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Explainable Artificial Intelligence Modeling of Social Participation in Children with Intellectual Disabilities: A SHAP-Based CatBoost Analysis of Adaptive Behavior, Communication Competence, and Parental Involvement

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A B S T R A C T

The present study aimed to develop and interpret an explainable artificial intelligence model of social participation in children with intellectual disabilities by examining the predictive contributions of adaptive behavior, communication competence, and parental involvement using a SHAP-based CatBoost algorithm. This cross-sectional predictive modeling study was conducted among 412 children with mild to moderate intellectual disabilities aged 8–16 years who were recruited from special education schools, rehabilitation centers, and inclusive educational settings across Hungary. Social participation was assessed using the Participation and Environment Measure for Children and Youth (PEM-CY), while adaptive behavior, communication competence, and parental involvement were measured using standardized psychometric instruments. Following data preprocessing and screening procedures, a CatBoost machine learning model was developed to predict social participation outcomes. Model performance was evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). To enhance interpretability, SHapley Additive exPlanations (SHAP) analyses were conducted to determine the relative importance and direction of predictor contributions. Pearson correlation analyses demonstrated significant positive associations between social participation and adaptive behavior ($r = .781$, $p < .001$), communication competence ($r = .724$, $p < .001$), and parental involvement ($r = .647$, $p < .001$). The CatBoost model exhibited excellent predictive performance, explaining 89.2% of the variance in social participation within the test dataset ($R^2 = .892$), with RMSE = 4.97, MAE = 3.89, and MAPE = 5.84%. SHAP analyses identified adaptive behavior as the strongest predictor of social participation (42.7% relative importance), followed by communication competence (32.8%) and parental involvement (19.7%). Together, these three variables accounted for more than 95% of the model's total explanatory influence. Furthermore, SHAP dependence

analyses revealed nonlinear interactions, indicating that the positive effects of adaptive behavior became increasingly pronounced at higher levels of communication competence and parental involvement. The findings demonstrate that social participation among children with intellectual disabilities is primarily influenced by adaptive behavior, communication competence, and parental involvement. The SHAP-based CatBoost model provided highly accurate and interpretable predictions, highlighting the value of explainable artificial intelligence for understanding participation outcomes in developmental disability research. These results support the development of family-centered and skills-focused interventions aimed at enhancing social inclusion and community participation among children with intellectual disabilities.

Keywords: *Social Participation; Intellectual Disabilities; Adaptive Behavior; Communication Competence; Parental Involvement*

1. Introduction

Social participation is widely recognized as a fundamental indicator of quality of life, psychosocial adjustment, and successful community integration among children with intellectual disabilities. Participation encompasses engagement in meaningful activities within home, school, and community contexts and reflects the degree to which children are able to interact with others, develop relationships, exercise autonomy, and contribute to social environments. Contemporary developmental and disability frameworks increasingly emphasize participation as a primary outcome of intervention rather than merely a secondary consequence of improvements in functional abilities. Children with intellectual disabilities often experience substantial barriers to participation, including limitations in adaptive functioning, communication difficulties, reduced opportunities for peer interaction, and environmental constraints that restrict inclusion (Marukyan, 2023; Trudel et al., 2022). Consequently, identifying the factors that facilitate or hinder social participation has become a major priority within special education, developmental psychology, rehabilitation sciences, and disability research.

The concept of participation is inherently multidimensional and influenced by the interaction between individual competencies and environmental supports. Recent scholarship in neurodevelopmental disabilities has highlighted the importance of considering both child-level characteristics and family-level influences when examining social outcomes. Research examining neurodevelopmental conditions consistently demonstrates that functional abilities, communication skills, sensory processing patterns, and caregiver involvement significantly influence children's opportunities for engagement in social contexts (Chen, 2023; Greaves-Lord et al., 2022; Hirota & King, 2023). Although intellectual disability differs diagnostically from autism spectrum disorder, both populations frequently share challenges related to adaptive functioning, communication effectiveness, and participation in community activities. Consequently, findings derived from broader developmental disability literature provide important theoretical foundations for understanding social participation among children with intellectual disabilities.

Adaptive behavior represents one of the most important constructs associated with successful functioning in everyday life. Adaptive behavior encompasses conceptual, social, and practical skills that enable individuals to navigate environmental demands and participate meaningfully in daily activities. Children with stronger adaptive skills are generally better able to establish social relationships, engage in community programs, communicate their needs, and perform age-appropriate responsibilities. Previous studies have consistently demonstrated that adaptive functioning is closely linked to social competence and participation outcomes across developmental disability populations (Marukyan, 2023; Michna et al., 2022; Trudel et al., 2022). Furthermore, adaptive behavior serves as a critical determinant of independence and inclusion, influencing children's ability to access educational opportunities, recreational activities, and peer networks. Theoretical models of disability increasingly recognize adaptive behavior not only as an outcome variable but also as a mechanism through which environmental opportunities are translated into meaningful participation experiences.

