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A LightGBM-Based Prediction Model of Emotional Dysregulation in Children with ADHD: The Roles of Parent–Child Conflict, Cognitive Control, and Sleep Quality

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A B S T R A C T

The present study aimed to develop and evaluate a Light Gradient Boosting Machine (LightGBM) model for predicting emotional dysregulation in children with Attention-Deficit/Hyperactivity Disorder (ADHD) based on parent–child conflict, cognitive control difficulties, and sleep quality, while identifying the relative contribution of each predictor using explainable artificial intelligence techniques. This cross-sectional predictive modeling study was conducted among 428 Canadian children diagnosed with ADHD between the ages of 8 and 12 years. Participants were recruited from pediatric neuropsychology clinics, child mental health centers, and educational support programs. Emotional dysregulation was assessed using the Emotion Regulation Checklist, parent–child conflict was measured using the Child–Parent Relationship Scale, cognitive control difficulties were evaluated through the Behavior Rating Inventory of Executive Function–Second Edition, and sleep quality was assessed using the Children's Sleep Habits Questionnaire. Data preprocessing included standardization, missing-value imputation, and outlier screening. The dataset was divided into training (80%) and testing (20%) subsets. A LightGBM algorithm with five-fold cross-validation and Bayesian hyperparameter optimization was employed. Model performance was evaluated using R^2, RMSE, MAE, and MAPE indices, and predictor importance was examined using Shapley Additive Explanations (SHAP). Correlation analyses indicated significant positive associations between emotional dysregulation and parent–child conflict ($r = .68$, $p < .001$), cognitive control difficulties ($r = .61$, $p < .001$), and poor sleep quality ($r = .57$, $p < .001$). The optimized LightGBM model demonstrated excellent predictive performance, explaining 84.2% of variance in the training dataset and 78.1% of variance in the testing dataset. Cross-validation yielded a mean R^2 of .792, indicating strong model stability. SHAP analyses revealed that parent–child conflict was the most influential predictor (41.8%), followed by cognitive control difficulties (33.6%) and poor sleep quality (24.6%).

Higher levels of each predictor were associated with increased emotional dysregulation. The findings demonstrate that emotional dysregulation in children with ADHD can be accurately predicted using a machine learning framework that integrates family, cognitive, and sleep-related factors. Parent–child conflict emerged as the strongest determinant, highlighting the importance of family relationships in emotional functioning. The results support the application of explainable artificial intelligence approaches for identifying clinically meaningful risk factors and informing personalized assessment and intervention strategies for children with ADHD.

Keywords: *Attention-Deficit/Hyperactivity Disorder; Emotional Dysregulation; LightGBM; Machine Learning; Parent–Child Conflict; Cognitive Control*

1. Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is one of the most prevalent neurodevelopmental disorders of childhood and is characterized by persistent patterns of inattention, hyperactivity, and impulsivity that interfere with functioning across multiple settings. Contemporary conceptualizations of ADHD extend beyond these core symptoms and emphasize a broader constellation of cognitive, emotional, behavioral, and social impairments that significantly affect developmental trajectories. Recent advances in neuroscience have highlighted the complex interactions among neurochemical systems, neural network functioning, and environmental influences that contribute to the heterogeneous presentation of ADHD (Alsoqih et al., 2025). Epidemiological evidence suggests that ADHD affects millions of children worldwide and is frequently accompanied by substantial impairments in academic performance, peer relationships, family functioning, and psychological well-being (Wei, 2022). Moreover, ADHD commonly co-occurs with other neurodevelopmental and neurological conditions, including tic disorders, epilepsy, and sleep-related disorders, suggesting the existence of shared neurobiological vulnerabilities that influence symptom expression and developmental outcomes (Ahmed et al., 2022; Rothenberger & Heinrich, 2022). As research increasingly recognizes the multidimensional nature of ADHD, greater attention has been directed toward understanding factors that contribute to emotional functioning and psychological adjustment among affected children.

Among the various difficulties experienced by children with ADHD, emotional dysregulation has emerged as one of the most clinically significant yet historically underappreciated features of the disorder. Emotional dysregulation refers to difficulties in monitoring, evaluating, and modifying emotional responses in a manner appropriate to situational demands. Children with ADHD frequently exhibit excessive emotional reactivity, irritability, frustration intolerance, mood instability, and difficulty recovering from emotionally arousing experiences. These emotional difficulties often persist even when traditional ADHD symptoms are effectively managed and have been associated with poorer academic achievement, interpersonal conflict, reduced quality of life, and increased risk for psychiatric comorbidity (Peña et al., 2020; Zadjali et al., 2024). Emerging evidence suggests that emotional dysregulation may represent a central component of ADHD-related impairment rather than a secondary consequence of attentional difficulties alone. Neuropsychological investigations have demonstrated that children with ADHD exhibit deficits in emotional self-regulation that are closely intertwined with impairments in executive functioning, reward processing, and arousal regulation systems (Alsoqih et al., 2025; Kay et al., 2025). Consequently, identifying factors that contribute to emotional dysregulation has become a major priority for both researchers and clinicians seeking to improve long-term outcomes among children with ADHD.

