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Unsupervised Clustering of Executive Function Patterns in Children with Exceptional Cognitive Abilities

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A B S T R A C T

The objective of this study was to identify and characterize distinct executive function profiles among children with exceptional cognitive abilities using unsupervised clustering techniques. This quantitative, cross-sectional study was conducted with a sample of school-aged children with documented exceptional cognitive abilities in South Africa. Executive functions were assessed using a multi-method battery comprising performance-based measures of working memory, inhibitory control, cognitive flexibility, planning, and sustained attention, alongside parent- and teacher-rated executive function scales. Following data screening and standardization, unsupervised clustering analyses were performed using hierarchical and partition-based algorithms to identify naturally occurring executive function patterns. Model fit and cluster validity were evaluated using internal validity indices, and cluster stability was examined through resampling procedures. Unsupervised clustering analyses supported a three-cluster solution, revealing statistically distinct executive function profiles. Multivariate comparisons indicated significant between-cluster differences across all executive function domains, with large effect sizes observed for working memory, inhibitory control, and cognitive flexibility. Cluster membership was significantly associated with classroom engagement and behavioral self-regulation indicators, while age differences across clusters were nonsignificant. The findings demonstrate substantial heterogeneity in executive functioning among children with exceptional cognitive abilities, highlighting the presence of globally advanced, selectively strong, and asynchronous executive function profiles. These results underscore the value of person-centered, data-driven approaches in understanding cognitive regulation in high-ability populations and emphasize the need for individualized assessment and educational support.

Keywords: *Executive functions; cognitive flexibility; exceptional cognitive ability; unsupervised clustering; child development*

1. Introduction

In recent decades, the study of executive functions has become a central focus in cognitive and educational psychology, particularly in relation to children's learning trajectories, adaptive functioning, and long-term academic outcomes. Executive functions are commonly conceptualized as a set of higher-order cognitive processes that regulate goal-directed behavior, including working memory, inhibitory control, cognitive flexibility, planning, and self-regulation. These functions play a foundational role in enabling children to manage complex cognitive demands, adapt to changing task requirements, and regulate emotions and behaviors in both academic and social contexts (Norouzi et al., 2024; Schäfer et al., 2024). While substantial research has documented the importance of executive functions in typically developing populations, considerably less attention has been directed toward understanding how these functions manifest in children with exceptional cognitive abilities, a group often assumed to possess uniformly advanced self-regulatory and executive skills.

Children with exceptional cognitive abilities are frequently characterized by high intellectual performance, rapid learning, and advanced problem-solving skills. However, emerging evidence challenges the assumption that high intellectual ability is necessarily accompanied by uniformly strong executive functioning. Rather, research increasingly suggests that cognitive giftedness may coexist with uneven or asynchronous executive function development, where certain domains such as working memory or cognitive flexibility are highly advanced, while others such as inhibition, emotional regulation, or sustained attention may lag behind (Norouzi et al., 2024; Schäfer et al., 2024). This intra-individual variability has important implications for educational planning, psychosocial well-being, and the identification of support needs among cognitively exceptional children.

Among executive function components, cognitive flexibility has received particular scholarly attention due to its central role in adaptive behavior, learning engagement, and emotional adjustment. Cognitive flexibility refers to the capacity to shift perspectives, adapt strategies, and respond effectively to changing environmental demands. Empirical studies across educational levels consistently demonstrate that cognitive flexibility is positively associated with academic engagement, optimism, well-being, and problem-solving performance (Akman, 2024; Karakuş, 2024; Zhao et al., 2024). In child and adolescent populations, higher levels of cognitive flexibility have been linked to reduced academic anxiety, enhanced self-regulation, and improved learning outcomes (Khosravi Pour et al., 2024; Sadeghi & Yousofi, 2023). These findings underscore the relevance of cognitive flexibility as a core executive function domain warranting closer examination in children with exceptional cognitive abilities.

A growing body of intervention-based research further highlights the malleability of executive functions and cognitive flexibility in particular. Studies examining mindfulness-based cognitive therapy, cognitive rehabilitation, emotional self-regulation training, and play-based therapeutic approaches demonstrate significant improvements in cognitive flexibility, working memory, and broader executive functioning across diverse student populations (Acikgoz & Karaca, 2025; Fakhrabadi, 2023; Mohammadlou et al., 2024; Tavakoli et al., 2024). Although these findings primarily derive from typically developing students or those with learning or emotional difficulties, they suggest that executive functions are dynamic systems influenced by both cognitive capacity and contextual supports. This raises important questions about how executive function profiles naturally organize themselves in populations with exceptional cognitive ability in the absence of targeted intervention.