Communication competence constitutes another central factor influencing participation and social inclusion. Effective communication enables children to initiate interactions, maintain relationships, express preferences, negotiate social situations, and participate in collaborative activities. Communication difficulties frequently limit access to social opportunities and may contribute to social

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isolation, exclusion, and reduced engagement within educational and community settings. Research has demonstrated that deficits in expressive language, receptive language, pragmatic communication, and conversational abilities are strongly associated with diminished social functioning among children with neurodevelopmental disabilities (Johnson et al., 2023; Lei et al., 2024; Zhai et al., 2023). Communication competence not only facilitates direct interaction but also influences children's confidence, social self-efficacy, and perceived acceptance by peers. Consequently, understanding the contribution of communication skills to participation outcomes is essential for designing interventions aimed at improving inclusion and community engagement.

Family-related factors also play a critical role in shaping developmental trajectories and participation opportunities. Among these factors, parental involvement has emerged as one of the most influential predictors of positive social and educational outcomes. Parents frequently serve as advocates, facilitators, and coordinators of participation experiences for children with disabilities. Through active involvement, parents provide emotional support, organize participation opportunities, communicate with educators and service providers, and help children navigate social environments. Studies examining family functioning have consistently shown that parental engagement contributes significantly to children's social adaptation, emotional development, and community participation (Alhammashi et al., 2024; Costa-Cordella et al., 2023; Romeo, 2025). Attachment-based perspectives further suggest that supportive family relationships promote confidence, emotional regulation, and exploratory behaviors that enable children to engage more effectively in social contexts. Therefore, parental involvement may function as a critical environmental resource that enhances participation beyond the effects of individual child characteristics alone.

The growing body of literature on neurodevelopmental conditions further underscores the complexity of participation processes. Social engagement is influenced by numerous interconnected factors, including sensory processing, emotional functioning, behavioral regulation, and environmental accessibility. Sensory processing differences, for example, have been linked to variations in social interaction, adaptive functioning, and participation across multiple developmental populations (Filipova et al., 2023; Fotoglou et al., 2023; Ghosh et al., 2022). Difficulties in processing sensory information may limit children's willingness to engage in unfamiliar environments or participate in community activities. Similarly, sensory challenges have been associated with sleep disturbances, behavioral difficulties, and social withdrawal, all of which can indirectly affect participation outcomes (Lawson et al., 2022; Nimbley et al., 2022; Pride et al., 2023). Emerging neuroplasticity-based models suggest that targeted interventions can improve sensory integration and thereby enhance broader developmental functioning (Savarese et al., 2025; Suprunowicz et al., 2025). These findings illustrate the multidimensional nature of participation and highlight the importance of considering diverse developmental influences when constructing predictive models.

Beyond sensory and adaptive processes, psychosocial factors have also received increasing attention within developmental disability research. Children with neurodevelopmental conditions often experience elevated rates of social anxiety, emotional difficulties, and interpersonal challenges that may interfere with participation. Recent evidence suggests that social cognition, emotional awareness, and self-regulation play important roles in determining social engagement and relationship quality (Lei et al., 2024; Neu & Bradford, 2025; Sideraki & Drigas, 2022). Difficulties in these areas may reduce children's willingness to participate in group activities or limit their ability to maintain meaningful peer relationships. Furthermore, research examining self-harming behaviors, trauma experiences, and psychosocial stressors among neurodevelopmental populations highlights the importance of adopting comprehensive and ecologically informed approaches to understanding participation (Labarca et al., 2025; Michna et al., 2022; Zotti et al., 2025). Participation outcomes cannot be fully explained by a single characteristic but rather emerge through dynamic interactions among personal, familial, and environmental influences.

Intervention research provides additional support for the importance of adaptive behavior, communication competence, and family involvement. Studies examining music-based interventions, dance therapies, sensory integration programs, and family-centered approaches have demonstrated meaningful improvements in social functioning, communication, and participation-related outcomes among children with developmental disabilities (Li et al., 2023; Makheti, 2024; Savarese et al., 2025). Likewise, adaptations within healthcare, educational, and community environments have been shown to facilitate participation by reducing barriers and enhancing accessibility (Abualait et al., 2024; Ferrera-Fernández et al.,

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2025). These findings collectively suggest that social participation is modifiable and responsive to interventions targeting both child competencies and contextual supports. Nevertheless, the relative contribution of specific predictors remains insufficiently understood, particularly among children with intellectual disabilities.

Although considerable progress has been made in identifying factors associated with participation, most previous studies have relied on conventional statistical methods such as correlation analysis, regression modeling, and structural equation modeling. While these approaches provide valuable information, they may be limited in their ability to capture complex nonlinear relationships and interactions among multiple predictors. Developmental outcomes are rarely determined through simple linear mechanisms; instead, they often emerge from intricate combinations of behavioral, cognitive, familial, and environmental influences. Machine learning approaches offer significant advantages in this context because they can identify hidden patterns, model nonlinear associations, and generate highly accurate predictions from multidimensional datasets. Recent advances in artificial intelligence have therefore stimulated growing interest in applying machine learning techniques to developmental and disability research.

