KMAN PUBLISHING INSTITUTE
Journal Website

Article history:
Received 15 March 2026
Revised 20 June 2026
Accepted 27 June 2026
Initial Publication 01 July 2026
Final Publication 10 November 2026

Journal of Adolescent and Youth Psychological Studies

Volume 7, Issue 11, pp 1-14

E-ISSN: 2981-2526

Prediction of Cognitive Flexibility Based on Attention Control, Working Memory, and Problem-Solving Skills in Adolescents Using CatBoost

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Article Info

Article type:
Original Research

How to cite this article:
Sanjarinia, N. (2026). Prediction of Cognitive Flexibility Based on Attention Control, Working Memory, and Problem-Solving Skills in Adolescents Using CatBoost. *Journal of Adolescent and Youth Psychological Studies, 7*(11), 1-14.
http://dx.doi.org/10.61838/kman.jayps.5718

ABSTRACT

Objective: The present study aimed to predict cognitive flexibility based on attention control, working memory, and problem-solving skills in adolescents using the CatBoost machine learning algorithm.
Methods and Materials: This study was conducted using a quantitative, descriptive-correlational, and predictive design. The statistical population included adolescents studying in secondary schools in Tehran during the 2025–2026 academic year. The final sample consisted of 384 adolescents selected through multistage cluster sampling. Data were collected using standardized self-report instruments measuring cognitive flexibility, attention control, working memory, and problem-solving skills. After preliminary data screening, descriptive indices, reliability coefficients, Pearson correlation coefficients, and machine learning-based predictive analyses were conducted. The CatBoost algorithm was used to predict cognitive flexibility, and the dataset was divided into training and test subsets. Model performance was evaluated using mean absolute error, mean squared error, root mean squared error, coefficient of determination, and five-fold cross-validation. Feature importance analysis was also performed to determine the relative contribution of each predictor.
Findings: The results showed that cognitive flexibility had significant positive correlations with problem-solving skills ($r = 0.61$, $p < 0.01$), attention control ($r = 0.55$, $p < 0.01$), and working memory ($r = 0.48$, $p < 0.01$). The CatBoost model demonstrated acceptable predictive accuracy. In the training set, the model explained 76.5% of the variance in cognitive flexibility, while in the test set, it explained 65.2% of the variance. The cross-validation results also supported the stability of the model, with an average R^2 of 0.636. Feature importance analysis indicated that problem-solving skills had the highest predictive contribution, followed by attention control and working memory.
Conclusion: The findings indicate that cognitive flexibility in adolescents can be meaningfully predicted by problem-solving skills, attention control, and working memory. The CatBoost algorithm provided an effective predictive model and showed that problem-solving skills were the most important predictor.
Keywords: *Cognitive flexibility; attention control; working memory; problem-solving skills; adolescents; CatBoost; machine learning; executive functions.*

1. Introduction

Adolescence is a developmental period in which cognitive, emotional, social, and educational demands increase rapidly, requiring individuals to adapt to changing expectations, regulate behavior, manage complex information, and respond flexibly to novel or stressful situations. Within this developmental context, cognitive flexibility is one of the most important executive functions because it enables adolescents to shift perspectives, modify ineffective strategies, generate alternative solutions, and adapt their thinking and behavior when environmental conditions change. Cognitive flexibility is not an isolated skill; rather, it is embedded in a broader executive system that includes attention regulation, working memory, inhibition, planning, self-monitoring, and goal-directed problem solving. Contemporary developmental accounts emphasize that executive functions undergo substantial maturation during childhood and adolescence, with changes in cognitive control supporting academic learning, emotional regulation, interpersonal functioning, and adaptive decision-making (Happaney & Zelazo, 2022; Sayar, 2024). Because adolescents frequently encounter academic pressure, peer-related challenges, identity development, and emotional instability, the ability to think flexibly and reorganize cognitive strategies can be considered a central indicator of adaptive psychological functioning.

Cognitive flexibility has received increasing attention in developmental cognitive neuroscience because it reflects the adolescent's capacity to move beyond rigid response patterns and engage in adaptive, context-sensitive cognition. Developmental neuroimaging evidence indicates that cognitive flexibility is associated with distributed neural systems involved in control, salience detection, attentional shifting, and integration of internal and external information, and that these systems continue to mature across adolescence (Kupis & Uddin, 2023). This developmental sensitivity makes cognitive flexibility especially important in adolescent populations, as individual differences in flexible cognition may contribute to variability in academic performance, mental health, creativity, social adjustment, and resilience. Research on prenatal environmental exposure has also highlighted cognitive flexibility as a meaningful developmental outcome, suggesting that adolescents' flexible thinking can be shaped by both biological and environmental influences across development (Oppenheimer et al., 2021). Therefore, identifying cognitive predictors of cognitive flexibility is essential for understanding how adolescents adapt to complex educational and psychosocial contexts.

The broader literature on executive functioning shows that cognitive flexibility is closely connected with other cognitive processes, particularly attention control, working memory, and problem-solving skills. Executive functioning difficulties have been reported across diverse child and adolescent populations, including adolescents born extremely or very preterm, children and adolescents with neurodevelopmental conditions, and youth with chronic health or psychological difficulties (Beckmann & Mano, 2021; Lee et al., 2024; Raj et al., 2025). These findings indicate that executive functions are not merely laboratory-based cognitive constructs, but are directly related to everyday functioning, school adaptation, and psychological well-being. Studies on dysexecutive symptoms in adolescents have shown that executive difficulties can interfere with academic achievement and daily functioning, emphasizing the importance of assessing executive abilities in ecologically meaningful ways (Pablo-Ríos et al., 2024). Accordingly, cognitive flexibility should be examined not only as a theoretical construct, but also as a practically relevant capacity that may be predicted from measurable cognitive and behavioral variables.