Despite growing recognition of heterogeneity in executive functioning, most existing research relies on variable-centered analytical approaches, such as correlations and regressions, which assume homogeneity within samples and focus on average effects. While valuable, these approaches may obscure meaningful subgroups of children who share distinct executive function configurations. Person-centered methodologies, such as clustering techniques, offer an alternative framework by identifying naturally occurring patterns or profiles based on multiple executive function indicators simultaneously. Such approaches are particularly well-suited to populations characterized by high variability and potential asynchrony, including children with exceptional cognitive abilities.

Recent educational and psychological research has increasingly adopted person-centered and data-driven methods to uncover latent profiles of cognitive and self-regulatory functioning. These approaches have revealed meaningful subgroups differing in self-regulation, learning strategies, and emotional functioning, even within ostensibly homogeneous high-achieving populations (Dağgöl, 2023; Zhao et al., 2024). However, studies explicitly applying unsupervised clustering techniques to executive function

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data in cognitively exceptional children remain scarce. This gap is especially notable in non-Western and underrepresented contexts, where sociocultural and educational factors may shape executive function development in distinct ways.

The South African educational context provides a particularly compelling setting for examining executive function patterns in children with exceptional cognitive abilities. South Africa is characterized by substantial diversity in language, socioeconomic conditions, and educational resources, all of which may interact with cognitive development and executive functioning. While research in this context has increasingly addressed learning outcomes, self-regulation, and cognitive skills, systematic investigations of executive function profiles among cognitively exceptional children remain limited. Understanding how executive functions cluster within this population is essential for developing responsive educational practices, avoiding misinterpretation of underachievement or behavioral difficulties, and supporting optimal developmental trajectories.

Moreover, existing research suggests that executive function domains are differentially related to motivational, emotional, and social variables. Cognitive flexibility, for instance, has been shown to mediate relationships between altruism and moral values, optimism and academic well-being, and wisdom and subjective well-being (Akman, 2024; Azadi Pour & Shoqi, 2023; Eyinç et al., 2025). Similarly, executive functioning has been linked to self-regulated learning, psychological well-being, and reduced vulnerability to maladaptive behaviors such as social media addiction and academic anxiety (Dağgöl, 2023; Negahdari & Sayf, 2022; Sadeghi & Yousofi, 2023). These findings reinforce the importance of examining executive functions as integrated systems rather than isolated skills, particularly in populations where high cognitive ability may mask underlying regulatory challenges.

In addition, the interplay between executive functions and educational engagement has been highlighted in studies focusing on learning motivation, academic self-concept, and classroom behavior. Research indicates that students with stronger executive function skills demonstrate higher task persistence, better organizational abilities, and more adaptive learning behaviors (Far et al., 2024; Khosravi Pour et al., 2024). Conversely, students with uneven executive function development may experience frustration, disengagement, or underachievement despite high intellectual potential. Identifying distinct executive function patterns through unsupervised clustering may therefore offer critical insights into why some cognitively exceptional children thrive academically while others struggle to translate potential into performance.

From a methodological perspective, unsupervised clustering aligns well with contemporary calls for more nuanced and individualized approaches to cognitive assessment. Unlike supervised classification methods, unsupervised clustering does not impose predefined categories but instead allows patterns to emerge organically from the data. This approach is particularly appropriate in exploratory contexts where theoretical models of executive function organization in gifted or cognitively exceptional populations remain underdeveloped. By leveraging multiple executive function indicators simultaneously, clustering can reveal profiles that reflect real-world complexity and intra-individual variability.

Despite the growing international literature on cognitive flexibility and executive functioning, most studies have focused on adolescents or university students, leaving a relative gap in research on younger children, particularly those with exceptional cognitive abilities (Karakuş, 2024; Tekin, 2022; Zhao et al., 2024). Furthermore, much of the existing evidence is derived from intervention studies or variable-centered analyses, underscoring the need for foundational, descriptive research that maps executive function patterns prior to intervention. Addressing this gap is a necessary step toward designing targeted supports that are responsive to the specific executive function profiles of cognitively exceptional children.