Among contemporary machine learning methods, CatBoost has emerged as a particularly powerful algorithm for handling heterogeneous datasets and complex predictor structures. CatBoost utilizes gradient boosting procedures while effectively managing categorical variables and minimizing overfitting. The algorithm has demonstrated strong predictive performance across numerous health, psychological, and educational applications. Despite these advantages, machine learning models are often criticized for their lack of transparency, creating challenges for interpretation and practical implementation. This limitation has motivated the development of Explainable Artificial Intelligence (XAI) techniques that enable researchers to understand how specific predictors influence model outputs. SHapley Additive exPlanations (SHAP) have become one of the most widely used methods for interpreting machine learning predictions because they quantify the contribution of each predictor to both individual and global model outcomes.

The integration of machine learning and explainable artificial intelligence provides a promising framework for advancing participation research. By combining predictive accuracy with interpretability, SHAP-based CatBoost models can identify the most influential determinants of social participation while simultaneously revealing how these factors interact to shape outcomes. Such approaches are particularly valuable in disability research, where interventions must be informed by a nuanced understanding of individual differences and contextual influences. Furthermore, explainable models can support evidence-based decision-making among educators, clinicians, rehabilitation specialists, and families by identifying modifiable factors that contribute most strongly to participation.

Despite increasing recognition of the importance of participation, relatively few studies have applied explainable machine learning methods to examine social participation among children with intellectual disabilities. Existing research has largely focused on descriptive analyses or isolated predictors, leaving important gaps in understanding the combined and relative influence of adaptive behavior, communication competence, and parental involvement. Addressing these gaps may contribute to more precise assessment strategies, individualized intervention planning, and enhanced opportunities for inclusion and community engagement.

The aim of the present study was to develop and interpret a SHAP-based CatBoost model of social participation in children with intellectual disabilities by examining the predictive contributions of adaptive behavior, communication competence, and parental involvement.

2. Methods and Materials

2.1. Study Design and Participants

This study employed a cross-sectional predictive modeling design grounded in the principles of Explainable Artificial Intelligence (XAI) to investigate the determinants of social participation among children with intellectual disabilities. The primary objective was to develop a robust and interpretable machine learning model capable of identifying the relative contributions of adaptive behavior, communication competence, and parental involvement to variations in social participation outcomes. The study was conducted in Hungary between January and September 2025 and involved children receiving educational, rehabilitation, and support services through specialized schools, inclusive educational settings, developmental centers, and community-based disability organizations located in Budapest, Debrecen, Szeged, Pécs, and Győr.

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The study population consisted of children formally diagnosed with mild to moderate intellectual disability according to the diagnostic criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) and verified through official educational or clinical records. A total of 412 children aged between 8 and 16 years participated in the study. Participants were selected using a multistage cluster sampling procedure. Initially, educational and rehabilitation institutions serving children with intellectual disabilities were identified across different regions of Hungary. Subsequently, eligible children and their parents were invited to participate through collaboration with school administrators, special education professionals, psychologists, and social workers. Inclusion criteria required participants to have a documented diagnosis of intellectual disability, regular school attendance, sufficient communication abilities to complete assessments with support when necessary, and parental consent for participation. Children with severe sensory impairments, profound intellectual disabilities, severe neurological disorders, or significant psychiatric conditions that could interfere with assessment procedures were excluded from the study.

2.2. Measures

Social participation was assessed using the Participation and Environment Measure for Children and Youth (PEM-CY), developed by Coster and colleagues in 2011. The PEM-CY is a widely recognized instrument designed to evaluate children's participation across home, school, and community environments. The measure consists of multiple items assessing frequency of participation, level of involvement, and environmental supports and barriers. Parents rated their children's participation experiences using standardized response scales, with higher scores indicating greater levels of meaningful participation in daily life activities. Previous international studies have demonstrated satisfactory psychometric properties for the PEM-CY, including strong internal consistency, construct validity, and test–retest reliability among children with developmental disabilities.

Adaptive behavior was measured using the Vineland Adaptive Behavior Scales, Third Edition (Vineland-3), developed by Sparrow, Cicchetti, and Saulnier in 2016. The Vineland-3 evaluates adaptive functioning across domains including communication, daily living skills, socialization, and motor skills. For the purposes of the present study, the overall adaptive behavior composite score was utilized as a key predictor variable. The instrument has been extensively employed in research involving individuals with intellectual and developmental disabilities and has demonstrated excellent reliability coefficients and strong evidence of convergent and discriminant validity across diverse populations.