Family dynamics constitute one of the most influential environmental contexts affecting emotional development during childhood. Among these dynamics, parent–child conflict has consistently been identified as a critical factor associated with emotional and behavioral adjustment. Children with ADHD often experience higher levels of family stress and conflict than their neurotypical peers due to the challenges associated with symptom management, behavioral difficulties, and academic concerns. Repeated cycles of negative interactions may contribute to escalating emotional reactivity and reduced opportunities for the development of adaptive emotion regulation skills. Research examining social relationships among children with ADHD has demonstrated that difficulties in interpersonal functioning frequently extend beyond peer contexts and are closely linked to family relationship quality (Taylor et al., 2023a, 2023b). Furthermore, problematic engagement with

E-ISSN: 3060-6713

digital media and electronic devices has been associated with disruptions in family communication and emotional functioning, potentially exacerbating conflictual parent–child interactions (Dekkers & Hoorn, 2022; Zhang et al., 2025). Given the central role of parents in supporting emotional development, understanding the contribution of parent–child conflict to emotional dysregulation among children with ADHD remains essential for the design of effective family-centered interventions.

In addition to environmental influences, cognitive processes play a fundamental role in emotional regulation. Cognitive control refers to a collection of executive functions that enable individuals to regulate attention, inhibit inappropriate responses, update working memory, and flexibly adapt behavior in response to changing demands. Deficits in cognitive control are widely recognized as a hallmark feature of ADHD and have been linked to difficulties across numerous domains of functioning. Neuropsychological investigations have consistently reported impairments in executive functioning among children with ADHD relative to neurotypical peers (Zadjali et al., 2024). These deficits may compromise a child's ability to manage emotional responses effectively, particularly during challenging or stressful situations. Evidence from intervention studies indicates that improvements in executive functioning can lead to meaningful enhancements in behavioral and emotional outcomes. For example, exercise-based interventions have been shown to improve executive function among children with ADHD, suggesting that cognitive control mechanisms remain modifiable and potentially influential targets for intervention (Liang, Li, et al., 2022; Martín-Rodríguez et al., 2025). Furthermore, nutritional and physical activity interventions have demonstrated concurrent improvements in executive functioning, cognitive performance, and emotional adjustment, highlighting the close interrelationship among these domains (Ye & Wang, 2025). These findings suggest that cognitive control deficits may represent a key pathway through which emotional dysregulation develops and persists in children with ADHD.

Another factor increasingly recognized as central to ADHD-related functioning is sleep quality. Sleep disturbances are highly prevalent among children with ADHD and have been documented across a wide range of populations and developmental stages. Systematic reviews have consistently reported elevated rates of insomnia, delayed sleep onset, fragmented sleep, circadian rhythm disruptions, daytime sleepiness, and sleep-disordered breathing among children diagnosed with ADHD (Bondopadhyay et al., 2021; Pratiwi et al., 2021). Sleep difficulties have been associated with greater symptom severity, impaired cognitive functioning, emotional instability, and reduced adaptive functioning. Studies examining sleep processes have demonstrated that both homeostatic and circadian mechanisms contribute to neurobehavioral outcomes in ADHD, affecting attention, executive functioning, and emotional regulation capacities (Gruber et al., 2023). Moreover, sleep instability has been linked directly to attentional impairment among boys with ADHD, suggesting that disrupted sleep may intensify core neurocognitive deficits (Gagnon et al., 2021). These findings underscore the importance of considering sleep quality as a potentially modifiable determinant of emotional and behavioral functioning in ADHD populations.

The relationship between sleep and cognitive functioning appears particularly relevant to emotional dysregulation. Sleep disturbances have been associated with both externalizing and internalizing behavioral problems among children and adolescents with ADHD, highlighting their broad psychological consequences (Dimakos et al., 2021). Polysomnographic research has demonstrated significant associations among sleep quality, cognitive performance, and academic achievement in children with ADHD (Ruiz-Herrera et al., 2021). Similarly, investigations of social jetlag, time in bed, and sleep disturbances have revealed meaningful relationships with cognitive performance and executive functioning deficits (Qu et al., 2023). During periods of environmental disruption such as the COVID-19 pandemic, sleep disturbances were accompanied by increased anxiety and declines in executive functioning among youth with ADHD, further illustrating the interconnected nature of sleep, cognition, and emotional functioning (Sória et al., 2021). Collectively, these findings suggest that poor sleep quality may contribute to emotional dysregulation both directly and indirectly through its impact on executive control processes.

