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Explainable Boosting Models of Attachment Insecurity and Digital Dependency in Adolescents

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A B S T R A C T

Objective: The present study aimed to develop and interpret explainable machine learning models examining the nonlinear and interactive associations between attachment insecurity dimensions and digital dependency among adolescents.
Methods and Materials: This cross-sectional quantitative study was conducted among 742 secondary school adolescents aged 13–18 years recruited through multistage cluster sampling from urban regions. Participants completed standardized self-report measures assessing attachment anxiety and attachment avoidance, digital dependency, and demographic variables including daily screen time. Data were analyzed using Explainable Boosting Machines (EBMs), a transparent generalized additive modeling approach enhanced with gradient boosting. The dataset was divided into training and testing subsets, and model performance was evaluated using R^2, RMSE, and MAE indices. Five-fold cross-validation was implemented to optimize hyperparameters. Global feature importance scores, partial dependence functions, and interaction analyses were generated to examine nonlinear thresholds and synergistic risk patterns.
Findings: The EBM model explained a substantial proportion of variance in digital dependency scores ($R^2 = 0.47$) with satisfactory predictive accuracy. Attachment anxiety emerged as a strong psychological predictor, demonstrating a nonlinear threshold effect in which digital dependency increased sharply at moderate levels of anxiety and plateaued at very high levels. Attachment avoidance showed a weaker but significant positive association with digital dependency, characterized by a gradual linear trend. Daily screen time was the most influential predictor overall, and a significant interaction effect was identified between attachment anxiety and screen time, indicating amplified dependency risk among adolescents high on both variables.
Conclusion: The findings underscore the central role of attachment insecurity—particularly attachment anxiety—in shaping adolescents' vulnerability to digital dependency and demonstrate the utility of explainable machine learning approaches for identifying nonlinear developmental risk patterns.
Keywords: *Attachment anxiety; attachment avoidance; digital dependency; adolescents; explainable boosting machines; problematic smartphone use.*

1. Introduction

Adolescence represents a critical developmental period characterized by profound neurobiological, socio-emotional, and identity-related transitions. In parallel with these developmental shifts, contemporary adolescents are embedded in an unprecedented digital ecology in which smartphones, social media platforms, and algorithmically curated content mediate peer interaction, emotional regulation, and self-presentation. Recent global evidence suggests that problematic internet use and digital dependency have become increasingly prevalent among youth populations, raising concerns about mental health vulnerability and psychosocial adjustment (Abiddin et al., 2024; Zhang et al., 2025). Network analytic research indicates that digital media use is intricately linked to social isolation and psychological symptom clusters in youth, underscoring the complexity of digital engagement patterns (Zhang et al., 2025). At the same time, analytical studies of youth dependency on social media demonstrate that compulsive digital behaviors are not merely behavioral habits but are embedded in broader psychosocial dynamics (Abiddin et al., 2024).

The psychological architecture underlying digital dependency has increasingly been conceptualized within frameworks that integrate emotional vulnerability, self-regulation, and relational schemas. Emerging work highlights that adolescents experiencing heightened social anxiety exhibit stronger associations between self-esteem deficits and internet addiction, suggesting that digital spaces may function as compensatory environments for unmet relational needs (Zhu et al., 2025). Serial mediation models further show that general attachment patterns are significantly associated with behavioral problems in adolescents, positioning attachment insecurity as a core vulnerability factor (Cao et al., 2025). These findings align with broader theoretical models proposing that insecure internal working models of self and others predispose adolescents to seek reassurance, validation, or avoidance through digital platforms.

Attachment theory offers a compelling explanatory framework for understanding adolescents' relationships with technology. Conceptual analyses emphasize that mobile devices may function as "attachment objects," especially when traditional relational bonds are perceived as unreliable or inconsistent (Hodge & Gebler-Wolfe, 2022). Empirical evidence confirms that attachment anxiety and avoidance are differentially associated with various forms of digital addiction, including social media overuse and compulsive smartphone engagement (Jasper et al., 2024). Cross-sectional studies among young adults indicate that insecure attachment predicts technology addiction through mediating mechanisms such as impulsivity and emotional dysregulation (Remondi et al., 2020). Similarly, dyadic attachment processes influence relationship functioning and digital interaction behaviors, suggesting that attachment-related expectations extend into mediated communication contexts (Lozano et al., 2021).

