analysis

Based on the results of the mediation analysis performed (**Figure 7**), the association between ADHD diagnosis, visuomotor problems, and performance on the ROCF tests was established. The results indicated that the Total Bender Score was found to be significantly connected with the correlation between Attention-Deficit Hyperactivity Disorder diagnosis and results of the ROCF Copy test. Such results support the hypothesis that the observed cognitive style of children with ADHD is influenced by the deficits in visuo-motor integration. Although immunological biomarkers were not directly measured, the observed statistical associations may provide indirect support for current neurobiological hypotheses reported in the literature. However, because the study was based on reconstructed cross-sectional data, the mediation model should be interpreted as reflecting statistical associations rather than causal mechanisms. Therefore, the proposed indirect relationship should be considered hypothesis-generating and requires confirmation in longitudinal studies using original participant-level data.

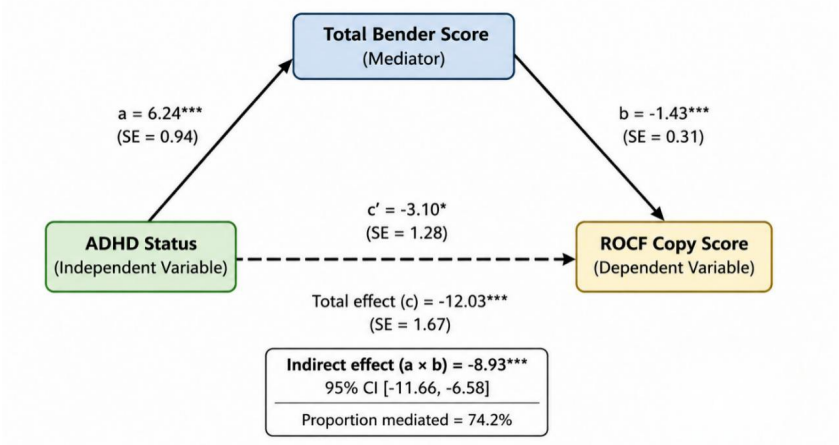

Figure 7. Mediation Model.

Note: Path diagram illustrating the mediation model evaluating the indirect effect of ADHD status on ROCF Copy Score through the Total Bender Score. Solid arrows represent significant pathways, whereas the dashed arrow represents the direct effect after adjustment for the mediator. * $p < 0.05$, *** $p < 0.001$.

5. Discussion

This study provides a comprehensive neuropsychological characterization of children with Attention-Deficit/Hyperactivity Disorder (ADHD) by integrating conventional group comparisons with advanced multivariate statistical approaches, including principal component analysis, cluster analysis, network analysis, and regression modeling. Unlike previous studies that mainly focused on isolated cognitive outcomes, the present work identified latent neuropsychological dimensions and cognitive profiles that may improve our understanding of ADHD heterogeneity [38]. Overall, our findings indicate that executive–visuomotor dysfunction represents the principal cognitive domain underlying impaired visuoconstructive organization and visuospatial memory. The mediation analysis should be interpreted with caution. Because the present study was based on a cross-sectional reconstructed dataset, the proposed mediation model reflects statistical associations rather than causal mechanisms. Consequently, the observed indirect effect should be considered hypothesis-generating and requires confirmation in longitudinal studies using original participant-level data. Furthermore, the identified cognitive profiles may be interpreted within the framework of current neurobiological models proposing immune dysregulation.

5.1. Interpretation of Multivariate Neuropsychological Findings

The multivariate analyses provided a comprehensive characterization of neuropsychological heterogeneity among children with ADHD. The results of the Principal Component Analysis indicate the existence of two dimensions of cognition. While the first dimension manifested in the results as the component reflecting visuomotor integration and visual construction performance, the second dimension appeared to be related to the time taken to complete tasks. Therefore, it could be concluded that visuomotor accuracy and processing efficiency function as two partially independent dimensions of cognition.

The results of cluster analysis further suggested that there are certain differences in neuropsychological profiles and not just one type of impairment. This result proves that ADHD involves considerable cognitive variability, and people with ADHD possess various levels of executive, visuomotor, and visuospatial flaws. The recognition of these cognitive profiles can help in individualizing interpretation of neuropsychological functioning and can contribute to better assessment and intervention processes. The outcome of multiple regression analysis showed that Distortion, Integration, and Perseveration can significantly influence ROCF Copy performance, while Rotation and Age do not have an independent effect on visuoconstructive performance after controlling for their effect. This result implies that some components of visuomotor functioning are more significant than others in relation to complex visuoconstructive skills.