Growing evidence from biological and neurophysiological research further supports the importance of sleep-related mechanisms in ADHD. Studies have identified associations between ADHD symptoms and sleep-disordered breathing, altered electroencephalographic markers, chronotype differences, and atypical sleep spindle activity (Demirci et al., 2024; Ma et al., 2024; Özbudak et al., 2022). Pediatric obstructive sleep apnea has also been linked to ADHD symptomatology and neurobehavioral difficulties, suggesting that sleep-related physiological

E-ISSN: 3060-6713

disruptions may play an important role in symptom expression (Urbano et al., 2021; Yücel & Ekici, 2021). Additional evidence has demonstrated elevated rates of sleep disturbances among children with ADHD and co-occurring developmental disorders, including specific learning disorders and fetal alcohol spectrum disorders (Gerstner et al., 2023; Saccani et al., 2022). Research examining sluggish cognitive tempo has similarly revealed significant associations between sleep problems, cognitive difficulties, and psychological impairment among children with ADHD (Mayes et al., 2020; Mayes et al., 2021). These findings collectively reinforce the notion that sleep disturbances constitute a fundamental component of ADHD-related dysfunction and may substantially influence emotional regulation capacities.

Recent intervention research has increasingly targeted sleep, cognition, and neurobehavioral functioning as interconnected treatment pathways. Reviews of melatonin treatment have reported beneficial effects on sleep disturbances among children with ADHD, while investigations of non-invasive brain stimulation have highlighted emerging possibilities for improving both symptom severity and sleep-related outcomes (Rzepka-Migut & Paprocka, 2020; Santos et al., 2024). Nutritional supplementation strategies have also demonstrated promise in alleviating ADHD symptoms and enhancing cognitive and behavioral functioning (Shahab et al., 2025). Physical activity interventions represent another promising avenue, with evidence indicating that exercise can improve executive functioning, sleep quality, and overall health indicators among children and adolescents with ADHD (Liang et al., 2026; Liang, Qiu, et al., 2022; Martín-Rodríguez et al., 2025). These findings suggest that emotional dysregulation may emerge from complex interactions among cognitive, behavioral, physiological, and environmental factors rather than from isolated symptom domains.

Despite substantial progress in understanding ADHD, significant limitations remain in the existing literature. Most studies have examined parent–child conflict, cognitive control, or sleep quality independently, with relatively few investigations considering their simultaneous contribution to emotional dysregulation. Furthermore, traditional statistical approaches often assume linear relationships among variables and may fail to capture the complex, nonlinear interactions characteristic of neurodevelopmental disorders. Contemporary machine learning techniques provide opportunities to address these limitations by identifying intricate predictive patterns and improving the accuracy of individualized risk assessment. Light Gradient Boosting Machine (LightGBM) models are particularly advantageous due to their ability to manage nonlinear relationships, handle complex feature interactions, and generate highly accurate predictions while maintaining computational efficiency. Although machine learning approaches have become increasingly common in health research, their application to understanding emotional dysregulation among children with ADHD remains limited. Given the multifactorial nature of ADHD and the interconnected influences of family relationships, executive functioning, and sleep quality, predictive modeling approaches may provide valuable insights beyond those available through conventional analytic techniques.

Therefore, the aim of the present study was to develop and evaluate a LightGBM-based prediction model of emotional dysregulation in children with ADHD by examining the predictive contributions of parent–child conflict, cognitive control, and sleep quality.

2. Methods and Materials

2.1. Study Design and Participants

This study employed a cross-sectional predictive modeling design to investigate the extent to which parent–child conflict, cognitive control, and sleep quality contribute to the prediction of emotional dysregulation among children diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD). The study was conducted between September 2025 and March 2026 in several pediatric neuropsychology clinics, child mental health centers, and specialized educational support programs across the provinces of Ontario and British Columbia, Canada. The research was designed within a machine learning framework, with emotional dysregulation serving as the target outcome variable and parent–child conflict, cognitive control, and sleep quality functioning as predictor variables.

The study sample consisted of 428 children diagnosed with ADHD according to the diagnostic criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5-TR). Participants were recruited using a stratified convenience sampling method to ensure representation across age groups and ADHD presentations. The children ranged in age from 8 to 12 years, with a mean age of 10.17 years (SD = 1.41). Among the participants, 267 were boys (62.4%) and 161 were girls (37.6%). Eligibility criteria included a formal diagnosis of ADHD confirmed by a licensed child psychiatrist or clinical psychologist,

E-ISSN: 3060-6713

enrollment in a mainstream or specialized educational setting, and sufficient cognitive functioning to complete age-appropriate assessments. Children with severe intellectual disability, psychotic disorders, neurological conditions affecting cognitive performance, or major sensory impairments were excluded from the study. Parents completed questionnaires regarding family interactions and sleep-related behaviors, while children participated in standardized assessments of cognitive control under the supervision of trained researchers.

2.2. *Measures*

Emotional dysregulation was assessed using the Emotion Regulation Checklist (ERC), originally developed by Shields and Cicchetti (1997). The ERC is a widely used parent-report instrument designed to evaluate emotional functioning and regulation capacities in children. The scale consists of 24 items rated on a four-point Likert continuum ranging from 1 (never) to 4 (almost always). The instrument measures dimensions associated with emotional lability, negative affect, and adaptive emotional regulation. Higher scores on the emotional lability component indicate greater emotional dysregulation. The ERC has demonstrated strong psychometric properties across clinical and non-clinical populations, with reported Cronbach's alpha coefficients typically exceeding .80. Previous studies have confirmed its construct validity, criterion validity, and reliability among children with ADHD and related neurodevelopmental conditions.