Attention control is one of the most theoretically important predictors of cognitive flexibility. It refers to the ability to focus attention on relevant stimuli, resist distraction, shift attention when task demands change, and maintain cognitive engagement in the presence of competing information. In adolescence, attention control is essential for learning, emotional regulation, and adaptive decision-making, because adolescents must continuously select relevant information from complex academic and social environments. Systematic reviews on attentional and executive functioning in developmental coordination disorder and related conditions have shown that attentional regulation is deeply intertwined with executive performance and may be affected by comorbid developmental difficulties (Lachambre et al., 2021). Similarly, research on executive functions in children and adolescents with hearing loss has shown that limitations in sensory input and communication contexts may influence executive processes, including attention regulation and flexible adaptation (Charry-Sánchez et al., 2022). These findings support the view that attention control forms a foundational cognitive mechanism through which adolescents organize behavior and adjust responses to changing demands.

Working memory is another core predictor of cognitive flexibility because it enables adolescents to hold information in mind, update it, manipulate it, and compare alternative responses while performing complex cognitive tasks. When adolescents solve problems, make decisions, or shift strategies, they must maintain task goals and relevant information while inhibiting irrelevant or outdated responses. The role of working memory in executive functioning has been emphasized in developmental models in which working memory, inhibition, and cognitive flexibility are treated as interrelated but distinguishable components of executive control (Filipiak & Hawrot, 2024). Studies of sleep quality and creativity have also suggested that executive function may mediate the relationship between broader psychological or lifestyle variables and higher-order cognitive outcomes, further demonstrating that working memory and executive control processes contribute to adaptive cognition (Guo et al., 2022). In adolescent learning contexts, weak working memory may reduce the ability to compare alternatives, integrate feedback, or restructure ineffective strategies, thereby limiting cognitive flexibility.

Problem-solving skills are also conceptually and empirically related to cognitive flexibility. Effective problem solving requires adolescents to define a problem, evaluate available resources, generate multiple possible responses, select an appropriate strategy, and revise that strategy when it fails. This process depends heavily on flexible cognition, but it may also strengthen cognitive flexibility by encouraging adolescents to approach difficult situations from multiple perspectives. Research on executive functions in real-world and everyday contexts has emphasized the importance of performance-based and ecologically valid assessment of executive abilities, since executive functioning is most meaningful when it is reflected in complex tasks that resemble daily demands (Finnanger et al., 2022). Similarly, studies on virtual reality assessment have argued that ecologically valid methods can provide a more realistic understanding of executive functioning in children and adolescents, especially when traditional measures fail to capture how executive processes operate in dynamic environments (Ayuso et al., 2024). Since problem solving reflects the practical application of executive control, it is reasonable to assume that adolescents with stronger problem-solving skills will demonstrate higher levels of cognitive flexibility.

A growing body of research has examined executive functions in clinical and neurodevelopmental populations, showing that cognitive flexibility and related executive processes are important across multiple developmental conditions. Studies on autism spectrum disorder have emphasized the importance of executive function assessment and management in cognitive impairment, as well as the role of family and school environments in shaping executive performance (Gentil-Gutiérrez et al., 2022; Raj et al., 2025). Meta-analytic evidence also indicates that cognitive behavioral interventions can improve executive functions in children with high-functioning autism spectrum disorder, suggesting that executive capacities are modifiable and can be strengthened through structured intervention (Singh et al., 2024). Research on children and adolescents with ADHD similarly differentiates between hot and cool executive functions and emphasizes that executive profiles may vary according to motivational, emotional, and cognitive demands (Košíková et al., 2024). These findings show that cognitive flexibility is embedded in a complex developmental system and may be influenced by attention control, working memory, emotion regulation, learning experiences, and intervention exposure.

Clinical research has also highlighted the importance of cognitive flexibility in adolescent mental health. For example, cognitive flexibility has been identified as a key target in adolescents with anorexia nervosa, where rigidity in thinking and behavior can maintain maladaptive patterns and interfere with recovery (Timko et al., 2024). A narrative review on childhood and adolescent headaches further indicated that psychiatric comorbidity, resilience, and executive function may jointly affect health-related outcomes, supporting the importance of executive processes in both psychological and somatic conditions (Arruda et al., 2025). Research on emotional memory management training has shown that interventions targeting emotional and cognitive processes may improve executive functions and reduce difficulties in emotional regulation among adolescents (Hoseini et al., 2022). Likewise, pilot work on chess as a therapeutic approach in adolescents with mental disorders suggests that cognitively demanding structured activities may support executive functioning and mental health through repeated engagement in planning, anticipation, and strategic flexibility (Gerhardt et al., 2025). These studies collectively indicate that cognitive flexibility is clinically meaningful and closely associated with adolescents' capacity to cope with emotional and cognitive challenges.