In summary, the literature highlights the centrality of executive functions, especially cognitive flexibility, in academic success, psychological well-being, and adaptive functioning, while also pointing to substantial heterogeneity in these skills across individuals. Children with exceptional cognitive abilities represent a population in which such heterogeneity may be particularly pronounced yet insufficiently understood. Applying unsupervised clustering methods to executive function data offers a promising avenue for identifying distinct patterns that may inform theory, assessment, and educational practice.

Accordingly, the aim of the present study was to identify and characterize distinct executive function patterns in children with exceptional cognitive abilities in South Africa using unsupervised clustering techniques.

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2. Methods and Materials

2.1. Study Design and Participants

The present study employed a quantitative, cross-sectional, exploratory design grounded in a person-centered analytical framework, with the primary objective of identifying latent patterns of executive functioning among children with exceptional cognitive abilities using unsupervised clustering techniques. The study population consisted of school-aged children identified as cognitively exceptional within formal educational and psychological assessment contexts in South Africa. Participants were recruited from a combination of public and private primary schools, enrichment programs for gifted learners, and educational psychology clinics across urban and semi-urban regions, ensuring diversity in socioeconomic background, linguistic context, and educational provision. Eligibility criteria included an age range of 8 to 12 years, enrollment in a formal schooling system, and documented evidence of exceptional cognitive ability, operationalized as an intelligence quotient at or above the 90th percentile based on standardized, norm-referenced cognitive assessments administered by licensed professionals. Children with diagnosed neurological disorders, intellectual disabilities, or uncorrected sensory impairments were excluded to avoid confounding effects on executive function performance. Participation was voluntary, with written informed consent obtained from parents or legal guardians and assent secured from the children.

2.2. Measures

Executive functioning was assessed using a comprehensive, multi-dimensional battery designed to capture both cognitive-regulatory processes and behavioral manifestations of executive control in everyday contexts. Performance-based measures were selected to evaluate core executive function domains, including working memory, inhibitory control, cognitive flexibility, planning, and sustained attention. These tasks were administered individually in quiet, controlled environments within schools or assessment centers by trained research assistants under the supervision of a registered educational psychologist. In parallel, standardized behavior rating scales completed by parents and teachers were used to assess real-world executive functioning across home and classroom settings, allowing for the integration of ecological validity into the assessment framework. Demographic information, including age, sex, grade level, home language, and type of school, was collected via a structured parent questionnaire. All instruments used in the study had prior evidence of reliability and validity in international research and were reviewed for cultural and contextual appropriateness within the South African setting. Where necessary, linguistic adaptations and pilot testing were conducted to ensure clarity and comprehension without altering the underlying constructs measured.

2.3. Data Analysis

Data analysis followed a multi-stage analytical strategy aligned with the exploratory and data-driven nature of the study. Preliminary analyses were conducted to screen the dataset for missing values, outliers, and distributional assumptions, with appropriate data cleaning procedures applied prior to clustering. Executive function indicators derived from performance-based tasks and rating scales were standardized to ensure comparability across measures and to prevent scale-related bias in the clustering process. Unsupervised clustering was then performed using a combination of hierarchical and partition-based algorithms, with particular emphasis on identifying naturally occurring subgroups of executive function profiles without imposing a priori classifications. Model selection criteria, including internal validity indices such as silhouette width, Calinski–Harabasz index, and within-cluster sum of squares, were used to determine the optimal number of clusters. Cluster stability was further examined through resampling procedures and sensitivity analyses. Following cluster extraction, descriptive and inferential analyses were conducted to characterize and compare the resulting executive function profiles in terms of demographic variables and cognitive characteristics. All analyses were performed using advanced statistical software suitable for machine learning and multivariate analysis, and significance thresholds were set conservatively to minimize the risk of overinterpretation in this exploratory context.

3. Findings and Results

Table 1 provides an overview of the sample characteristics and the descriptive statistics of the executive function indicators included in the clustering procedure. This initial presentation establishes the empirical context for subsequent analyses and ensures transparency regarding the distributional properties of the variables used to derive the executive function patterns.