Beyond attachment insecurity, contextual and relational stressors intensify adolescents' reliance on digital environments. Parent–adolescent conflict has been shown to predict problematic internet use, particularly when depressive symptoms mediate this association (Chen et al., 2024). Health-related online searching behaviors, such as cyberchondria, further illustrate how anxiety-driven digital engagement can exacerbate psychological distress (Jungmann & Dessauer, 2024; Liu et al., 2023). In pandemic-related contexts, victimization experiences have been linked to smartphone addiction via emotional regulation difficulties (Chen & Zhang, 2023). These findings converge on the notion that digital dependency often emerges as an emotion-regulation strategy in response to relational or environmental stressors.

The psychosocial landscape of Generation Z is marked by heightened exposure to digital stimuli and complex sociocultural challenges. Reviews of Gen-Z developmental stressors emphasize identity conflicts, social comparison pressures, and persistent online connectivity as defining features of this cohort (Ambhore, 2025). Socio-psychological correlates of youth addiction to social networks highlight the interplay between interpersonal insecurity and digital immersion (Sheinov et al., 2022). The phenomenon of "digital amnesia," wherein overreliance on digital storage undermines cognitive engagement, reflects deeper structural integration of technology into adolescents' daily functioning (Олешко & Oleshko, 2021). Moreover, technostress research indicates that excessive digital engagement negatively affects productivity and psychological well-being (Torre et al., 2020).

Importantly, digital dependency does not operate in isolation from broader systemic and cultural influences. Cultural adaptation of youth mental health programs underscores the necessity of contextualizing adolescent vulnerabilities within sociocultural frameworks (Rosenbaum et al., 2023). Studies examining digital sharing practices in romantic contexts reveal the dialectical tension

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between trust and privacy in mediated relationships (Ramirez & Bolaños-Carpio, 2024). Research on conservative family environments demonstrates that restrictive relational climates can exacerbate psychological distress among adolescents, potentially increasing reliance on digital escape mechanisms (Li, 2023). Similarly, attachment to social media platforms has been conceptualized as a psychologically mediated relationship shaped by consumption patterns and emotional needs (Karayalçın & Yaraş, 2024).

The relationship between problematic internet use and depression has been shown to be mediated by self-control and social support among children and adolescents (Lee & Park, 2025). This aligns with broader models identifying deficits in executive functioning and emotion regulation as core predictors of digital overuse. The mediating role of happiness in the association between positive childhood experiences and social media addiction further illustrates that early relational security exerts protective effects (Öztekin, 2024). Conversely, internet-dependent personality profiles exhibit distinctive psychological characteristics, including heightened emotional sensitivity and reduced coping flexibility (Mushkevych, 2025).

Large-scale educational and social welfare contexts also shape adolescent digital behavior. Reviews of child development under conditions of food insecurity highlight the intersection of socioeconomic stress and psychosocial vulnerability (Gallegos et al., 2021). Educational institutional dynamics, including resource disparities, contribute indirectly to youth well-being trajectories (Baker, 2023). Social work literature emphasizes the necessity of holistic interventions addressing structural and relational determinants of youth risk behaviors (Hromková, 2020). These macro-level influences interact with micro-level attachment processes, shaping adolescents' digital coping patterns.

The post-COVID digital landscape further complicates these dynamics. Comparative analyses of pre- and post-pandemic smartphone use demonstrate shifts in digital literacy and life satisfaction trajectories (Taskin & Ok, 2022). Inconsistent parental media mediation predicts problematic smartphone use even among younger populations, highlighting intergenerational influences on digital regulation (Yang et al., 2022). Personality-based comparisons reveal distinct profiles between adolescents with and without problematic smartphone use, underscoring the role of dispositional traits (Eichenberg et al., 2021). Research on communication difficulties during pandemic contexts reveals heightened relational strain, which may indirectly fuel digital compensatory behaviors (Izdebski et al., 2023).