Educational and physical activity research has further demonstrated that executive functions can be influenced by structured learning environments, movement-based interventions, and cognitively enriched activities. Systematic reviews and meta-analyses have shown that physical exercise can improve cognitive function and executive performance in adolescents, particularly when activities require sustained attention, coordination, planning, and adaptive regulation (Liu et al., 2025; Shi et al., 2022). Research on cardiorespiratory fitness has also linked physical fitness with performance across multiple domains of executive functions in school-aged adolescents (Cabral et al., 2021). Moreover, studies comparing different types of sports practice suggest that sports involving strategy, adaptation, and complex decision-making may produce distinct executive benefits in schoolchildren (Contreras-Osorio et al., 2022). Soccer-based integrative practice and complex motor schemes have similarly been proposed as ways to stimulate cognitive development in children and adolescents by combining motor coordination with attentional and executive demands (Latino et al., 2025; Mao et al., 2024). These findings strengthen the argument that cognitive flexibility develops through the interaction of cognitive, behavioral, and environmental factors.

The relationship between motor, sensorimotor, and executive functions also supports a multidimensional understanding of cognitive flexibility. Developmental research has shown that sensorimotor and executive functions are related, although these relationships may vary across age and developmental stage (Gordon-Murer et al., 2021). Studies of pediatric patients with Down syndrome have also shown that motor skills and executive functions are connected, indicating the need to tailor interventions that address both cognitive and physical dimensions of development (Vandoni et al., 2023). Research comparing gifted and non-gifted students has further shown that executive functions may differ according to cognitive profiles and high capability status, suggesting that executive abilities contribute to individual differences in learning potential and adaptive performance (Rocha et al., 2020). These lines of evidence indicate that cognitive flexibility should not be understood as a narrow mental operation, but as part of a broader adaptive system involving cognition, behavior, motivation, and developmental context.

In parallel with theoretical and empirical advances in executive function research, artificial intelligence and machine learning approaches have increasingly been used to assess, predict, stimulate, and rehabilitate executive functions. Systematic reviews on artificial cognitive systems have shown that intelligent systems can be applied in executive function stimulation and rehabilitation programs, offering new possibilities for personalized assessment and intervention (Robledo-Castro et al., 2022). Recent work on artificial intelligence in education has also demonstrated the value of decision tree learning in predicting secondary school students' outcomes based on cold and hot executive functions, suggesting that machine learning models can identify meaningful patterns that may not be captured by conventional linear analyses (Escolano-Pérez & Losada, 2024). Robotics-based STEAM education has similarly been discussed as a way to enhance executive functioning among typical students and students with ADHD through activities that require planning, sequencing, inhibition, and cognitive flexibility (Drakatos & Drigas, 2024). These developments show that computational approaches are becoming increasingly relevant for both understanding and improving executive functioning in children and adolescents.

The use of artificial intelligence is especially important because executive functions are complex, nonlinear, and interactive. Traditional statistical models often assume linear associations and may underestimate the combined contribution of attention control, working memory, and problem-solving skills to cognitive flexibility. In contrast, machine learning algorithms can model nonlinear patterns, interaction effects, and hierarchical structures among predictors. Recent systematic work on AI chatbots and cognitive control has suggested that artificial intelligence-based interactions may contribute to the enhancement of executive functions, while also requiring careful evaluation of cognitive mechanisms and developmental appropriateness (Pergantis et al., 2025). In another domain, research on executive functions and driving has demonstrated how cognitive control processes influence complex real-world behaviors that require sustained attention, rapid updating, inhibition, and flexible response adjustment (Pergantis et al., 2024). These studies support the broader claim that executive functions should be studied through models capable of handling dynamic, multicomponent cognitive systems.

Among machine learning algorithms, CatBoost is particularly suitable for predictive modeling in psychological and educational datasets because it can capture complex relationships among variables, reduce overfitting through ordered boosting, and perform efficiently with structured tabular data. Although the present study focuses on psychological prediction rather than clinical diagnosis or educational classification, the logic of using CatBoost is consistent with the increasing movement toward

JAYPS Adolescent and Youth Psychological Studies
E-ISSN: 2981-2526

data-driven modeling of executive functions. Adolescents' cognitive flexibility may be influenced simultaneously by attentional focusing, attentional shifting, working memory capacity, problem-solving confidence, emotional regulation, and contextual learning demands. Machine learning models can help identify the relative importance of these predictors and produce a more nuanced understanding of how cognitive flexibility emerges from the interaction of multiple executive and metacognitive processes. This approach is particularly valuable in adolescent research, where developmental variability is high and conventional models may fail to reflect the full complexity of cognitive adaptation.

Despite the expansion of research on executive functioning, several gaps remain. First, many studies have examined executive functions in clinical or special populations, while fewer studies have focused on general adolescent samples in educational contexts. Second, although attention control, working memory, and problem-solving skills are theoretically linked to cognitive flexibility, their simultaneous predictive contribution has not been sufficiently examined using advanced machine learning methods. Third, much of the existing research has relied on traditional statistical approaches, while fewer studies have used algorithms capable of detecting nonlinear patterns among executive variables. Finally, there is a need for culturally and educationally contextualized research among adolescents in Tehran, where academic demands, social pressures, and developmental challenges may shape executive functioning in distinctive ways. Addressing these gaps can contribute to both theoretical understanding and practical screening by identifying which cognitive variables are most informative in predicting adolescents' cognitive flexibility.

The aim of the present study was to predict cognitive flexibility based on attention control, working memory, and problem-solving skills in adolescents using the CatBoost machine learning algorithm.