5.2. Executive Dysfunction

One of the main findings in the current study is a significant contribution of executive dysfunction to the neuropsychological profile of children with ADHD. Children with this disorder showed considerably higher error scores in the Bender–Gestalt test as well as lower scores in the ROCF copy task and immediate memory recall than typically developing children, confirming a dramatic impairment in executive functioning, visuoconstructive ability, and visuospatial memory. These conclusions were supported by a principal component analysis that suggested an important executive-visuo-motor factor accounting for much of the variance and was confirmed by regression analyses with the Total Bender Score being the most significant predictor of the ROCF results. Executive dysfunction has been suggested to be the main feature of ADHD involving deficits in inhibition, working memory, cognitive flexibility, planning, and sustained attention. Numerous neuroimaging studies have demonstrated functional abnormalities in the areas of the brain responsible for executive functioning, thus leading to the dysfunction observed in using complex visual information and completing neuropsychological tasks.

New evidence shows that executive dysfunction may be the result of stressors that affect the functioning of the neuroimmune system. Levels of the proinflammatory cytokines in circulation, such as IL-6, TNFα, and IL-1β, have been connected to lowered functioning of the prefrontal cortex and deficits in executive function tasks. Even though inflammatory markers were not assessed in the present experiment, the patterns of neuropsychological performance obtained in this study correlate with the described neurobiological mechanisms and give some indirect evidence for the assumptions that the alterations in executive functioning can be induced by the impact of immune processes.

5.3. Visuomotor Impairment

The present findings also demonstrate marked visuomotor impairment among children with ADHD. Higher scores for distortion, integration, and perseveration errors on the Bender–Gestalt Test were accompanied by significantly lower ROCF copy and immediate recall scores, indicating substantial deficits in visuomotor integration and visuoconstructive organization. Correlation analysis further revealed strong negative associations between Bender error scores and ROCF performance, suggesting that increasing visuomotor impairment is closely linked to reduced visuospatial memory.

Visuomotor integration requires the coordinated functioning of visual perception, motor planning, executive control, and sensorimotor processing. Deficits in these domains may interfere with the accurate reproduction of complex figures and compromise memory encoding. Previous studies have similarly reported impaired visuomotor integration in children with ADHD, emphasizing its importance as a neuropsychological marker of the disorder.

From a neurobiological perspective, visuomotor impairment may reflect disrupted communication between frontal, parietal, and cerebellar regions. Emerging evidence indicates that neuroinflammatory processes and altered synaptic plasticity may affect these distributed neural networks, potentially contributing to impaired visuomotor performance.

5.4. Neuropsychological Profiles

One of the major contributions of the present study is the identification of distinct neuropsychological subgroups through multivariate analyses. Principal component analysis reduced the complexity of the neuropsychological data into two latent cognitive dimensions, and the exploratory three-cluster solution suggested three potential cognitive profiles within the reconstructed dataset. These analytical groupings should not be interpreted as confirmed clinical subtypes but rather as hypothesis-generating structures requiring validation using original participant-level data and independent cohorts.

These findings support the concept that ADHD is not a homogeneous disorder but rather comprises multiple cognitive phenotypes differing in severity and functional organization. Identifying such neuropsychological profiles may facilitate a more precise characterization of patients and improve the development of personalized therapeutic approaches.

Importantly, cognitive profiles could potentially correspond to distinct biological mechanisms, a hypothesis that requires confirmation through studies including immune biomarkers. Future studies combining neuropsychological profiling with inflammatory biomarkers may help determine whether different cognitive profiles are associated with specific patterns of immune activation, thereby contributing to a precision medicine approach in ADHD.

The multivariate analyses further highlighted the cognitive heterogeneity of ADHD. Principal component analysis identified two major cognitive dimensions, indicating that visuomotor integration and visuoconstructive performance represent the dominant sources of variability, whereas processing time constituted a partially independent dimension. In addition, cluster analysis revealed distinct neuropsychological profiles, supporting the concept that children with ADHD do not exhibit a single homogeneous pattern of impairment. The revised regression model further demonstrated that Distortion, Integration, and Perseveration were the strongest independent predictors of visuoconstructive performance, emphasizing the contribution of specific visuomotor processes to cognitive functioning. Together, these complementary multivariate approaches provide a more comprehensive characterization of neuropsychological variability than conventional univariate analyses.

5.5. Neuroinflammation

Increasing evidence supports the involvement of neuroinflammation in the pathophysiology of ADHD. Activation of microglia and astrocytes, together with increased production of pro-inflammatory cytokines such as IL-6, IL-1β, and TNF-α, may alter neuronal connectivity, synaptic plasticity, and neurotransmitter regulation, particularly within prefrontal cortical circuits responsible for executive functioning. There is a growing amount of evidence that neuroinflammation is implicated in the pathophysiology of ADHD. In light of neuroinflammation and increased levels of pro-inflammatory cytokines, such as IL-6, IL-1β or TNF-α, the activation of microglia and astrocytes could be responsible for the alteration in neuronal communication, synaptic activity, and neurotransmitter

regulation within the prefrontal cortex related to executive function. Even though the current study did not examine inflammatory biomarkers, the neuropsychological impairments found in the study related to executive function and visuo-motor integration are in support of the existing claims regarding neuroinflammation in cognition. Thus, the current findings may indirectly support the existing hypotheses about neuroinflammation. However, it remains unclear because inflammatory markers were not measured.