Parent–child conflict was measured using the Conflict subscale of the Child–Parent Relationship Scale (CPRS), developed by Pianta (1992). The CPRS evaluates the quality of the parent–child relationship and includes items assessing tension, disagreement, emotional distance, and problematic interactions between parents and children. The conflict dimension comprises 15 items rated on a five-point Likert scale ranging from 1 (definitely does not apply) to 5 (definitely applies). Higher scores indicate greater levels of conflict and relational strain. The CPRS has been extensively utilized in developmental and clinical research and has consistently demonstrated satisfactory reliability and validity. Studies involving children with behavioral and emotional difficulties have reported Cronbach's alpha values ranging from .78 to .90 for the conflict subscale.

Cognitive control was assessed using the Behavior Rating Inventory of Executive Function, Second Edition (BRIEF-2), developed by Gioia, Isquith, Guy, and Kenworthy (2015). The Cognitive Regulation Index of the BRIEF-2 was used as an indicator of executive functioning and cognitive control abilities. The measure evaluates capacities such as inhibitory control, working memory, task monitoring, planning, and cognitive flexibility. Parents rated 63 items using a three-point response format ranging from 1 (never) to 3 (often). Higher scores indicate greater executive functioning difficulties and reduced cognitive control. The BRIEF-2 has demonstrated excellent psychometric characteristics, including strong internal consistency, test–retest reliability, and clinical validity across diverse pediatric populations. The instrument has been particularly effective in identifying executive deficits associated with ADHD.

Sleep quality was evaluated using the Children's Sleep Habits Questionnaire (CSHQ), developed by Owens, Spirito, and McGuinn (2000). The CSHQ is a parent-report instrument containing 33 items that assess common sleep behaviors and disturbances among school-aged children. The questionnaire measures domains including bedtime resistance, sleep onset delay, sleep duration, sleep anxiety, night waking, parasomnias, sleep-disordered breathing, and daytime sleepiness. Responses are recorded on a three-point scale reflecting the frequency of each behavior. Higher scores indicate poorer sleep quality and more significant sleep-related difficulties. Extensive research has demonstrated the reliability and validity of the CSHQ in both community and clinical samples, including children diagnosed with ADHD. Internal consistency estimates generally range between .70 and .85, and previous studies have supported its sensitivity in detecting sleep disturbances associated with emotional and behavioral problems.

2.3. *Data Analysis*

Data analysis was performed using Python version 3.12 and the LightGBM machine learning framework. Prior to model development, all data were screened for missing values, outliers, and distributional abnormalities. Missing values representing less than 5% of the dataset were imputed using k-nearest neighbor imputation procedures. Continuous variables were standardized to facilitate model optimization and improve interpretability. Descriptive statistics, including means, standard deviations, skewness, and kurtosis indices, were calculated to summarize participant characteristics and study variables. Pearson correlation analyses were also conducted to examine preliminary associations among emotional dysregulation, parent–child conflict, cognitive control, and sleep quality.

E-ISSN: 3060-6713

The primary analytical approach involved the development of a Light Gradient Boosting Machine (LightGBM) prediction model. The dataset was randomly divided into training and testing subsets using an 80:20 ratio. Hyperparameter optimization was performed through five-fold cross-validation combined with Bayesian optimization procedures to identify the optimal combination of learning rate, maximum tree depth, number of leaves, feature fraction, bagging fraction, and regularization parameters. Model performance was evaluated using multiple metrics, including the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE). These indices provided complementary information regarding predictive accuracy and model generalizability.

To enhance interpretability, explainable artificial intelligence techniques were incorporated into the analytical framework. Shapley Additive Explanations (SHAP) were employed to quantify the relative contribution of each predictor variable to the model's predictions. Global SHAP importance plots were generated to identify the most influential determinants of emotional dysregulation, while local SHAP analyses were conducted to examine individual prediction patterns. Partial dependence plots were additionally used to explore nonlinear relationships between predictor variables and emotional dysregulation. Model robustness was assessed through repeated cross-validation procedures and sensitivity analyses. Statistical significance for conventional analyses was evaluated at the .05 level, while machine learning performance was interpreted according to established predictive modeling standards.

3. Findings and Results

A total of 428 children diagnosed with ADHD participated in the study. The sample consisted of 267 boys (62.4%) and 161 girls (37.6%), with ages ranging from 8 to 12 years (M = 10.17, SD = 1.41). Regarding ADHD presentation, 189 participants (44.2%) were classified as predominantly inattentive type, 112 participants (26.2%) as predominantly hyperactive-impulsive type, and 127 participants (29.7%) as combined type. The majority of participants were enrolled in public schools (71.5%), while 28.5% attended private educational institutions. Descriptive screening indicated acceptable distributions for all study variables, with skewness and kurtosis values falling within the acceptable range of ±2. No substantial multicollinearity was observed among predictor variables, as variance inflation factor (VIF) values ranged from 1.21 to 2.08.