2. Methods and Materials

2.1. Study Design and Participants

This study was conducted using a quantitative, descriptive-correlational, and predictive design with an applied orientation. The main objective of the study was to predict cognitive flexibility based on attention control, working memory, and problem-solving skills among adolescents using the CatBoost machine learning algorithm. The statistical population consisted of male and female adolescents studying in secondary schools in Tehran during the 2025–2026 academic year. The participants were selected from different educational districts of Tehran in order to obtain a heterogeneous sample in terms of gender, school grade, and socioeconomic background. Using multistage cluster sampling, several educational districts were first selected from Tehran, then schools were randomly chosen from each district, and finally eligible students were invited to participate in the study. The final sample included exactly 384 adolescents aged 13 to 18 years. Inclusion criteria were being enrolled in a secondary school in Tehran, being within the age range of adolescence, willingness to participate in the study, and obtaining written informed consent from parents or legal guardians as well as assent from the adolescents themselves. Exclusion criteria included incomplete responses to the questionnaires, unwillingness to continue participation, reported history of severe neurological or psychiatric disorders, and failure to follow the instructions for completing the study instruments. Participants were informed that their participation was voluntary, that their responses would remain confidential, and that the collected data would be analyzed only for research purposes.

2.2. Measures

Cognitive flexibility was assessed using the Cognitive Flexibility Inventory developed by Dennis and Vander Wal in 2010. This instrument is designed to evaluate individuals' perceived ability to generate alternative solutions, adapt to changing situations, and perceive difficult situations as controllable. The inventory includes 20 items and is commonly scored on a Likert-type scale ranging from strong disagreement to strong agreement. Higher scores indicate greater cognitive flexibility. The scale generally includes two main dimensions: alternatives, which refers to the ability to perceive multiple explanations and solutions, and control, which reflects the tendency to view difficult situations as manageable. The Cognitive Flexibility Inventory has been widely used in adolescent and student populations, and previous studies have reported acceptable validity and reliability for its total score and subscales. In the present study, the total score of this instrument was considered the dependent variable to be predicted by the machine learning model.

Attention control was measured using the Attentional Control Scale developed by Derryberry and Reed in 2002.

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This scale evaluates individual differences in the ability to focus, shift, and regulate attention in daily cognitive and emotional situations. The instrument includes items that assess attentional focusing and attentional shifting, with responses typically recorded on a Likert-type scale. Higher scores indicate stronger perceived attentional control. The attentional focusing component reflects the ability to maintain attention on a task despite distraction, whereas the attentional shifting component reflects the ability to flexibly move attention between tasks, thoughts, or environmental demands. Previous psychometric studies have confirmed the validity and reliability of this scale in adolescent and young adult samples. In the present study, the total score and subscale scores of attention control were used as predictor variables in the predictive model.

Working memory was assessed using the Working Memory Questionnaire developed to evaluate everyday manifestations of working memory functioning in learning, attention, and cognitive regulation. This instrument measures the extent to which individuals can temporarily retain, manipulate, and update information while performing cognitive tasks. The questionnaire includes items related to remembering instructions, maintaining concentration during mental activities, organizing information, and completing tasks that require simultaneous storage and processing of information. Responses are scored on a Likert-type scale, and higher scores indicate stronger working memory functioning. The questionnaire has been used in educational and developmental research, and its validity and reliability have been supported in previous studies. In the present study, working memory was included as one of the main cognitive predictors of cognitive flexibility, because the ability to hold and manipulate information is theoretically related to flexible thinking and adaptive problem solving.

Problem-solving skills were measured using the Problem-Solving Inventory developed by Heppner and Petersen in 1982. This instrument assesses individuals' perceptions of their problem-solving ability rather than their actual performance on a specific problem-solving task. The inventory includes items related to problem-solving confidence, approach–avoidance style, and personal control during problem-solving situations. Responses are recorded on a Likert-type scale, and the scoring procedure is interpreted according to the scale guidelines. The problem-solving confidence dimension reflects individuals' belief in their ability to solve problems effectively, the approach–avoidance dimension reflects the tendency to confront or avoid problems, and the personal control dimension reflects perceived emotional and behavioral control during problem-solving processes. Previous research has confirmed the validity and reliability of this instrument across different student and adolescent populations. In the present study, the total score and relevant subscale scores were used as predictor variables for estimating cognitive flexibility.

2.3. Data Analysis

Data analysis was conducted in two main phases: preliminary statistical analysis and machine learning-based predictive analysis. In the preliminary phase, the collected data were screened for missing values, incomplete responses, outliers, and inconsistencies. Descriptive statistics, including mean, standard deviation, minimum, maximum, skewness, and kurtosis, were calculated for cognitive flexibility, attention control, working memory, and problem-solving skills. The internal consistency of the instruments was evaluated using Cronbach's alpha coefficient. Pearson correlation coefficients were also calculated to examine the bivariate relationships among the study variables and to provide an initial understanding of the associations between cognitive predictors and cognitive flexibility.

In the predictive phase, the CatBoost algorithm was used to predict cognitive flexibility based on attention control, working memory, and problem-solving skills. CatBoost was selected because it is a gradient boosting algorithm that performs effectively with structured data, can model nonlinear relationships, is resistant to overfitting through ordered boosting, and is able to handle complex interactions among predictors. Before model training, the dataset was randomly divided into training and testing subsets, with 80% of the data used for training and 20% used for testing. Model tuning was conducted by adjusting key hyperparameters, including learning rate, depth, number of iterations, and regularization parameters. The predictive performance of the model was evaluated using standard regression indices, including mean absolute error, mean squared error, root mean squared error, and coefficient of determination. To improve the reliability of the findings, cross-validation was applied during the training process. Feature importance analysis was also performed to identify the relative contribution of attention control, working memory, and problem-solving skills in predicting cognitive flexibility. All statistical analyses were conducted at a significance level of 0.05, and the machine learning procedures were performed using Python-based analytical libraries.