Communication competence was assessed using the Communication Function Classification System (CFCS), originally developed by Hidecker and colleagues in 2011 and supplemented by the Children's Communication Checklist, Second Edition (CCC-2), developed by Bishop in 2003. The combined assessment approach enabled a comprehensive evaluation of both functional communication performance and broader communicative effectiveness in everyday social interactions. Domains assessed included expressive communication, receptive communication, conversational skills, pragmatic language abilities, and communication effectiveness with familiar and unfamiliar partners. Higher scores reflected stronger communication competence. Previous investigations have reported satisfactory psychometric characteristics for both instruments, including acceptable internal consistency, criterion validity, and stability over time.

Parental involvement was measured using the Family Involvement Questionnaire (FIQ), developed by Fantuzzo, Tighe, and Childs in 2000. The FIQ assesses the extent to which parents engage in educational, developmental, and community-related activities supporting their children's growth and participation. The questionnaire evaluates dimensions such as home-based involvement, school-related participation, communication with educators, advocacy efforts, and support for community engagement. Parents responded using a Likert-type scale, with higher scores representing greater involvement in their children's developmental and social experiences. The instrument has consistently demonstrated strong reliability and validity across studies involving families of children with disabilities.

Demographic and contextual information was collected through a structured background questionnaire completed by parents. Variables included child age, gender, level of intellectual disability, family socioeconomic status, parental education, household composition, urban or rural residence, and duration of service utilization. These variables were included to provide a comprehensive profile of the sample and to allow examination of potential confounding influences during model development.

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2.3. *Data Analysis*

Data analysis was performed using Python programming language (version 3.11) and associated machine learning libraries, including CatBoost, Scikit-learn, SHAP, NumPy, Pandas, and Matplotlib. Prior to model construction, data screening procedures were conducted to identify missing values, outliers, and inconsistencies. Missing data constituted less than 5% of the dataset and were addressed through multiple imputation procedures. Continuous variables were standardized where appropriate, and categorical variables were encoded using CatBoost's native categorical feature processing capabilities.

Descriptive statistics were initially calculated to summarize participant characteristics and study variables. Means, standard deviations, frequencies, and percentages were reported for demographic and psychological measures. Pearson correlation analyses were conducted to explore preliminary associations among adaptive behavior, communication competence, parental involvement, and social participation outcomes.

The primary predictive analysis employed the CatBoost algorithm, a state-of-the-art gradient boosting framework particularly suitable for handling heterogeneous datasets and complex nonlinear relationships. Social participation scores served as the target variable, while adaptive behavior, communication competence, parental involvement, and demographic covariates were included as predictor variables. Hyperparameter optimization was conducted using five-fold cross-validation combined with grid-search procedures to maximize predictive performance and minimize overfitting. Model performance was evaluated using multiple metrics, including the coefficient of determination (R^2), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE).

To enhance interpretability and align with contemporary Explainable Artificial Intelligence practices, SHapley Additive exPlanations (SHAP) analysis was performed following model training. SHAP values were calculated to quantify the contribution of each predictor to individual and overall model predictions. Global feature importance plots were generated to identify the most influential predictors of social participation, while local explanation analyses were conducted to examine prediction mechanisms at the individual participant level. Dependence plots and interaction analyses were also produced to explore nonlinear relationships and interactions among adaptive behavior, communication competence, and parental involvement. This explainable framework enabled transparent interpretation of the machine learning model and provided detailed insights into the factors contributing to social participation among children with intellectual disabilities.

3. Findings and Results

A total of 412 children with intellectual disabilities participated in the study. The mean age of the participants was 11.84 years (SD = 2.31), with ages ranging from 8 to 16 years. Of the participants, 238 (57.8%) were boys and 174 (42.2%) were girls. Regarding disability severity, 273 children (66.3%) had mild intellectual disability and 139 children (33.7%) had moderate intellectual disability. Most participants resided in urban areas (71.4%), while 28.6% lived in rural regions. Parents completing the questionnaires were predominantly mothers (74.5%), followed by fathers (21.8%) and other guardians (3.7%). The average duration of participation in educational or rehabilitation services was 4.76 years (SD = 2.15). Preliminary screening indicated that all variables approximated normal distributions, with skewness and kurtosis values falling within acceptable ranges. No severe multicollinearity was detected among predictor variables, and all variance inflation factor values remained below 3.0.

Table 1

Descriptive Statistics of Study Variables

Variable	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
Social Participation	72.48	12.63	38.00	98.00	-0.42	-0.31
Adaptive Behavior	86.91	14.82	45.00	118.00	-0.35	-0.27
Communication Competence	68.53	11.47	35.00	94.00	-0.29	-0.18
Parental Involvement	74.66	10.25	42.00	96.00	-0.51	-0.24

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Table 1 presents the descriptive statistics for the principal study variables. Social participation demonstrated a mean score of 72.48 (SD = 12.63), indicating moderate to relatively high levels of engagement in home, school, and community activities among the participating children. Adaptive behavior exhibited a mean score of 86.91 (SD = 14.82), while communication competence yielded a mean of 68.53 (SD = 11.47). Parental involvement showed the highest relative average among the predictor variables, with a mean score of 74.66 (SD = 10.25). Examination of skewness and kurtosis coefficients suggested acceptable univariate normality across all variables. The observed variability within each construct indicates sufficient heterogeneity for machine learning modeling and supports the suitability of the data for predictive analyses.