Table 1

Descriptive Statistics and Correlations Among Study Variables

Variable	Mean	SD	1	2	3	4
1. Emotional Dysregulation	42.63	9.18	—			
2. Parent–Child Conflict	48.71	8.94	.68**	—		
3. Cognitive Control Difficulties	65.38	10.26	.61**	.54**	—	
4. Poor Sleep Quality	51.84	7.63	.57**	.46**	.49**	—

Table 1 presents the descriptive statistics and bivariate correlations among the primary study variables. The results demonstrated that emotional dysregulation was significantly and positively associated with parent–child conflict ($r = .68$, $p < .001$), cognitive control difficulties ($r = .61$, $p < .001$), and poor sleep quality ($r = .57$, $p < .001$). The strongest correlation was observed between emotional dysregulation and parent–child conflict, indicating that children experiencing greater levels of conflictual interactions with parents tended to exhibit substantially higher emotional dysregulation. Significant positive correlations were also identified among all predictor variables, suggesting that greater parent–child conflict was associated with poorer cognitive control and lower sleep quality. The magnitude of the correlations ranged from moderate to strong, providing preliminary evidence that all predictor variables may contribute meaningfully to the prediction of emotional dysregulation in children with ADHD.

E-ISSN: 3060-6713

Table 2

Performance Metrics of the Optimized LightGBM Prediction Model

Metric	Training Set	Testing Set
R^2	.842	.781
RMSE	3.62	4.71
MAE	2.89	3.76
MAPE (%)	7.13	9.28
Adjusted R^2	.840	.777
Cross-Validation R^2 (5-Fold Mean)	.792	—

The predictive performance of the optimized LightGBM model is presented in Table 2. The model demonstrated excellent predictive accuracy across both training and testing datasets. Specifically, the model explained 84.2% of the variance in emotional dysregulation scores within the training dataset and 78.1% of the variance within the testing dataset, indicating strong generalizability and minimal evidence of overfitting. The root mean square error values of 3.62 and 4.71 for the training and testing samples, respectively, suggested a relatively low level of prediction error. Similarly, the mean absolute error remained below four points in the testing dataset, indicating that model predictions closely approximated observed emotional dysregulation scores. The five-fold cross-validation procedure yielded a mean R^2 value of .792, further supporting the robustness and stability of the prediction model across multiple subsamples. Collectively, these findings indicate that the LightGBM algorithm achieved a high level of predictive performance in identifying emotional dysregulation among children with ADHD based on parent–child conflict, cognitive control, and sleep quality indicators.

Table 3

SHAP-Based Feature Importance Rankings in the LightGBM Model

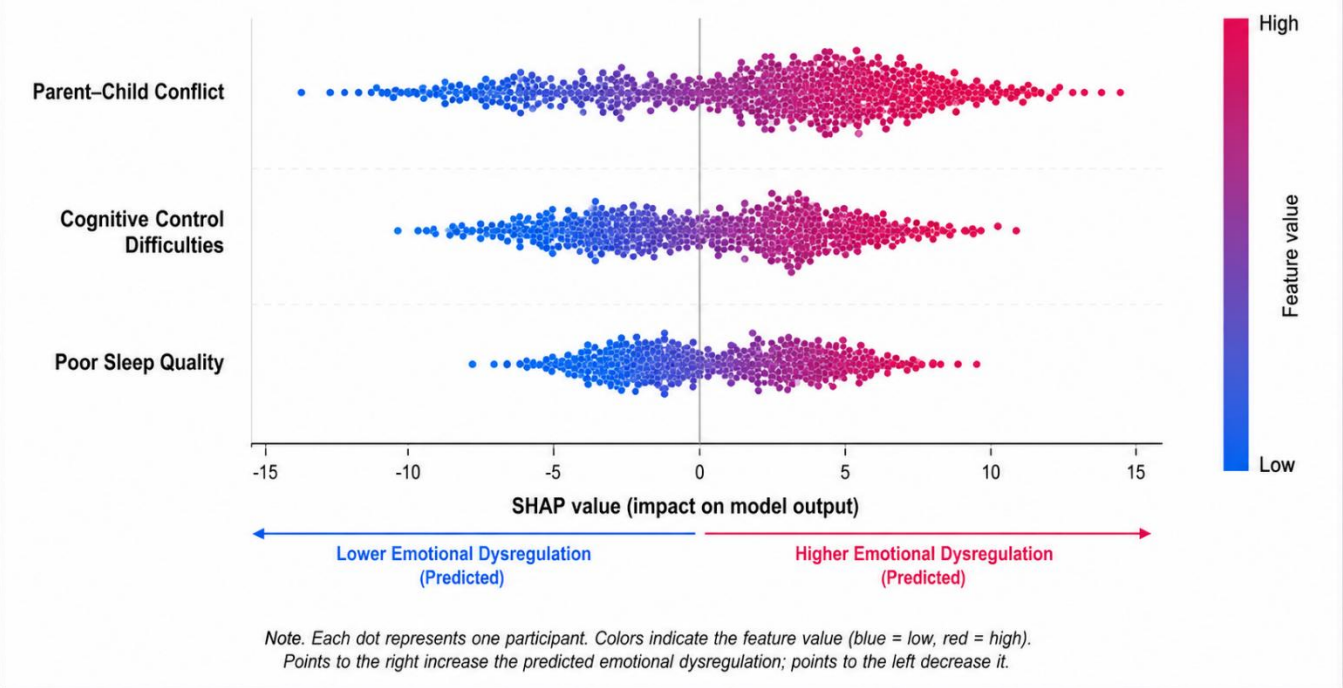
Predictor Variable	Mean Absolute SHAP Value	Relative Importance (%)	Rank
Parent–Child Conflict	4.87	41.8	1
Cognitive Control Difficulties	3.92	33.6	2
Poor Sleep Quality	2.86	24.6	3