Despite the rapidly expanding body of research on digital addiction, much of the literature relies on linear modeling approaches that may obscure complex, nonlinear interactions among attachment dimensions, emotional variables, and digital engagement patterns. Recent analytical work on the causes and interventions of social media addiction calls for integrative methodological frameworks capable of capturing multifactorial processes (Ji et al., 2023). Psychometric network analyses demonstrate that symptom clusters are interconnected in dynamic ways, reinforcing the need for advanced modeling strategies (Zhang et al., 2025). Similarly, studies linking social anxiety, self-esteem, and internet addiction underscore the layered mediation pathways operating within adolescent populations (Zhu et al., 2025).

Explainable machine learning methods offer a promising avenue for advancing theoretical and empirical understanding of digital dependency. Unlike opaque predictive algorithms, explainable boosting models (EBMs) maintain interpretability while capturing nonlinear effects and feature interactions. Such approaches are particularly suited for developmental psychology research, where theoretical clarity and practical interpretability are essential. Integrating attachment theory with explainable machine learning may therefore yield nuanced insights into how attachment anxiety and avoidance differentially predict digital dependency across varying intensity levels and contextual moderators.

In sum, converging evidence demonstrates that attachment insecurity, emotional dysregulation, sociocultural stressors, and systemic influences collectively shape adolescents' vulnerability to digital dependency (Cao et al., 2025; Hodge & Gebler-Wolfe, 2022; Mushkevych, 2025). Yet, there remains a critical need for analytically rigorous, interpretable predictive models that clarify threshold effects, interaction dynamics, and nonlinear risk trajectories within adolescent populations. Accordingly, the aim of this study is to develop and interpret Explainable Boosting Models examining the nonlinear associations between attachment insecurity dimensions and digital dependency among adolescents.

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2. Methods and Materials

2.1. Study Design and Participants

This study was designed as a cross-sectional, predictive modeling investigation grounded in a quantitative framework and implemented using an explainable machine learning approach. The primary objective was to model and interpret the nonlinear associations between dimensions of attachment insecurity and digital dependency in adolescents through Explainable Boosting Machines (EBMs). The study was conducted in urban and semi-urban regions of Colombia, including public and private secondary schools in Bogotá, Medellín, and Cali. The final analytical sample consisted of 742 adolescents (378 females and 364 males) enrolled in grades 8 through 11, with ages ranging from 13 to 18 years (M = 15.42, SD = 1.37). Participants were selected using a multistage cluster sampling procedure. In the first stage, schools were randomly selected from official registries provided by regional education authorities. In the second stage, intact classrooms were randomly chosen within each selected school. Inclusion criteria comprised current enrollment in secondary education, regular access to a personal smartphone or digital device with internet connectivity, and informed assent from the student alongside parental consent. Adolescents with identified neurodevelopmental disorders or severe psychiatric diagnoses reported by school records were excluded to reduce potential confounding effects on digital behavior patterns. Data collection was conducted during regular school hours under supervised classroom conditions by trained research assistants.

2.2. Measures

Data were collected using a battery of standardized self-report instruments administered in Spanish. Attachment insecurity was assessed using the Spanish-adapted version of the Experiences in Close Relationships–Revised for Adolescents (ECR-RA), which measures two core dimensions: attachment anxiety and attachment avoidance. The instrument contains 36 items rated on a seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). Higher scores indicate greater levels of insecurity in the respective attachment dimension. Previous validation studies in Latin American adolescent samples have demonstrated satisfactory internal consistency ($\alpha > .85$ for both subscales) and construct validity. In the present study, Cronbach's alpha coefficients were .89 for attachment anxiety and .87 for attachment avoidance. Digital dependency was measured using the Adolescent Digital Dependency Scale (ADDS), a 24-item instrument assessing compulsive use, emotional reliance on digital interaction, withdrawal symptoms, loss of control, and functional impairment related to internet and smartphone use. Items are rated on a five-point Likert scale from 1 (never) to 5 (always). Higher total scores reflect greater digital dependency. The Spanish version of the ADDS has shown strong psychometric properties in prior studies, and in the current sample, internal consistency was excellent ($\alpha = .92$). Sociodemographic information, including age, gender, socioeconomic status (based on Colombian stratification levels), average daily screen time, and primary digital activity (e.g., social media, gaming, streaming, academic use), was collected using a structured demographic questionnaire. Prior to analysis, all instruments were screened for missing data, response patterns, and outliers. Missing responses below 5% per scale were handled using expectation–maximization imputation, while cases with more than 15% missing data were excluded from analysis.