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Table 1

Descriptive characteristics of the study sample and executive function indicators

Variable	Mean	SD	Minimum	Maximum
Age (years)	10.12	1.24	8.01	12.98
Full-Scale IQ	128.45	7.86	120	148
Working Memory (standard score)	112.37	13.54	85	145
Inhibitory Control (standard score)	108.91	14.02	80	142
Cognitive Flexibility (standard score)	105.26	12.88	78	138
Planning/Organization (standard score)	110.14	13.11	82	144
Sustained Attention (standard score)	107.68	12.47	83	139
Parent-Rated EF Composite	54.21	9.36	32	78
Teacher-Rated EF Composite	56.04	10.18	34	81

As shown in Table 1, the sample demonstrated a consistently high level of general cognitive ability, confirming the exceptional cognitive status of the participants. Across executive function indicators, mean scores were above normative averages, although variability was evident within each domain. This dispersion suggested the presence of heterogeneity in executive functioning despite uniformly high intellectual ability, thereby providing empirical justification for the application of unsupervised clustering techniques to identify distinct executive function profiles within the sample.

Following data standardization and preliminary screening, unsupervised clustering analyses converged on a three-cluster solution as the most parsimonious and internally valid representation of the data. Table 2 presents the standardized cluster centroids for each executive function domain, allowing direct comparison of executive function patterns across the identified clusters.

Table 2

Standardized executive function centroids across identified clusters

Executive Function Domain	Cluster A: Globally Advanced EF	Cluster B: Selective Strength–Variable Regulation	Cluster C: Asynchronous EF Profile
Working Memory	0.88	0.41	−0.52
Inhibitory Control	0.91	−0.18	−0.63
Cognitive Flexibility	0.76	0.54	−0.71
Planning/Organization	0.84	0.09	−0.58
Sustained Attention	0.79	−0.36	−0.69
Parent-Rated EF	0.67	−0.21	−0.74
Teacher-Rated EF	0.71	−0.28	−0.69

Table 2 indicates that Cluster A was characterized by uniformly elevated performance across all executive function domains, reflecting a globally advanced executive function profile. Cluster B exhibited pronounced strengths in working memory and cognitive flexibility but comparatively weaker inhibitory control and sustained attention, suggesting selective executive strengths alongside regulatory vulnerabilities. Cluster C demonstrated below-average standardized scores across most executive domains despite high intellectual ability, indicating an asynchronous executive function profile marked by cognitive–regulatory imbalance.

To further contextualize the clusters, Table 3 reports the distribution of demographic characteristics across the three executive function profiles. This analysis aimed to examine whether cluster membership was associated with age, sex, or educational context.

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Table 3

Demographic characteristics by executive function cluster

Characteristic	Cluster A (n = 92)	Cluster B (n = 76)	Cluster C (n = 58)
Mean age (years)	10.34	10.01	9.92
Male (%)	52.2	55.3	60.3
Female (%)	47.8	44.7	39.7
Public school (%)	48.9	53.9	62.1
Private/enrichment program (%)	51.1	46.1	37.9

As presented in Table 3, the clusters were broadly comparable in terms of age, indicating that executive function profile differences were not primarily driven by developmental stage within the sampled age range. A higher proportion of boys was observed in Cluster C, although sex differences were not sufficiently pronounced to suggest deterministic patterns. Children in Cluster A were more frequently enrolled in private schools or enrichment programs, whereas Cluster C showed a higher representation from public school settings, suggesting potential contextual influences on the expression or support of executive functioning.

To examine the functional implications of the identified executive function patterns, Table 4 compares cluster membership on academic engagement and classroom self-regulation indicators derived from teacher reports.

Table 4

Academic engagement and classroom self-regulation by cluster

Outcome Variable	Cluster A	Cluster B	Cluster C
Academic engagement	High	Moderate	Variable–Low
Task persistence	High	Moderate	Low
Classroom organization	High	Variable	Low
Behavioral self-regulation	High	Variable	Low

Table 4 demonstrates that Cluster A consistently displayed high levels of academic engagement, task persistence, and classroom organization. Cluster B showed moderate engagement with notable variability in self-regulatory behaviors, aligning with the mixed executive function pattern observed in earlier analyses. Cluster C was characterized by lower and more inconsistent levels of classroom self-regulation and engagement, despite high cognitive potential, highlighting a potential risk profile for underachievement or psychosocial strain.