The SHAP analysis results shown in Table 3 revealed the relative contribution of each predictor variable to the LightGBM model. Parent–child conflict emerged as the most influential predictor of emotional dysregulation, accounting for 41.8% of the overall explanatory contribution. Cognitive control difficulties represented the second most important predictor, contributing 33.6% of the model's predictive power. Poor sleep quality ranked third, accounting for 24.6% of total feature importance. The results suggest that although all three variables played meaningful roles in predicting emotional dysregulation, family relational factors exerted the strongest influence. The prominence of parent–child conflict indicates that emotional dysregulation among children with ADHD may be particularly sensitive to negative interaction patterns within the family environment. Furthermore, the substantial contribution of cognitive control difficulties highlights the importance of executive functioning deficits in the development and maintenance of emotional regulation problems. Sleep quality, while comparatively less influential, nevertheless contributed nearly one-quarter of the total predictive power, demonstrating its meaningful role within the multidimensional prediction framework.

E-ISSN: 3060-6713

Figure 1

SHAP Summary Plot Illustrating the Relative Contributions of Parent–Child Conflict, Cognitive Control Difficulties, and Sleep Quality to Emotional Dysregulation Predictions



Note. Each dot represents one participant. Colors indicate the feature value (blue = low, red = high). Points to the right increase the predicted emotional dysregulation; points to the left decrease it.

Figure 1 presents the SHAP summary plot generated from the optimized LightGBM model. The figure demonstrates that higher levels of parent–child conflict consistently increased predicted emotional dysregulation scores across participants. Similarly, greater cognitive control difficulties were associated with elevated emotional dysregulation predictions, particularly among children exhibiting severe executive functioning deficits. Poor sleep quality also demonstrated a positive association with emotional dysregulation, although its impact was somewhat less pronounced than that of the other predictors. Visual inspection of the SHAP distribution further indicated nonlinear relationships among variables, suggesting that increases in parent–child conflict and executive dysfunction exert disproportionately larger effects at higher severity levels. These findings underscore the value of explainable artificial intelligence techniques in identifying both the magnitude and direction of predictor effects. Overall, the SHAP analysis confirmed that emotional dysregulation in children with ADHD is best understood as a multifactorial phenomenon shaped by the interaction of family relationship quality, executive functioning capacity, and sleep-related processes.

4. Discussion

The present study developed and evaluated a LightGBM-based prediction model of emotional dysregulation in children with ADHD by examining the contributions of parent–child conflict, cognitive control difficulties, and sleep quality. The findings demonstrated that all three predictors were significantly associated with emotional dysregulation and collectively explained a substantial proportion of variance in emotional functioning. The optimized LightGBM model achieved strong predictive performance, accounting for approximately 78% of the variance in emotional dysregulation within the testing dataset. Furthermore, explainable artificial intelligence analyses revealed that parent–child conflict emerged as the most influential predictor, followed by cognitive control difficulties and poor sleep quality. These findings suggest that emotional dysregulation in children with ADHD is best conceptualized as a multifactorial phenomenon shaped by the interaction of family relational experiences, executive functioning capacities, and sleep-related processes. The results contribute to a growing body of evidence emphasizing that emotional difficulties in ADHD extend beyond traditional symptoms of inattention and

E-ISSN: 3060-6713

hyperactivity and reflect the influence of broader neuropsychological and environmental mechanisms.

One of the most important findings of the present study was the strong predictive role of parent–child conflict. The SHAP analysis identified parent–child conflict as the most influential determinant of emotional dysregulation, indicating that children who experienced higher levels of conflictual interactions with their parents exhibited significantly greater difficulties regulating emotions. This finding aligns with developmental theories suggesting that family relationships provide the primary context through which children learn emotional regulation skills. Frequent criticism, hostility, inconsistent responses, and negative communication patterns may undermine children's ability to develop adaptive strategies for managing frustration, anger, and emotional distress. Children with ADHD are particularly vulnerable to such processes because impulsivity, attentional difficulties, and behavioral challenges often increase family stress and contribute to recurring conflict cycles. The present findings are consistent with previous research demonstrating that social and interpersonal difficulties are strongly associated with emotional and behavioral outcomes among children with ADHD (Taylor et al., 2023a, 2023b). Moreover, evidence suggests that environmental stressors, including excessive engagement with digital technologies and problematic media use, may indirectly contribute to family conflict and emotional difficulties among youth with ADHD (Dekkers & Hoorn, 2022; Zhang et al., 2025). The strong predictive influence of parent–child conflict observed in the current study therefore supports the growing recognition that family functioning represents a critical target for interventions aimed at improving emotional outcomes in ADHD populations.