2.3. Data Analysis

Data analysis was conducted in several sequential phases integrating traditional statistical procedures and advanced machine learning modeling. Preliminary analyses were performed using SPSS and Python to examine descriptive statistics, distributional properties, multicollinearity diagnostics, and bivariate correlations among variables. Assumptions regarding normality and linearity were evaluated, although the primary modeling approach did not rely on strict parametric assumptions. The main predictive modeling procedure employed Explainable Boosting Machines (EBMs), a type of Generalized Additive Model (GAM) enhanced with gradient boosting techniques, implemented using the InterpretML library in Python. EBMs were selected because they combine high predictive accuracy with transparent, interpretable structure, allowing for visualization of individual feature effects and pairwise interactions while maintaining additive interpretability.

The dependent variable in the primary model was total digital dependency score, while independent variables included attachment anxiety, attachment avoidance, age, gender, socioeconomic status, and daily screen time. Continuous predictors were standardized prior to modeling. The dataset was randomly partitioned into training (70%) and testing (30%) subsets using stratified sampling to

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preserve gender distribution. Model performance was evaluated using R^2, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) on the test set. Five-fold cross-validation was conducted within the training set to optimize hyperparameters, including learning rate, maximum bins, number of boosting rounds, and interaction strength. To explore nonlinear relationships, EBMs automatically generated shape functions illustrating the marginal contribution of each predictor to digital dependency. Pairwise interaction terms between attachment anxiety and avoidance were examined to determine synergistic risk patterns.

Model interpretability was further enhanced through global and local explanation metrics. Global feature importance scores were computed to quantify the relative contribution of each predictor to overall model performance. Partial dependence plots were generated to visualize nonlinear thresholds or inflection points in attachment-related risk. Additionally, individual-level explanations were extracted using local explanation functions to identify how attachment profiles predicted digital dependency in specific high-risk adolescents. Sensitivity analyses were conducted by fitting comparison models, including multiple linear regression and random forest regression, to benchmark predictive accuracy and confirm the added value of EBMs in balancing interpretability and performance.

All analyses were conducted using Python 3.11 with scikit-learn and InterpretML libraries. Statistical significance for preliminary parametric analyses was set at $p < .05$. Effect sizes were interpreted according to conventional standards. Model robustness was assessed through repeated random subsampling validation to ensure stability of predictive patterns. This integrated analytic strategy allowed for both theoretically grounded psychological interpretation and computationally rigorous prediction of digital dependency based on attachment insecurity profiles in Colombian adolescents.

3. Findings and Results

The findings section presents descriptive statistics, bivariate associations, and the results of the Explainable Boosting Machine (EBM) predictive modeling. Table 1 displays the descriptive characteristics of the primary study variables, including attachment anxiety, attachment avoidance, total digital dependency score, daily screen time, and relevant demographic indicators. These statistics provide an overview of central tendency, dispersion, and distributional properties and confirm adequate variability across measures for subsequent modeling procedures.