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3. Findings and Results

The demographic characteristics of the participants showed that the final sample consisted of 384 adolescents studying in secondary schools in Tehran. Of these participants, 186 students were male (48.4%) and 198 students were female (51.6%), indicating a relatively balanced gender distribution. The age of the participants ranged from 13 to 18 years, with a mean age of 15.54 years and a standard deviation of 1.62. In terms of educational grade, 63 students were in the seventh grade (16.4%), 64 students were in the eighth grade (16.7%), 65 students were in the ninth grade (16.9%), 65 students were in the tenth grade (16.9%), 64 students were in the eleventh grade (16.7%), and 63 students were in the twelfth grade (16.4%). Regarding school type, 245 participants studied in public schools (63.8%) and 139 participants studied in private schools (36.2%). Overall, the demographic distribution of the sample showed that the participants represented different age groups, school grades, and educational contexts within Tehran, which provided a suitable basis for examining cognitive flexibility and its cognitive predictors among adolescents.

Table 1

Descriptive Statistics, Reliability Coefficients, and Distribution Indices of the Study Variables

Variable	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis	Cronbach's Alpha
Cognitive flexibility	91.46	15.38	48	129	-0.23	0.11	0.88
Attention control	53.72	8.64	30	75	-0.18	0.32	0.84
Working memory	102.35	17.16	57	143	-0.09	-0.27	0.87
Problem-solving skills	128.74	20.65	68	178	-0.31	0.19	0.90

As shown in Table 1, the mean score of cognitive flexibility was 91.46 with a standard deviation of 15.38, indicating that the adolescents generally obtained a moderate to relatively high level of cognitive flexibility. The mean score of attention control was 53.72, suggesting that the participants had a moderate level of perceived ability to focus and shift attention in cognitive and emotional situations. The mean score of working memory was 102.35, which indicates a relatively acceptable level of working memory functioning in the sample. The mean score of problem-solving skills was 128.74, showing that the participants reported a moderate to high level of perceived problem-solving ability. The values of skewness and kurtosis for all variables were within the acceptable range of -2 to +2, indicating that the distributions of the variables did not show serious deviation from normality. In addition, the Cronbach's alpha coefficients ranged from 0.84 to 0.90, demonstrating acceptable to excellent internal consistency for all instruments used in the study. These results confirmed that the data were suitable for further correlational and predictive analyses.

Table 2

Pearson Correlation Matrix Among Cognitive Flexibility, Attention Control, Working Memory, and Problem-Solving Skills

Variable	1	2	3	4
1. Cognitive flexibility	1			
2. Attention control	0.55**	1		
3. Working memory	0.48**	0.42**	1	
4. Problem-solving skills	0.61**	0.46**	0.52**	1

The correlation results presented in Table 2 showed that cognitive flexibility had a positive and statistically significant relationship with all three predictor variables. The strongest correlation was observed between cognitive flexibility and problem-solving skills ($r = 0.61$, $p < 0.01$), indicating that adolescents with stronger perceived problem-solving skills tended to report higher cognitive flexibility. A significant positive correlation was also found between cognitive flexibility and attention control ($r = 0.55$, $p < 0.01$), showing that adolescents who were better able to focus, regulate, and shift their attention were more likely to demonstrate flexible cognitive responses. In addition, working memory was significantly and positively related to cognitive flexibility ($r = 0.48$, $p < 0.01$), suggesting that adolescents with better capacity to maintain and manipulate information during cognitive tasks tended to show higher flexibility in thinking. The correlations among the predictor variables were also significant but moderate, indicating that attention control, working memory, and problem-solving skills were related constructs but not identical. Therefore, the predictor variables were appropriate for entry into the CatBoost model because each had a meaningful relationship with cognitive flexibility while still contributing distinct information.

Table 3

Predictive Performance of the CatBoost Model for Cognitive Flexibility

Dataset	MAE	MSE	RMSE	R^2
Training set	5.74	55.46	7.45	0.765
Test set	7.18	82.11	9.06	0.652
Five-fold cross-validation	7.36	86.45	9.28	0.636

The results of the CatBoost model presented in Table 3 indicated that the model had acceptable predictive performance in estimating cognitive flexibility based on attention control, working memory, and problem-solving skills. In the training set, the model explained 76.5% of the variance in cognitive flexibility, with a mean absolute error of 5.74 and a root mean squared error of 7.45. In the test set, the model explained 65.2% of the variance in cognitive flexibility, with a mean absolute error of 7.18 and a root mean squared error of 9.06. The reduction in predictive accuracy from the training set to the test set was expected and did not indicate severe overfitting, because the difference between the training and test performance was moderate. The five-fold cross-validation results also supported the stability of the model, with an average R^2 value of 0.636 and an RMSE value of 9.28. These findings suggest that CatBoost was able to model both linear and nonlinear patterns among the predictor variables and produce a reliable estimation of adolescents' cognitive flexibility. Overall, the predictive indices showed that the model had satisfactory generalizability and that the selected cognitive variables were meaningful predictors of cognitive flexibility.