The findings also demonstrated that cognitive control difficulties were a major predictor of emotional dysregulation. Children exhibiting poorer executive functioning showed substantially higher levels of emotional instability, supporting theoretical models that conceptualize emotion regulation as a higher-order executive process. Effective emotional regulation requires inhibitory control, attentional flexibility, working memory, and the capacity to monitor and modify emotional responses in real time. Deficits in these abilities may limit children's capacity to manage emotional experiences, resulting in increased irritability, frustration, impulsive reactions, and mood instability. These findings are highly consistent with previous neuropsychological investigations reporting significant executive functioning impairments among children with ADHD (Zadjali et al., 2024). The results also align with evidence suggesting that interventions targeting executive functioning can improve broader behavioral and emotional outcomes. Randomized controlled trials examining physical activity interventions have demonstrated significant improvements in executive function among children with ADHD, indicating that cognitive control mechanisms remain malleable and clinically relevant (Liang, Li, et al., 2022). Similarly, exercise and movement-based interventions have been associated with enhanced cognitive functioning and social adjustment in ADHD populations (Martín-Rodríguez et al., 2025). The present findings extend this literature by demonstrating that executive functioning deficits are not merely associated with core ADHD symptoms but also serve as important predictors of emotional dysregulation.

Another notable finding was the significant contribution of sleep quality to emotional dysregulation. Although sleep quality ranked third in relative importance, its predictive effect remained substantial and clinically meaningful. Children experiencing poorer sleep quality demonstrated elevated levels of emotional dysregulation, supporting a large body of literature linking sleep disturbances to emotional and behavioral difficulties in ADHD. Sleep disruption may impair prefrontal cortical functioning, reduce attentional resources, increase emotional reactivity, and compromise executive control processes. These mechanisms collectively contribute to difficulties managing emotional responses and maintaining behavioral regulation. The current findings are consistent with systematic reviews documenting high rates of sleep disturbances among children with ADHD and emphasizing the importance of sleep for psychological functioning (Bondopadhyay et al., 2021; Pratiwi et al., 2021). Research examining homeostatic and circadian sleep processes has similarly demonstrated significant associations between sleep quality and neurobehavioral functioning among individuals with ADHD (Gruber et al., 2023). Moreover, studies have shown that sleep instability is associated with attentional impairments and executive dysfunction, both of which may increase vulnerability to emotional dysregulation (Gagnon et al., 2021). The present findings therefore reinforce the view that sleep quality should be considered a central component of comprehensive ADHD assessment and intervention.

The observed association between sleep quality and emotional dysregulation is further supported by evidence from studies investigating sleep and psychological

E-ISSN: 3060-6713

adjustment in ADHD populations. Research has consistently demonstrated relationships between sleep disturbances and both externalizing and internalizing problems among children and adolescents with ADHD (Dimakos et al., 2021). Sleep problems have also been linked to poorer academic performance, reduced cognitive functioning, and impaired executive processes (Ruiz-Herrera et al., 2021). Investigations examining social jetlag, time in bed, and sleep disturbances have similarly identified significant associations with cognitive performance deficits among children with ADHD (Qu et al., 2023). During periods of environmental stress, such as the COVID-19 pandemic, disruptions in sleep were accompanied by increased anxiety and reductions in executive functioning among youth with ADHD (Sória et al., 2021). Collectively, these findings support the interpretation that sleep difficulties contribute to emotional dysregulation through multiple cognitive, physiological, and psychological pathways.

The importance of sleep quality observed in the current study is also consistent with emerging neurobiological evidence. Several investigations have identified links between ADHD symptoms and physiological sleep-related abnormalities, including altered EEG activity, sleep spindle irregularities, chronotype differences, and sleep-disordered breathing (Demirci et al., 2024; Ma et al., 2024; Özbudak et al., 2022). Research examining pediatric obstructive sleep apnea has likewise demonstrated significant associations between sleep-disordered breathing and ADHD symptomatology (Urbano et al., 2021; Yücel & Ekici, 2021). Furthermore, sleep disturbances appear particularly common among children with ADHD who present with additional developmental or neurological challenges (Gerstner et al., 2023; Saccani et al., 2022). Studies focusing on sluggish cognitive tempo have also documented significant relationships between sleep problems, cognitive difficulties, and emotional impairment (Mayes et al., 2020; Mayes et al., 2021). The consistency of these findings across diverse populations suggests that sleep disturbances may represent a fundamental mechanism contributing to emotional and behavioral dysfunction in ADHD.