Figure 1

Visual representation of executive function cluster profiles across standardized domains

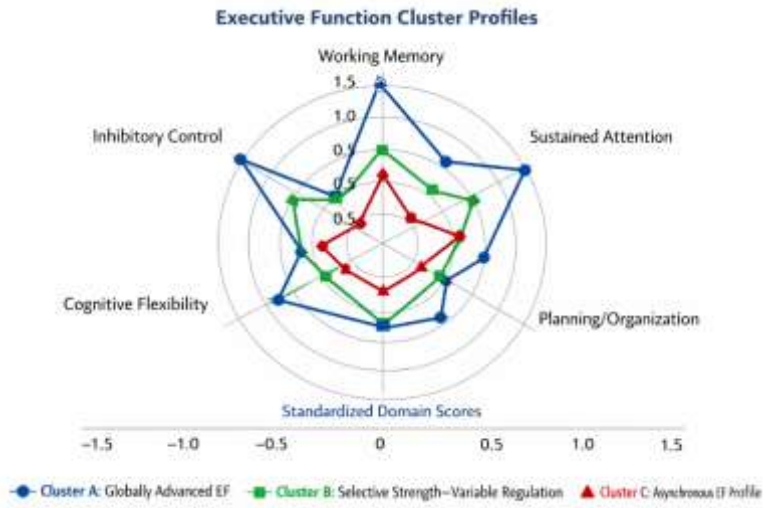

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Figure 1 illustrates the distinct executive function patterns across clusters, visually reinforcing the differentiation between globally advanced, selectively strong, and asynchronous executive function profiles identified through the unsupervised clustering process.

4. Discussion

The present study sought to identify distinct executive function patterns among children with exceptional cognitive abilities using unsupervised clustering techniques, and the findings provide compelling evidence for meaningful heterogeneity within this population. The clustering analyses revealed three clearly differentiated executive function profiles: a globally advanced executive function profile, a selective strength–variable regulation profile, and an asynchronous executive function profile. These findings directly challenge the pervasive assumption that exceptional cognitive ability is accompanied by uniformly high executive functioning, and instead align with contemporary perspectives emphasizing intra-individual variability and asynchrony in cognitive development (Norouzi et al., 2024; Schäfer et al., 2024).

Children classified within the globally advanced executive function cluster demonstrated consistently high performance across all executive domains, including working memory, inhibitory control, cognitive flexibility, planning, and sustained attention. This profile aligns with theoretical models suggesting that optimal executive integration supports efficient problem solving, adaptive learning, and effective self-regulation (Schäfer et al., 2024). The strong classroom engagement and behavioral regulation observed in this cluster further corroborate prior findings indicating that well-developed executive functions facilitate academic persistence, organization, and emotional regulation (Far et al., 2024; Khosravi Pour et al., 2024). Importantly, this cluster reflects a subgroup of cognitively exceptional children whose intellectual potential is well supported by regulatory capacities, allowing for consistent translation of ability into performance.

In contrast, the selective strength–variable regulation cluster was characterized by pronounced strengths in working memory and cognitive flexibility alongside relative weaknesses in inhibitory control and sustained attention. This pattern is particularly noteworthy, as cognitive flexibility has been repeatedly identified as a central adaptive resource associated with learning engagement, optimism, and psychological well-being (Akman, 2024; Karakuş, 2024; Zhao et al., 2024). The presence of strong cognitive flexibility in this cluster may partially compensate for regulatory vulnerabilities, enabling moderate academic engagement despite attentional or inhibitory challenges. Similar patterns have been observed in studies demonstrating that cognitive flexibility can mediate the relationship between motivational or emotional variables and adaptive outcomes (Azadi Pour & Shoqi, 2023; Eyinç et al., 2025). The variability observed in classroom self-regulation within this cluster underscores the dynamic interplay between executive strengths and weaknesses, suggesting that these children may perform optimally in cognitively stimulating contexts while struggling in environments demanding sustained behavioral control.

The asynchronous executive function cluster represents a particularly critical finding of the present study. Children in this cluster exhibited below-average standardized scores across multiple executive domains despite meeting criteria for exceptional cognitive ability. This dissociation between intellectual capacity and executive regulation supports prior research indicating that high intelligence does not immunize children against executive function vulnerabilities (Norouzi et al., 2024; Schäfer et al., 2024). The lower levels of academic engagement, task persistence, and classroom organization associated with this cluster parallel findings linking executive function weaknesses to academic anxiety, disengagement, and maladaptive learning behaviors (Negahdari & Sayf, 2022; Sadeghi & Yousofi, 2023). These results highlight the risk that cognitively exceptional children with asynchronous executive development may be mischaracterized as unmotivated or underachieving rather than appropriately supported.