Table 4

Relative Importance of Predictors in the CatBoost Model

Predictor	Relative Importance (%)	Rank
Problem-solving skills	34.82	1
Attention control	27.46	2
Working memory	22.19	3
Attention focusing	6.84	4
Attention shifting	4.73	5
Problem-solving confidence	2.41	6
Personal control in problem solving	1.55	7

The feature importance results presented in Table 4 showed that problem-solving skills had the highest contribution to the prediction of cognitive flexibility, accounting for 34.82% of the total predictive importance in the CatBoost model. This finding indicates that adolescents' perceived ability to define problems, generate solutions, evaluate alternatives, and regulate their behavior during challenging situations played the most central role in predicting cognitive flexibility. Attention control was the second most important predictor, with a relative importance of 27.46%, suggesting that the ability to sustain attention, resist distraction, and shift attention when necessary was highly influential in explaining individual differences in cognitive flexibility. Working memory was ranked third, with a relative importance of 22.19%, indicating that the capacity to hold, update, and manipulate information contributed substantially to flexible thinking. Among the more specific components, attention focusing and attention shifting had smaller but meaningful contributions, while problem-solving confidence and personal control had lower relative importance. Overall, the ranking of predictors showed that cognitive flexibility in adolescents is most strongly associated with adaptive problem-solving capacity, followed by attentional regulation and working memory functioning.

Figure 1

Predicted and Observed Cognitive Flexibility Scores in the Test Dataset Based on the CatBoost Model

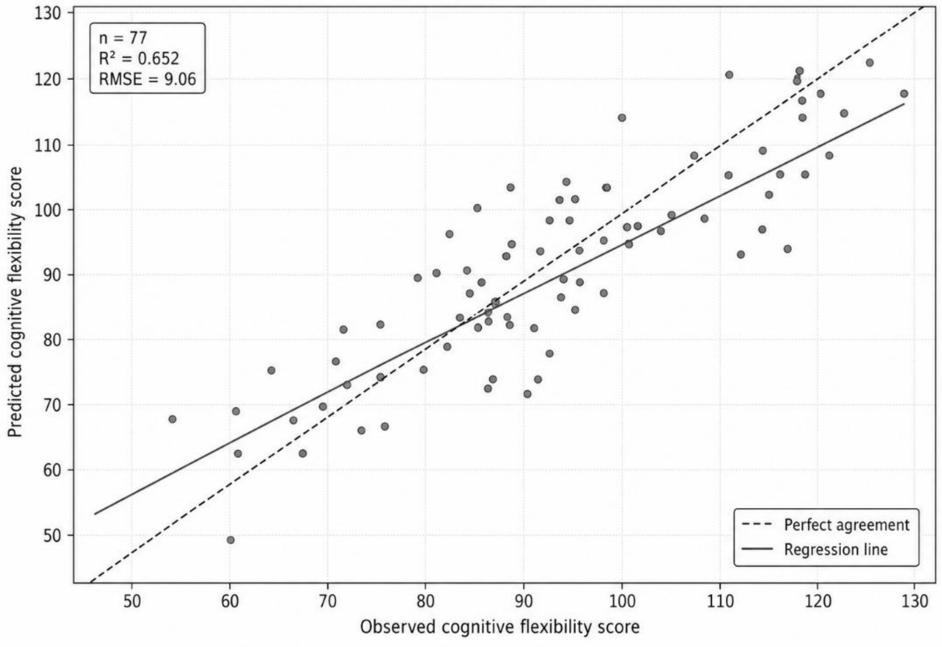

Figure 1 illustrates the agreement between the observed cognitive flexibility scores and the scores predicted by the CatBoost model in the test dataset. The distribution of predicted values was generally close to the observed values, indicating that the model was able to estimate cognitive flexibility with acceptable accuracy. Most predicted scores were concentrated around the central range of the observed scores, showing that the model performed particularly well in predicting moderate levels of cognitive flexibility. Some prediction errors were observed at the lower and higher ends of the score distribution, which is common in machine learning models when the number of extreme cases is smaller than the number of average cases. Nevertheless, the overall pattern demonstrated that the predicted values followed the same direction as the observed values, supporting the adequacy of the CatBoost algorithm for modeling cognitive flexibility based on attention control, working memory, and problem-solving skills. This result confirms that the combination of these cognitive variables provides a meaningful predictive structure for understanding cognitive flexibility among adolescents.

4. Discussion

The present study aimed to predict cognitive flexibility based on attention control, working memory, and problem-solving skills in adolescents using the CatBoost machine learning algorithm. The findings showed that cognitive flexibility had significant positive relationships with all three predictor variables, including attention control, working memory, and problem-solving skills. Among these variables, problem-solving skills had the strongest correlation with cognitive flexibility, followed by attention control and working memory. In the machine learning phase, the CatBoost model demonstrated acceptable predictive performance, explaining a substantial proportion of variance in cognitive flexibility in both the training and test datasets. The feature importance results further indicated that problem-solving skills were the most influential predictor of cognitive flexibility, followed by attention control and working memory. These findings suggest that adolescents who are more capable of defining problems, generating alternatives, regulating attention, and holding relevant information in mind are more likely to show flexible thinking and adaptive cognitive responses in academic and everyday situations. This pattern is consistent with

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E-ISSN: 2981-2526

developmental models of executive functioning, which conceptualize cognitive flexibility as a higher-order executive capacity that depends on the coordinated operation of attention, working memory, planning, inhibition, and adaptive control (Happaney & Zelazo, 2022; Sayar, 2024).

The positive association between problem-solving skills and cognitive flexibility was one of the central findings of the study. This result indicates that adolescents who perceive themselves as more competent in approaching, analyzing, and resolving problems tend to demonstrate higher levels of flexible cognition. Problem solving requires the individual to move beyond a single interpretation of a situation, compare alternative solutions, revise unsuccessful strategies, and maintain goal-directed behavior under uncertainty. These processes are closely aligned with the functional meaning of cognitive flexibility. The finding is supported by research emphasizing that executive functions are most visible in complex, everyday situations where individuals must organize actions, monitor outcomes, and adjust strategies dynamically (Finnanger et al., 2022; Pablo-Ríos et al., 2024). It is also consistent with studies that highlight the ecological value of executive function assessment, showing that executive abilities should be understood in relation to real-life adaptive demands rather than only isolated cognitive tasks (Ayuso et al., 2024; Beckmann & Mano, 2021). Therefore, the strong contribution of problem-solving skills in the present study can be explained by the fact that problem solving represents an applied form of executive control in which cognitive flexibility is continuously required.