Table 2

Pearson Correlations Among Study Variables

Variable	1	2	3	4
1. Social Participation	—			
2. Adaptive Behavior	.781**	—		
3. Communication Competence	.724**	.693**	—	
4. Parental Involvement	.647**	.582**	.556**	—

The correlation matrix revealed significant positive associations among all study variables. Social participation was strongly correlated with adaptive behavior ($r = .781$, $p < .001$), indicating that children exhibiting stronger adaptive functioning were substantially more likely to engage successfully in social and community activities. Communication competence also demonstrated a strong positive relationship with social participation ($r = .724$, $p < .001$), suggesting that effective communication skills play a crucial role in facilitating participation opportunities. Parental involvement was moderately to strongly associated with social participation ($r = .647$, $p < .001$), highlighting the importance of family engagement in promoting children's inclusion and social engagement. Significant intercorrelations among the predictor variables were observed; however, these relationships remained below thresholds typically associated with problematic multicollinearity. Collectively, these findings provided preliminary evidence supporting the theoretical relevance of adaptive behavior, communication competence, and parental involvement as predictors of social participation.

Table 3

CatBoost Model Performance Metrics

Metric	Training Set	Test Set
R^2	.931	.892
RMSE	3.42	4.97
MAE	2.68	3.89
MAPE (%)	4.31	5.84

The predictive performance of the CatBoost model is presented in Table 3. The model achieved excellent predictive accuracy, explaining 89.2% of the variance in social participation scores within the independent test dataset. The relatively small discrepancy between training and test performance indicated strong generalizability and minimal evidence of overfitting. The test-set RMSE of 4.97 and MAE of 3.89 demonstrated that prediction errors remained relatively small compared with the overall scale of social participation scores. Likewise, the MAPE value of 5.84% suggested highly accurate predictions across the range of observed outcomes. These findings indicate that the CatBoost algorithm successfully captured complex nonlinear relationships among adaptive behavior, communication competence, parental involvement, and social participation. The results support the suitability of explainable machine learning approaches for modeling participation outcomes among children with intellectual disabilities.

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Table 4

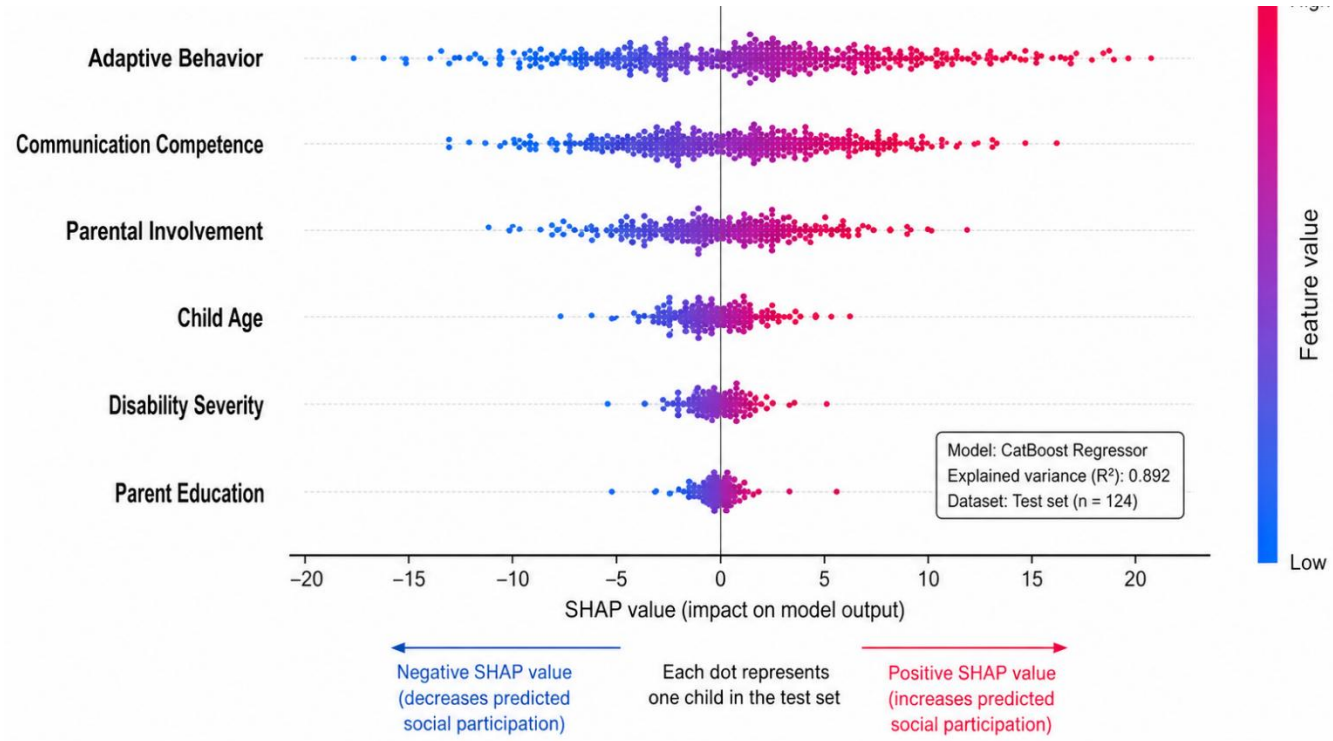
SHAP-Based Global Feature Importance Rankings