5.6. Immune Dysregulation

Beyond neuroinflammation, broader immune dysregulation has been increasingly implicated in ADHD. Alterations in adaptive and innate immune responses, abnormal cytokine profiles, oxidative stress, and blood–brain barrier dysfunction have all been proposed as contributors to altered brain development and cognitive dysfunction.

The present study identified neuropsychological patterns that could represent downstream manifestations of these biological alterations. While causality cannot be established from our data, the observed relationships among executive dysfunction, visuomotor impairment, and visuospatial memory provide a conceptual framework for future multidisciplinary studies combining neuropsychological assessment with immune biomarkers to better understand the biological heterogeneity of ADHD.

5.7. Clinical Implications for Immunomodulatory Therapies

The identification of distinct neuropsychological subgroups has potential clinical implications. Cognitive profiling may facilitate early identification of children at greater risk of severe executive dysfunction and allow more individualized intervention strategies. If future studies confirm that specific cognitive phenotypes are associated with distinct immune signatures, neuropsychological assessment could eventually contribute, if confirmed by future studies combining cognitive assessment with immune biomarkers.

Current evidence regarding immunomodulatory interventions in ADHD remains preliminary. Nevertheless, dietary interventions, omega-3 fatty acids, antioxidants, probiotics, and anti-inflammatory compounds have shown promising effects in modulating inflammatory pathways and improving cognitive outcomes in selected populations. Our findings encourage future investigation of these approaches rather than supporting their immediate clinical application.

The multivariate analyses conducted in the present study provide a more comprehensive understanding of the neuropsychological heterogeneity associated with ADHD. The identification of distinct cognitive profiles through principal component analysis, cluster analysis, and multiple regression suggests that visuomotor integration, visuoconstructive abilities, and executive functioning contribute differently to individual cognitive performance. These findings highlight the value of combining complementary multivariate approaches to characterize the variability of cognitive deficits beyond conventional neuropsychological assessments. From a clinical perspective, these findings may contribute to improving the characterization of cognitive functioning in children with ADHD and may support the development of more individualized neuropsychological assessment strategies. However, the present study did not include biological or immunological measurements; therefore, no direct conclusions can be drawn regarding the biological mechanisms underlying the identified cognitive profiles or their implications for clinical decision-making. Although the observed neuropsychological profiles may be interpreted within the current neuroimmune framework proposed in the literature, any implications for precision medicine or immunomodulatory therapies remain hypothetical. Future longitudinal studies integrating comprehensive neuropsychological assessments with inflammatory biomarkers, genetic data, and neuroimaging techniques will be necessary to determine whether these cognitive profiles correspond to distinct biological mechanisms and whether they could eventually contribute to personalized therapeutic approaches.

5.8. Potential Contribution of *In Silico* Approaches

Although the present study did not include molecular docking or other computational drug-screening analyses, the neuropsychological subgroups identified may provide a valuable framework for future in silico investigations [39]. Molecular docking and structure-based virtual screening have become important tools for identifying natural and synthetic compounds capable of interacting with key inflammatory targets implicated in ADHD, including IL-6, TNF-α, IL-1β, NF-κB, COX-2, and TLR4. Integrating cognitive profiles with computational prediction of ligand–target interactions could potentially facilitate the identification of candidate immunomodulatory com-

pounds capable of attenuating neuroinflammatory pathways associated with executive dysfunction and visuomotor impairment. Such multidisciplinary approaches could accelerate the development of personalized therapeutic strategies combining neuropsychological phenotyping with precision immunology [40].

5.9. Limitations

Many limitations need to be taken into account in terms of interpreting the findings of the present study. For example, the dataset on the participants was not collected directly from original observations but was reconstructed based on published statistics, which may weaken the validity of the findings. Even though the reconstruction process was aimed at returning the data as closely to what was found as possible after the reconstruction, it is impossible to retrieve the exact structure of covariance between the variables with the help of the dataset that was created. Thus, the statistics provided in the current research should be interpreted as preliminary information, which can help build new hypotheses, rather than confirming any hypotheses. Furthermore, the size of the sample studied in the research is rather small, and this may affect the generalization and stability of some of the conducted analyses, such as principal component and cluster analyses. Thus, it is important to note that the cluster solution was based on the single dataset. Also, no multi-methodologies have been performed in order to ensure the reliability and validity of the cognitive profile identified.