The finding that attention control significantly predicted cognitive flexibility also aligns with theoretical and empirical evidence. Attention control enables adolescents to maintain focus on relevant information, suppress distracting stimuli, and shift attention when task demands change. These abilities are necessary for cognitive flexibility because flexible thinking requires both stability and change: adolescents must maintain the current goal while also being able to disengage from ineffective strategies and redirect attention toward new information. Previous research has shown that attentional and executive functions are closely connected in children and adolescents, particularly in developmental conditions where attentional dysregulation limits adaptive functioning (Košíková et al., 2024; Lachambre et al., 2021). Studies on children and adolescents with hearing loss and other developmental challenges have also indicated that limitations in attention regulation may influence executive performance and adaptive cognitive functioning (Charry-Sánchez et al., 2022; Lee et al., 2024). Accordingly, the predictive role of attention control in the present study suggests that adolescents with stronger attentional regulation are better able to reorganize their thinking, consider alternative perspectives, and respond more adaptively to changing academic and social demands.

Working memory was also found to be a meaningful predictor of cognitive flexibility. This finding can be explained by the role of working memory in temporarily storing, updating, and manipulating information during cognitive tasks. Cognitive flexibility requires adolescents to compare different possibilities, keep task rules in mind, integrate feedback, and shift between alternative strategies. Without adequate working memory capacity, flexible thinking may become limited because the adolescent may have difficulty maintaining relevant information while evaluating new responses. This result is consistent with evidence showing that working memory, inhibition, and cognitive flexibility operate as interrelated components of executive functioning during development (Filipiak & Hawrot, 2024; Happaney & Zelazo, 2022). Research on sleep quality, creativity, and executive function has also shown that working memory and broader executive capacities can mediate important cognitive outcomes, suggesting that working memory contributes to complex forms of adaptive cognition (Guo et al., 2022). Similarly, studies on executive functioning in clinical and developmental populations demonstrate that weaknesses in working memory may interfere with emotional regulation, learning, planning, and adaptive decision-making (Hoseini et al., 2022; Raj et al., 2025). Thus, the present findings confirm that working memory provides a cognitive foundation for flexible thought and behavior in adolescents.

The performance of the CatBoost model provides an important methodological contribution to the study of adolescent executive functions. The model showed satisfactory predictive accuracy, with acceptable values for R^2, MAE, RMSE, and cross-validation performance. This indicates that the relationship between cognitive flexibility and its predictors can be modeled effectively using machine learning methods. Traditional statistical models are useful for identifying linear associations, but executive functions are often nonlinear, interactive, and context-dependent. CatBoost is particularly appropriate for such data because it can detect complex patterns among predictors and estimate the relative importance of each variable. This finding is consistent with recent studies showing the value of artificial intelligence and machine learning in education, executive

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function assessment, and cognitive intervention research (Escolano-Pérez & Losada, 2024; Robledo-Castro et al., 2022). Studies on AI chatbots and cognitive control further suggest that artificial intelligence-based methods may support the assessment and enhancement of executive functioning by identifying individualized cognitive patterns (Pergantis et al., 2025). Therefore, the present findings support the use of machine learning as a complementary approach for understanding adolescent cognitive flexibility.

The feature importance results showed that problem-solving skills had the greatest predictive contribution, followed by attention control and working memory. This ranking suggests that cognitive flexibility may be most strongly expressed through adolescents' ability to deal with complex and uncertain situations. Although attention control and working memory provide essential cognitive resources, problem-solving skills may reflect the integration of these resources into functional behavior. In other words, adolescents may need attention control to focus on the problem and working memory to maintain relevant information, but flexible cognition becomes most visible when they apply these capacities to generate and evaluate solutions. This interpretation is consistent with research showing that executive functions are strongly related to real-world functioning, academic achievement, and adaptive behavior (Finnanger et al., 2022; Pablo-Ríos et al., 2024). It also aligns with evidence from intervention-based studies showing that activities requiring planning, sequencing, strategic thinking, and adaptive response selection can stimulate executive functioning in children and adolescents (Drakatos & Drigas, 2024; Gerhardt et al., 2025). Therefore, the dominance of problem-solving skills in the CatBoost model suggests that cognitive flexibility should be understood not only as a cognitive capacity, but also as a practical adaptive skill.

The findings are also consistent with research showing that executive functions can be strengthened through cognitively and behaviorally enriched experiences. Studies on physical exercise, sports practice, motor coordination, and cardiorespiratory fitness have shown that structured physical activities may improve executive functions by requiring attention, planning, response inhibition, and flexible adaptation to changing conditions (Cabral et al., 2021; Contreras-Osorio et al., 2022; Liu et al., 2025; Shi et al., 2022). Similarly, research on soccer-based integrative practice and complex motor schemes has shown that activities combining motor demands with cognitive challenges can support cognitive development in children and adolescents (Latino et al., 2025; Mao et al., 2024). These findings are relevant to the present study because they show that cognitive flexibility is not a fixed trait, but a developmental capacity that may be influenced by educational, physical, social, and therapeutic experiences. Research on sensorimotor and executive functions also supports the idea that cognitive flexibility is part of a broader adaptive system involving movement, perception, cognition, and environmental interaction (Gordon-Murer et al., 2021; Vandoni et al., 2023). Therefore, the predictors identified in this study may be useful targets for developmental interventions.