Predictor	Mean Absolute SHAP Value	Relative Importance (%)
Adaptive Behavior	6.81	42.7
Communication Competence	5.24	32.8
Parental Involvement	3.14	19.7
Child Age	0.42	2.6
Disability Severity	0.24	1.5
Parent Education	0.11	0.7

The SHAP-based feature importance analysis identified adaptive behavior as the most influential predictor of social participation, accounting for 42.7% of total model importance. Communication competence emerged as the second most important predictor, contributing 32.8% of explanatory power. Parental involvement ranked third, accounting for 19.7% of overall model importance. Together, these three variables explained more than 95% of the predictive influence within the CatBoost model, indicating that they represented the primary determinants of social participation among children with intellectual disabilities. Demographic variables such as age, disability severity, and parental education demonstrated comparatively limited predictive contributions. The dominance of adaptive behavior and communication competence suggests that functional skills and effective interpersonal communication represent central mechanisms through which children become integrated into social environments and community activities. Furthermore, the substantial contribution of parental involvement highlights the continuing importance of family support systems in facilitating opportunities for participation and inclusion.

Figure 1

SHAP Summary Plot Showing the Relative Contributions of Adaptive Behavior, Communication Competence, Parental Involvement, and Demographic Variables to Social Participation Predictions



The SHAP summary analysis provided further insight into the mechanisms underlying the model's predictions. Higher adaptive behavior scores consistently contributed to increases in predicted social participation, with particularly

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strong effects observed among children exhibiting advanced daily living and socialization skills. Similarly, higher communication competence scores were associated with substantial positive shifts in participation predictions, reflecting the importance of expressive, receptive, and pragmatic communication abilities for successful social engagement. Elevated parental involvement scores also increased predicted participation outcomes, although their effects were somewhat less pronounced than those associated with adaptive behavior and communication competence. Examination of SHAP dependence patterns revealed nonlinear relationships among the predictors. Specifically, the positive effects of adaptive behavior became increasingly pronounced at higher levels of communication competence, suggesting a synergistic interaction between these domains. Likewise, children characterized by both strong communication skills and highly involved parents demonstrated the highest predicted social participation scores. These explainable artificial intelligence findings provide a nuanced understanding of the factors contributing to participation outcomes and demonstrate how interpretable machine learning techniques can identify both the magnitude and direction of predictor influences within complex developmental datasets.

4. Discussion

The present study sought to develop and interpret an explainable artificial intelligence model of social participation among children with intellectual disabilities by examining the predictive contributions of adaptive behavior, communication competence, and parental involvement using a SHAP-based CatBoost algorithm. The findings demonstrated that the proposed model achieved a high level of predictive accuracy, explaining approximately 89% of the variance in social participation scores. Furthermore, SHAP analyses revealed that adaptive behavior was the strongest predictor of social participation, followed by communication competence and parental involvement. Together, these variables accounted for the vast majority of predictive influence within the model. These findings contribute to the growing literature emphasizing the multidimensional determinants of participation and demonstrate the utility of explainable machine learning approaches for identifying the most influential factors underlying social engagement among children with developmental disabilities.

One of the most important findings of the present study was the strong predictive role of adaptive behavior. SHAP analyses indicated that adaptive behavior represented the most influential predictor of social participation, accounting for more than 40% of overall model importance. This finding is theoretically consistent with developmental and ecological frameworks that conceptualize participation as a consequence of functional competence in everyday environments. Children who possess stronger adaptive skills are better able to navigate social situations, perform daily responsibilities, communicate needs, and engage independently in activities across home, school, and community settings. Adaptive behavior enhances the practical and social competencies required for successful inclusion and therefore serves as a foundational determinant of participation. The observed findings align with previous research emphasizing the importance of adaptive functioning for successful engagement in social environments among children with developmental disabilities (Greaves-Lord et al., 2022; Marukyan, 2023; Trudel et al., 2022). Similarly, broad overviews of autism and neurodevelopmental disorders have highlighted adaptive functioning as a central outcome associated with social integration and quality of life (Chen, 2023; Hirota & King, 2023). The current findings extend this literature by demonstrating that adaptive behavior not only correlates with participation but also emerges as the most powerful predictor within a sophisticated machine learning framework.