An additional contribution of the present study lies in its use of machine learning methodology. Traditional statistical approaches have generated valuable insights into ADHD-related functioning; however, they may not adequately capture the complex nonlinear interactions among psychological, cognitive, and environmental variables. The strong predictive performance of the LightGBM model demonstrates the utility of machine learning techniques for identifying patterns that may remain undetected using conventional methods. The model's high explanatory power suggests that emotional dysregulation can be predicted with considerable accuracy when multiple risk factors are considered simultaneously. This finding is consistent with broader trends in mental health research emphasizing predictive analytics and individualized assessment approaches (Wei, 2022). The incorporation of SHAP analyses further enhanced interpretability by identifying the relative contributions of specific predictors, thereby addressing concerns regarding the “black box” nature of machine learning algorithms.

The findings also support emerging multidimensional models of ADHD that emphasize interactions among biological, cognitive, behavioral, and environmental systems. Contemporary perspectives increasingly recognize ADHD as a disorder involving complex brain–behavior relationships rather than isolated deficits in attention or impulse control (Alsoqih et al., 2025). Neurobiological investigations have highlighted the importance of arousal regulation, reward processing, and executive control systems in understanding ADHD-related functioning (Kay et al., 2025). Similarly, research examining physical activity, sleep, cognition, and overall health has demonstrated that these domains interact dynamically to influence developmental outcomes (Liang et al., 2026; Ye & Wang, 2025). Studies investigating movement behaviors have further shown that adherence to healthy lifestyle patterns is associated with reduced cognitive difficulties and improved social functioning among children with ADHD (Taylor et al., 2023a, 2023b). The current results extend these perspectives by demonstrating that emotional dysregulation emerges from the combined influence of family relational factors, executive functioning deficits, and sleep-related processes.

The findings should also be interpreted within the broader context of ADHD heterogeneity. ADHD is associated with diverse symptom presentations and developmental trajectories, and emotional dysregulation may be influenced by numerous additional factors not examined in the present study. Existing literature has identified associations between ADHD and conditions such as epilepsy, tic disorders, atopic dermatitis, and other neurodevelopmental challenges that may contribute to emotional functioning (Ahmed et al., 2022; Rothenberger & Heinrich, 2022; Xu et al., 2020). Consequently, emotional dysregulation likely reflects the cumulative influence of multiple interacting biological and environmental risk factors. Nevertheless, the substantial

E-ISSN: 3060-6713

predictive power achieved by the current model indicates that parent–child conflict, cognitive control difficulties, and sleep quality represent particularly important determinants deserving attention in both research and clinical practice.

5. Conclusion

The present study possesses several strengths, including a relatively large sample, the application of explainable machine learning techniques, and the simultaneous examination of environmental, cognitive, and physiological predictors. The integration of SHAP analyses provided clinically meaningful insights into the relative importance of predictors and enhanced the interpretability of model outputs. These methodological strengths contribute to the growing literature supporting the use of artificial intelligence approaches in developmental psychopathology and pediatric mental health research.

The study has several limitations that should be acknowledged. First, the cross-sectional design prevents causal inferences regarding the relationships among parent–child conflict, cognitive control, sleep quality, and emotional dysregulation. Second, several measures relied on parent-report data, creating the possibility of shared-method variance and reporting bias. Third, participants were recruited from clinical and educational settings within Canada, which may limit the generalizability of findings to other cultural and healthcare contexts. Fourth, the study focused on a restricted set of predictors and did not incorporate biological markers, genetic influences, medication status, socioeconomic factors, or peer relationship variables that may also affect emotional dysregulation. Finally, although the model demonstrated strong predictive accuracy, external validation using independent samples was not conducted.

Future research should employ longitudinal designs to examine developmental pathways linking family relationships, executive functioning, sleep quality, and emotional dysregulation over time. Researchers should also explore additional predictors, including neurobiological markers, genetic factors, school-related variables, and peer influences, to further improve predictive accuracy. Comparative studies evaluating different machine learning algorithms may identify optimal approaches for risk prediction in ADHD populations. Future investigations should additionally examine whether interventions targeting family conflict, executive functioning, and sleep quality produce measurable reductions in emotional dysregulation and whether these effects differ across ADHD presentations and developmental stages.

The findings have several practical implications. Clinicians should routinely assess emotional dysregulation alongside core ADHD symptoms and recognize the importance of family relationships, executive functioning deficits, and sleep disturbances in shaping emotional outcomes. Parent-training programs that reduce conflict and improve communication may help foster healthier emotional development. Educational and psychological interventions should incorporate strategies designed to strengthen cognitive control skills, including self-monitoring, inhibitory control, and problem-solving abilities. Sleep assessments should become a standard component of ADHD evaluations, and interventions promoting healthy sleep habits should be integrated into treatment plans. Finally, machine learning approaches may assist practitioners in identifying children at elevated risk for emotional dysregulation and facilitate the development of more personalized intervention strategies.

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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