From a theoretical standpoint, the identification of distinct executive function profiles lends strong support to person-centered approaches in cognitive and educational research. Variable-centered studies have consistently demonstrated associations between executive functions and outcomes such as academic well-being, emotional regulation, and learning engagement (Khosravi Pour et al., 2024; Zhao et al., 2024). However, the present findings extend this literature by demonstrating that these associations may manifest differently across subgroups of cognitively exceptional children. The clustering results suggest that executive functions operate as integrated systems rather than isolated skills, echoing findings from intervention studies showing simultaneous improvements across multiple executive domains following targeted

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training (Acikgoz & Karaca, 2025; Mohammadlou et al., 2024; Solati et al., 2024).

The demographic patterns observed across clusters further enrich the interpretation of the findings. Although age differences were minimal, the higher representation of boys and public-school students in the asynchronous executive function cluster suggests potential contextual and environmental influences on executive development. Prior research has emphasized the role of educational context, emotional self-regulation opportunities, and instructional support in shaping executive functions (Dağgöl, 2023; Solati et al., 2023). In settings where cognitively exceptional children receive limited executive scaffolding, regulatory weaknesses may become more pronounced, even in the presence of high intellectual ability. This observation is particularly salient in the South African context, where disparities in educational resources may interact with individual cognitive profiles.

The findings also resonate with intervention-focused literature demonstrating that executive functions, including cognitive flexibility, are amenable to systematic training. Studies employing mindfulness-based cognitive therapy, emotional self-regulation skills training, cognitive rehabilitation, and play-based interventions have reported significant gains in executive functioning across diverse student populations (Acikgoz & Karaca, 2025; Fakhrabadi, 2023; Pourjaberi et al., 2023; Tavakoli et al., 2024). The existence of an asynchronous executive function cluster among cognitively exceptional children underscores the importance of early identification and proactive support, rather than assuming that high cognitive ability alone ensures adaptive self-regulation.

Moreover, the central role of cognitive flexibility across clusters warrants particular emphasis. Cognitive flexibility emerged as a distinguishing feature differentiating adaptive and vulnerable profiles, consistent with evidence linking flexibility to reduced academic anxiety, enhanced optimism, and improved learning engagement (Akman, 2024; Sadeghi & Yousofi, 2023; Zhao et al., 2024). This finding aligns with studies positioning cognitive flexibility as a core mechanism through which students adapt to complex academic and social demands (Karakuş, 2024; Tekin, 2022). In cognitively exceptional children, strong flexibility may buffer against regulatory challenges, whereas its absence may exacerbate the impact of executive weaknesses.

Taken together, the results of the present study contribute to a growing body of evidence advocating for nuanced, individualized understandings of cognitive development in exceptional populations. By applying unsupervised clustering methods, the study moves beyond deficit-based or monolithic conceptions of giftedness and highlights the diversity of executive function profiles that coexist within high-ability groups. These findings have important implications for assessment practices, educational planning, and intervention design, particularly in contexts characterized by cultural and socioeconomic diversity.

5. Conclusion

Several limitations should be acknowledged when interpreting the findings of this study. First, the cross-sectional design precludes conclusions regarding developmental trajectories or causal relationships among executive function domains. Second, although multiple assessment methods were used, the reliance on standardized measures may not fully capture the contextual nuances of executive functioning in everyday settings. Third, the sample was drawn from specific regions and educational contexts within South Africa, which may limit the generalizability of the findings to other cultural or national contexts. Finally, clustering outcomes are inherently sample-dependent, and alternative solutions may emerge in larger or differently composed samples.

Future research should adopt longitudinal designs to examine the stability and developmental progression of executive function profiles in cognitively exceptional children. Expanding samples to include broader geographic and cultural contexts would enhance generalizability and allow for cross-cultural comparisons. Integrating neurocognitive, emotional, and motivational variables may further clarify the mechanisms underlying profile differentiation. Additionally, future studies could examine how executive function profiles interact with educational interventions over time, providing evidence for personalized support strategies.

Educational practitioners and psychologists should avoid assuming uniform executive strengths in cognitively exceptional children and instead adopt comprehensive assessment approaches that identify individual executive function profiles. Schools should implement flexible instructional strategies and targeted supports for children exhibiting asynchronous executive development. Early screening for executive function vulnerabilities, even among high-ability learners, may prevent academic disengagement and psychosocial difficulties. Finally, incorporating executive function and self-regulation training into

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enrichment programs may help cognitively exceptional children fully realize their academic and developmental potential.

Authors' Contributions

Authors equally contributed to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

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