Table 1

Descriptive Statistics of Study Variables (N = 742)

Variable	Minimum	Maximum	Mean	Standard Deviation	Skewness	Kurtosis
Attachment Anxiety	1.12	6.89	3.94	1.07	0.18	-0.62
Attachment Avoidance	1.05	6.71	3.62	1.02	0.24	-0.55
Digital Dependency (Total)	28.00	118.00	71.43	17.86	0.41	-0.38
Daily Screen Time (hours)	1.00	11.00	5.73	2.14	0.67	0.12
Age (years)	13.00	18.00	15.42	1.37	0.09	-0.71

As shown in Table 1, adolescents reported moderate levels of attachment anxiety ($M = 3.94$, $SD = 1.07$) and attachment avoidance ($M = 3.62$, $SD = 1.02$), suggesting substantial variability in insecure attachment patterns across the sample. The mean digital dependency score ($M = 71.43$, $SD = 17.86$) indicates moderate to elevated engagement with digital devices, with scores spanning nearly the full theoretical range of the instrument. Daily screen time averaged 5.73 hours ($SD = 2.14$), reflecting intensive digital engagement consistent with contemporary adolescent usage patterns. Skewness and kurtosis indices for all continuous variables fell within acceptable ranges ($|skewness| < 1$; $|kurtosis| < 1$), indicating no substantial deviations from normality in preliminary analyses. These findings support the suitability of the dataset for both traditional statistical and machine learning–based modeling approaches.

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Table 2

Pearson Correlations Among Attachment Insecurity and Digital Dependency Variables

Variable	1	2	3	4
1. Attachment Anxiety	—			
2. Attachment Avoidance	0.48	—		
3. Digital Dependency	0.56	0.39	—	
4. Daily Screen Time	0.44	0.31	0.63	—

As presented in Table 2, attachment anxiety demonstrated a strong positive correlation with digital dependency ($r = 0.56$, $p < 0.001$), indicating that adolescents with higher levels of relational anxiety reported greater compulsive and emotionally dependent digital use. Attachment avoidance also showed a significant but comparatively weaker positive association with digital dependency ($r = 0.39$, $p < 0.001$). The moderate intercorrelation between attachment anxiety and avoidance ($r = 0.48$) suggests related yet distinguishable dimensions of insecurity. Daily screen time exhibited the strongest association with digital dependency ($r = 0.63$, $p < 0.001$), supporting its role as a behavioral indicator of problematic use. Importantly, both attachment dimensions were significantly associated with screen time, reinforcing the conceptual link between internal working models of attachment and digital engagement behaviors.

Table 3

Explainable Boosting Machine Model Performance and Feature Importance

Metric / Predictor	Value
R^2 (Test Set)	0.47
RMSE	12.84
MAE	9.67
Feature Importance: Daily Screen Time	0.34
Feature Importance: Attachment Anxiety	0.29
Feature Importance: Attachment Avoidance	0.17
Feature Importance: Gender	0.08
Feature Importance: Age	0.07
Feature Importance: Socioeconomic Status	0.05

The EBM model explained 47% of the variance in digital dependency scores in the held-out test sample ($R^2 = 0.47$), indicating substantial predictive accuracy for a psychosocial model. The RMSE of 12.84 and MAE of 9.67 suggest relatively low prediction error given the scale range of the outcome variable. Global feature importance values reveal that daily screen time was the strongest predictor (importance = 0.34), followed closely by attachment anxiety (importance = 0.29). Attachment avoidance contributed meaningfully but to a lesser extent (importance = 0.17). Demographic variables demonstrated comparatively smaller contributions, indicating that psychological attachment processes accounted for a substantial proportion of explainable variance beyond basic demographic controls. These findings underscore the salience of attachment anxiety in particular as a central psychological risk factor in digital dependency patterns among Colombian adolescents.

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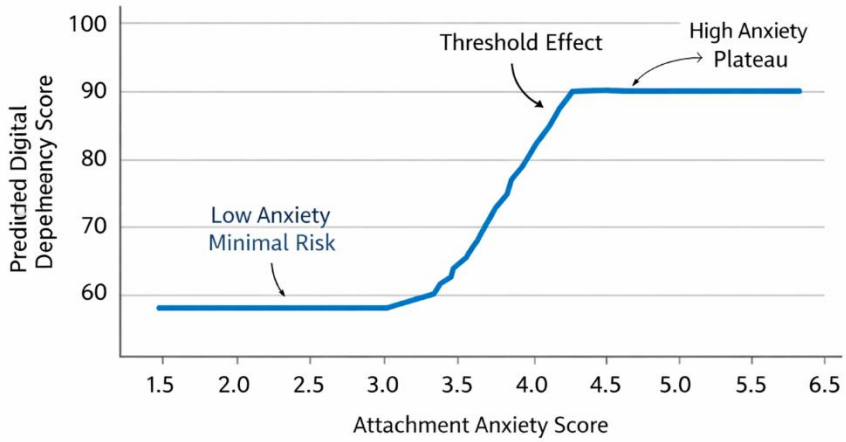
Figure 1