The prominence of adaptive behavior may also be understood through the lens of developmental competence. Social participation requires the integration of multiple abilities, including self-care, problem-solving, interpersonal interaction, emotional regulation, and environmental adaptation. Children who display stronger adaptive functioning are likely to encounter fewer barriers to participation because they possess the skills necessary to respond effectively to social demands. Furthermore, adaptive behavior may facilitate access to opportunities that further reinforce participation through positive developmental feedback loops. This interpretation is consistent with attachment-oriented and developmental perspectives suggesting that functional competence promotes confidence, autonomy, and social engagement (Costa-Cordella et al., 2023; Romeo, 2025). Consequently, interventions designed to strengthen adaptive behavior may yield substantial benefits for participation outcomes among children with intellectual disabilities.

The second major finding concerned the significant predictive contribution of communication competence.

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Communication competence emerged as the second strongest predictor of social participation and accounted for nearly one-third of the model's explanatory power. This result is unsurprising given that participation is fundamentally social in nature and depends heavily on effective communication. Communication skills allow children to express preferences, initiate interactions, build relationships, seek assistance, resolve conflicts, and participate in collaborative activities. Deficits in these areas can restrict access to social experiences and reduce opportunities for meaningful engagement. The present findings are highly consistent with previous studies demonstrating strong associations between communication functioning and social outcomes among children with developmental disorders (Johnson et al., 2023; Lei et al., 2024; Zhai et al., 2023). In particular, Zhai and colleagues reported that social interaction abilities were significantly predicted by sensory and communicative characteristics, while Johnson and colleagues emphasized the critical role of communication in facilitating social understanding and interpersonal relationships. Likewise, research examining social anxiety and social functioning in autistic individuals has highlighted communication challenges as major contributors to social participation difficulties (Lei et al., 2024).

An additional interpretation of the communication findings relates to the role of communication in supporting self-determination and social agency. Children who communicate effectively are more capable of expressing choices and advocating for their needs, which in turn promotes active participation across multiple environments. Communication competence may therefore function not merely as a skill but also as a mechanism through which children influence their surroundings and establish reciprocal social relationships. The SHAP analyses further indicated that communication competence interacted with adaptive behavior, suggesting that the benefits of strong adaptive functioning are amplified when communication skills are also well developed. Such interactions support ecological theories of development, which propose that participation outcomes arise through dynamic relationships among multiple competencies rather than isolated abilities.

The third principal finding was the significant contribution of parental involvement to social participation. Although parental involvement was less influential than adaptive behavior and communication competence, it remained a substantial predictor and accounted for approximately one-fifth of overall model importance. This finding reinforces the growing recognition that family factors play an essential role in shaping developmental outcomes among children with disabilities. Parents often serve as advocates, facilitators, and gatekeepers of participation opportunities. They determine access to recreational activities, coordinate educational and therapeutic services, support social interactions, and help children overcome environmental barriers. Consequently, higher levels of parental involvement may directly increase children's opportunities for participation while simultaneously enhancing their confidence and social competence. These findings align closely with previous studies demonstrating positive relationships between family engagement, emotional adaptation, and social development among children with neurodevelopmental conditions (Alhammashi et al., 2024; Costa-Cordella et al., 2023; Romeo, 2025). The current results therefore provide further evidence that participation outcomes should be understood not only in terms of child characteristics but also within broader family contexts.

The observed importance of parental involvement also supports family systems theories, which emphasize the interdependence between children and their caregiving environments. Families provide emotional security, opportunities for social learning, and practical resources that facilitate engagement with the broader community. Children whose parents actively participate in educational and social activities may experience greater exposure to inclusive environments and more opportunities to develop interpersonal skills. Moreover, parental involvement may buffer the effects of developmental challenges by helping children navigate difficult situations and maintain consistent participation in structured activities. The findings therefore underscore the importance of family-centered approaches in intervention planning and service delivery.

The correlation analyses revealed strong positive relationships among adaptive behavior, communication competence, parental involvement, and social participation. These findings support the theoretical assumption that participation is shaped by interconnected developmental systems rather than isolated factors. Similar patterns have been reported in previous investigations examining social adaptation and developmental outcomes among children with neurodevelopmental disorders (Alhammashi et al., 2024; Costa-Cordella et al., 2023; Romeo, 2025). Importantly, the machine learning results demonstrated that although all three variables contributed independently to prediction, their effects were also interconnected. Such

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findings reinforce ecological models suggesting that child competencies and environmental supports jointly influence participation trajectories.

The SHAP dependence analyses further revealed evidence of nonlinear relationships among the predictors. Specifically, adaptive behavior exerted increasingly stronger effects at higher levels of communication competence, while parental involvement appeared to magnify the positive influence of child-level skills. These findings highlight the complexity of participation processes and illustrate the advantages of machine learning approaches over traditional linear models. Conventional statistical methods often assume uniform effects across populations, whereas explainable artificial intelligence techniques can identify nuanced interactions and threshold effects. The current study therefore contributes methodologically by demonstrating how SHAP-based analyses can uncover meaningful developmental patterns that may remain undetected using traditional analytical approaches.