The present results also have implications for adolescents with clinical, developmental, or educational vulnerabilities. Previous studies have shown that executive functioning difficulties are common in autism spectrum disorder, ADHD, anorexia nervosa, chronic pain, headaches, restless sleep disorder, developmental coordination disorder, and other conditions affecting children and adolescents (Arruda et al., 2025; DelRosso et al., 2022; Gentil-Gutiérrez et al., 2022; Lachambre et al., 2021; Singh et al., 2024; Timko et al., 2024). These studies suggest that cognitive flexibility is closely linked with emotional regulation, health-related functioning, academic adaptation, and behavioral adjustment. For example, rigidity in thinking may maintain maladaptive patterns in eating disorders, while executive dysfunction may intensify difficulties in chronic pain or neurodevelopmental conditions (Beckmann & Mano, 2021; Timko et al., 2024). The present study extends this literature by showing that even in a general adolescent sample, cognitive flexibility can be predicted from attention control, working memory, and problem-solving skills. This suggests that early identification of weaknesses in these areas may help prevent broader difficulties in learning, emotional regulation, and everyday adaptation.

5. Conclusion

Overall, the findings support a multidimensional interpretation of cognitive flexibility in adolescence. Cognitive flexibility appears to emerge from the interaction of basic cognitive resources, such as attention control and working memory, with higher-order applied skills, such as problem solving. Adolescents who can focus attention, shift mental sets, maintain relevant information, and evaluate alternative solutions are better positioned to adapt to complex academic and social environments. The use of CatBoost added value by demonstrating that these predictors

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do not merely have isolated relationships with cognitive flexibility, but together form a meaningful predictive structure. This conclusion is consistent with contemporary research that views executive functions as dynamic, trainable, and context-sensitive abilities rather than fixed cognitive traits (Kupis & Uddin, 2023; Sayar, 2024). It is also aligned with studies comparing gifted and non-gifted students, which suggest that executive functions contribute to individual differences in cognitive performance and adaptive capacity (Rocha et al., 2020). Therefore, strengthening adolescents' attention regulation, working memory, and problem-solving skills may contribute to the development of more flexible and adaptive cognitive functioning.

6. Limitations & Suggestions

The present study had several limitations that should be considered when interpreting the findings. First, the study used a descriptive-correlational and predictive design, which means that causal conclusions cannot be drawn from the relationships among attention control, working memory, problem-solving skills, and cognitive flexibility. Second, the participants were selected from adolescents studying in Tehran, and although the sample was diverse in terms of age, gender, and school grade, the findings may not be fully generalizable to adolescents from other cities, rural areas, or different cultural and educational contexts. Third, the study relied on self-report questionnaires, which may be influenced by response bias, social desirability, self-perception errors, and differences in students' interpretation of items. Fourth, although the CatBoost model showed acceptable predictive performance, the model was trained and tested on a single dataset, and its generalizability should be confirmed using independent samples. Finally, the study focused on three cognitive predictors, while cognitive flexibility may also be influenced by emotional regulation, motivation, personality traits, family environment, sleep quality, academic stress, and neurological factors.

Future studies are recommended to use longitudinal and experimental designs to clarify the causal relationships among attention control, working memory, problem-solving skills, and cognitive flexibility. Researchers should examine whether improvements in attention regulation, working memory training, or problem-solving interventions can directly enhance cognitive flexibility over time. Future research should also replicate the present model in larger and more diverse samples from different cities, educational systems, socioeconomic backgrounds, and cultural contexts. In addition, it would be valuable to compare CatBoost with other machine learning algorithms, such as random forest, support vector regression, XGBoost, artificial neural networks, and ensemble models, in order to determine which method provides the most accurate and interpretable prediction of cognitive flexibility. Future studies should also include behavioral, neuropsychological, teacher-rated, and parent-rated measures alongside self-report tools to obtain a more comprehensive assessment of executive functioning. Finally, future research may examine additional predictors, such as emotional regulation, academic motivation, sleep quality, anxiety, resilience, physical activity, and classroom climate, to develop a more complete predictive model of cognitive flexibility in adolescence.

The findings of this study suggest that schools, counselors, educational psychologists, and adolescent mental health professionals should pay greater attention to cognitive flexibility as a key developmental capacity. Since problem-solving skills had the strongest predictive role, school-based programs should include structured activities that help students define problems, generate alternative solutions, evaluate consequences, and revise ineffective strategies. Attention control should also be strengthened through classroom practices that reduce distraction, support sustained concentration, and teach students how to shift attention effectively between tasks. Working memory can be supported by using step-by-step instructions, visual organizers, rehearsal strategies, summarization exercises, and learning tasks that gradually increase cognitive load. In practice, machine learning-based screening may help identify students who are at risk for lower cognitive flexibility and who may benefit from targeted cognitive, educational, or counseling interventions. Educational interventions should be designed in an integrated way so that adolescents learn not only to remember information, but also to use information flexibly, regulate attention, and solve problems adaptively in real-life academic and social situations.

Acknowledgments

We would like to express our appreciation and gratitude to all those who cooperated in carrying out this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

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

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

Funding

This research was carried out independently with personal funding and without the financial support of any governmental or private institution or organization.

Authors' Contributions

All authors equally contributed to this article.

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E-ISSN: 2981-2526