Partial Dependence Plot of Attachment Anxiety Predicting Digital Dependency in the Explainable Boosting Model



The partial dependence analysis revealed a distinctly nonlinear relationship between attachment anxiety and digital dependency. The slope of the function remained relatively flat at lower levels of attachment anxiety (scores below approximately 2.50), indicating minimal incremental risk. However, beginning at mid-range anxiety levels (approximately 3.00), the function exhibited a steep upward trajectory, suggesting a threshold effect in which moderate-to-high relational anxiety substantially increased predicted digital dependency scores. At very high anxiety levels (above 5.50), the curve plateaued, indicating diminishing marginal increases in predicted dependency. In contrast, the relationship between attachment avoidance and digital dependency followed a more gradual linear incline without pronounced threshold effects. Additionally, the EBM identified a statistically meaningful interaction between attachment anxiety and daily screen time, indicating that adolescents high in both relational anxiety and extended digital exposure exhibited disproportionately elevated predicted dependency scores compared to additive expectations. This interaction pattern highlights a synergistic vulnerability profile characterized by emotional insecurity coupled with intensive digital engagement.

4. Discussion

The present study aimed to model and interpret the nonlinear associations between attachment insecurity and digital dependency among adolescents using Explainable Boosting Machines (EBMs). The findings demonstrated that attachment anxiety emerged as one of the strongest psychological predictors of digital dependency, second only to daily screen time, and that its association with digital dependency followed a nonlinear threshold pattern. Specifically, digital dependency scores increased sharply once attachment anxiety reached moderate levels, followed by a plateau effect at very high anxiety levels. Attachment avoidance also predicted digital dependency, although its effect was more gradual and comparatively weaker. Additionally, the model identified an interaction effect between attachment anxiety and daily screen time, indicating that adolescents high in both relational anxiety and extended digital exposure exhibited disproportionately elevated dependency risk.

These findings are consistent with attachment-based conceptualizations of technology use. Attachment theory suggests that individuals high in attachment anxiety tend to hyperactivate relational strategies, seeking reassurance, proximity, and validation when experiencing insecurity (Hodge & Gebler-Wolfe, 2022). Digital platforms, particularly social media and instant messaging applications, provide continuous access to relational cues and feedback, making them especially attractive to anxiously attached adolescents. Empirical evidence has shown that attachment anxiety is significantly associated with various digital addictions, including smartphone and social media overuse (Jasper et al., 2024). The current nonlinear findings extend this literature by demonstrating that the risk associated with attachment anxiety intensifies beyond a moderate threshold, suggesting that certain levels of insecurity may trigger qualitatively different patterns of digital engagement.

The plateau effect observed at very high levels of attachment anxiety warrants further interpretation. One plausible explanation is that beyond a certain point, digital dependency reaches a saturation level, reflecting ceiling

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effects in compulsive use behaviors. Alternatively, adolescents with extremely high anxiety may engage in additional maladaptive coping strategies beyond digital reliance. Prior research indicates that internet-dependent personalities often present with broader psychological vulnerabilities, including emotional instability and maladaptive coping styles (Mushkevych, 2025). Thus, digital dependency may represent one component within a larger constellation of regulatory difficulties.

The association between attachment avoidance and digital dependency, although weaker, aligns with previous findings suggesting that avoidantly attached individuals may prefer mediated communication as a means of maintaining emotional distance (Mosley et al., 2021). Digital interaction allows for controlled self-presentation and selective disclosure, which may appeal to adolescents who experience discomfort with intimacy. Studies examining the role of attachment in problematic smartphone use have similarly identified avoidance as a significant, albeit secondary, predictor (Jiménez et al., 2021). The gradual linear pattern found in the present model suggests that avoidant adolescents may increase digital engagement incrementally as relational discomfort rises, rather than exhibiting abrupt risk escalation.