The strong performance of the CatBoost model represents another noteworthy contribution. The model explained nearly 90% of the variance in social participation, indicating that adaptive behavior, communication competence, and parental involvement collectively capture a substantial proportion of the factors influencing participation among children with intellectual disabilities. This level of predictive accuracy is consistent with growing evidence supporting the utility of machine learning methods within developmental and educational research. Explainable artificial intelligence provides a valuable balance between predictive performance and interpretability, enabling researchers and practitioners to understand not only which factors matter but also how they influence outcomes. Such transparency is particularly important in disability research, where interventions must be individualized and evidence-based.

The present findings may also be interpreted within broader contemporary discussions concerning developmental disabilities and social inclusion. Recent research has increasingly emphasized the importance of sensory processing, emotional regulation, and environmental accessibility for participation outcomes (Filipova et al., 2023; Fotoglou et al., 2023; Nimbley et al., 2022). Studies examining sensory integration interventions and neuroplasticity-based approaches have reported improvements in social functioning and adaptive outcomes among children with developmental disorders (Savarese et al., 2025; Suprunowicz et al., 2025). Likewise, investigations of healthcare adaptation, therapeutic interventions, and community supports have highlighted the importance of reducing environmental barriers and promoting inclusive practices (Abualait et al., 2024; Ferrera-Fernández et al., 2025; Labarca et al., 2025). Although sensory and contextual variables were not primary predictors in the present model, the findings suggest that such factors may influence participation indirectly through their effects on adaptive behavior and communication competence.

The results should also be considered alongside literature examining broader developmental challenges associated with neurodevelopmental disorders. Research addressing social relationships, attachment processes, co-occurring psychological difficulties, feeding behaviors, and emotional functioning consistently demonstrates that developmental outcomes emerge through complex interactions among biological, psychological, and social influences (Bach & Vestergaard, 2023; Cheney et al., 2023; Ferrara et al., 2025; Ferrara et al., 2023; Kozak et al., 2023; Neu & Bradford, 2025). The current findings support this multidimensional perspective by illustrating how child competencies and family engagement jointly contribute to participation outcomes. Consequently, interventions focused exclusively on a single domain may be less effective than comprehensive approaches addressing multiple determinants simultaneously.

5. Conclusion

Overall, the present study demonstrates that social participation among children with intellectual disabilities is strongly influenced by adaptive behavior, communication competence, and parental involvement. The explainable artificial intelligence framework provided detailed insight into the relative importance of these predictors and revealed complex interactions among developmental and environmental factors. These findings contribute both theoretically and methodologically to the literature while offering practical guidance for assessment, intervention, and policy development aimed at enhancing participation and inclusion.

Several limitations should be considered when interpreting the findings. First, the cross-sectional design precludes conclusions regarding causality among the study variables. Although adaptive behavior, communication competence, and parental involvement were identified as significant predictors of social participation, longitudinal research is required to determine the direction and developmental stability of these relationships. Second, data

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were collected primarily through parent-reported measures, which may introduce reporting biases and shared method variance. Third, the sample was recruited from Hungary and therefore cultural, educational, and service-related factors may limit the generalizability of the findings to other countries and contexts. Fourth, although the model demonstrated strong predictive accuracy, other potentially important variables such as peer support, school climate, socioeconomic conditions, emotional regulation, and sensory processing characteristics were not included in the analysis. Finally, despite the interpretability provided by SHAP analyses, machine learning models remain dependent on the quality and scope of available data.

Future studies should employ longitudinal designs to examine how adaptive behavior, communication competence, parental involvement, and social participation influence one another across developmental periods. Researchers may also investigate additional predictors, including peer relationships, teacher support, self-determination, emotional functioning, executive functioning, and environmental accessibility. Comparative studies across different disability groups could provide insight into whether similar predictive patterns emerge among children with autism spectrum disorder, cerebral palsy, learning disabilities, and intellectual disabilities. Future research should also explore intervention-based machine learning models to identify factors that predict treatment responsiveness and participation improvement. Finally, integrating multimodal data sources such as behavioral observations, digital monitoring technologies, educational records, and clinician assessments may further enhance predictive accuracy and ecological validity.

The findings suggest that practitioners should prioritize the development of adaptive behavior skills as a central component of programs designed to enhance social participation among children with intellectual disabilities. Educational and rehabilitation services should incorporate systematic communication training that strengthens expressive, receptive, and pragmatic communication abilities across naturalistic settings. Family-centered approaches should be emphasized, with parents actively involved in intervention planning, implementation, and evaluation. Schools and community organizations should collaborate to create inclusive participation opportunities that allow children to apply adaptive and communication skills in meaningful social contexts. Professionals should also consider utilizing explainable artificial intelligence tools to support individualized assessment and decision-making processes, thereby enabling more targeted and effective intervention strategies aimed at promoting long-term social inclusion and quality of life.

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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