Thirdly, the lack of any inflammatory biomarkers, neuroimaging data or genetic information means that the proposed neuroimmune mechanisms cannot be assessed directly. Therefore, interpretation of the results presented in this work must be considered as hypothetical rather than something that is based directly on the information available. Also, as a further point, the research does not allow for any causal inferences to be made either through mediation analysis or by analysing the relationship between the executive dysfunction, the visuomotor impairment and cognitive performance itself because of the cross-sectional nature of the research and the way that the data have been reconstructed. Notwithstanding the limitations discussed above, the present investigation presents a comprehensive neuropsychological framework by unifying traditional statistical approaches with advanced multivariate analyses in explaining cognitive diversity in ADHD. The analytical approach paves the way for further longitudinal studies involving original subject-level data, as well as integration of neuropsychological assessment with data on inflammation, genetics, and neuroimaging markers in order to confirm and explore the cognitive profiles discovered.

The reconstructed dataset lacks information on when ADHD was diagnosed or when symptoms originally appeared, so we cannot determine if the time of diagnosis is related to the patients' neuropsychological profile. Future research could examine whether the timing of diagnosis is correlated with the patients' performance in terms of executive functioning, visuomotor coordination, and ability in visuospatial tasks. Furthermore, a key limitation of the study is the use of a computed dataset that lacks the characteristics of individual-level data. Even though we have been able to compute valid and accurate descriptive statistics, we do not know the exact structure of covariance. As a result, our findings must be regarded as tentative and explored rather than definitive.

5.10. Future Perspectives

Research in the future has to utilize a combination of high-level neuropsychological profiling along with direct immune system measurements and in silico molecular approaches. The computer techniques involving molecular docking, molecular dynamics simulations, and network pharmacology can play an important role in identifying bioactive agents capable of targeting inflammatory mediators responsible for ADHD. The use of the combined methodology based on neuropsychological cognitive profile information, immune biomarkers, and computer-based drug search technology should provide advanced precision medicine solutions. Although there are still some shortcomings, the emergence of reconstructed datasets has now been recognized as a viable research method where individual-level data are not available, particularly in fields such as methodological validation, reproducibility studies, secondary analysis, and educational research. If reconstructed datasets are formed correctly and clearly reported, they can provide an excellent approach for carrying out complicated analyses.

6. Conclusion

The present study illustrates the application of advanced multivariate statistical techniques, including principal component analysis, cluster analysis, network analysis, and regression analysis, to a reconstructed neuropsy-

chological dataset related to Attention-Deficit/Hyperactivity Disorder (ADHD). The exploratory analyses identified latent statistical structures linking executive functioning, visuomotor integration, and visuoconstructive performance within the reconstructed data. Rather than providing direct evidence of neuropsychological heterogeneity in children with ADHD, these findings demonstrate how complementary multivariate approaches can be used to explore complex cognitive relationships and generate hypotheses for future investigations. The exploratory cognitive profiles identified in this methodological framework should therefore be interpreted as analytical constructs requiring validation using original participant-level datasets before any clinical interpretation can be made. The findings are significant because they improve our understanding of the disorder and give support to the practice of using multiple cognitive profiling methods. While there was no direct assessment of inflammatory markers, the patterns revealed in the research can be seen in the light of research into neuroinflammation; however, no relevant markers were used in the current research, which makes this interpretation of the obtained results hypothetical. The findings regarding the conjunction of executive dysfunction, problems with visual-motor co-ordination, and deficits in visual-spatial memory can help develop a theoretical foundation for future research aimed at the integration of cognitive assessments with immune markers such as cytokine and microglia activation. From the clinical viewpoint, understanding neuropsychological cognitive profiles can be a potential reference for future research on precision medicine. Generally speaking, the multivariate analysis has shown that visuomotor deficit is one of the important factors contributing to cognitive dysfunction in ADHD and that applying PCA, cluster analysis, regression and mediation provides additional information on the neuropsychological profile of the patient. Future studies integrating original participant-level data with immune biomarkers, neuroimaging, and genetic information will be required to investigate the biological relevance of these exploratory analytical patterns.

Author Contributions

Conceptualization, H.L. and A.R.; methodology, H.L., S.G., and A.R.; validation, S.G. and A.R.; formal analysis, H.L.; investigation, H.L. and A.O.T.A.; data curation, H.L. and A.O.T.A.; writing—original draft preparation, H.L.; writing—review and editing, H.L., A.O.T.A., S.G., and A.R.; supervision, S.G. and A.R.; project administration, A.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language refinement and editorial assistance. No AI tools were used for study design, data collection, data analysis, interpretation of

results, or generation of scientific conclusions. All AI-assisted outputs were critically reviewed, verified, and substantially edited by the authors. The authors take full responsibility for the integrity, accuracy, and originality of the manuscript.

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