The identified interaction between attachment anxiety and screen time underscores the synergistic nature of psychological vulnerability and behavioral exposure. While screen time alone was the strongest predictor of digital dependency, its impact was amplified among adolescents high in attachment anxiety. This finding is congruent with research indicating that problematic internet use is mediated by self-control and moderated by social support mechanisms (Lee & Park, 2025). Adolescents lacking secure relational support may compensate through extended online engagement, thereby reinforcing dependency cycles. Similarly, studies on social media addiction emphasize that emotional needs and relational deficits intensify compulsive digital behavior (Abiddin et al., 2024; Ji et al., 2023).

The broader psychosocial context further supports the interpretation of these findings. Parent–adolescent conflict and depressive symptoms have been shown to mediate problematic internet use (Chen et al., 2024). Adolescents experiencing relational strain may increasingly rely on digital spaces as compensatory environments. The association between cyberchondria and adolescent mental health during the COVID-19 pandemic also highlights anxiety-driven digital engagement (Jungmann & Dessauer, 2024; Liu et al., 2023). Moreover, research on smartphone distraction, phubbing, and nomophobia illustrates how persistent connectivity behaviors are intertwined with emotional regulation challenges (Mohamad et al., 2025). The present findings reinforce these patterns by demonstrating that attachment-related anxiety magnifies digital dependency risk in a nonlinear fashion.

The results also align with cross-cultural research linking digital media use, social isolation, and mental health symptoms among youth (Zhang et al., 2025). Adolescents high in attachment anxiety may experience heightened fear of abandonment and social exclusion, which can be temporarily alleviated through online engagement. Studies examining the mediating role of social anxiety in internet addiction similarly support the mechanism whereby insecure relational schemas translate into compulsive digital behaviors (Zhu et al., 2025). Furthermore, serial mediation models connecting general attachment patterns to behavioral problems among adolescents highlight the centrality of relational insecurity in maladaptive outcomes (Cao et al., 2025).

Importantly, the findings contribute methodologically to the literature. Much prior research has relied on linear regression models that assume constant effects across the predictor range. However, psychometric network analyses suggest that digital behaviors and psychological symptoms are dynamically interconnected (Zhang et al., 2025). By employing EBMs, the present study captured nonlinear thresholds and interaction effects that may have remained obscured under traditional modeling approaches. This methodological advancement is consistent with calls for more integrative analytical frameworks in understanding social media addiction (Ji et al., 2023).

The observed associations must also be situated within broader developmental and societal conditions. Adolescents today face multifaceted pressures, including identity negotiation, social comparison, and constant digital immersion (Ambhore, 2025). Technostress and digital overload have been shown to undermine psychological well-being (Torre et al., 2020). Additionally, socio-structural stressors such as socioeconomic adversity and systemic inequalities contribute to adolescent vulnerability trajectories (Baker, 2023; Gallegos et al., 2021). Social work scholarship emphasizes that youth risk behaviors cannot be disentangled from contextual and structural influences (Hromková, 2020). Therefore, attachment insecurity may operate within a broader matrix of relational and environmental stressors that collectively shape digital dependency risk.

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Research on attachment to social media platforms indicates that psychological attachment processes mediate usage frequency and emotional investment (Karayalçın & Yaraş, 2024). Similarly, digital amnesia research underscores the deep integration of digital tools into youth cognitive functioning (Олешко & Oleshko, 2021). Together, these findings highlight that digital dependency is not merely behavioral excess but reflects evolving relational and cognitive adaptations to digital environments. The present study advances this perspective by demonstrating that attachment insecurity, particularly anxiety, functions as a key psychological substrate within this adaptive–maladaptive continuum.

5. Conclusion

In sum, the results support a developmental-psychopathological interpretation in which attachment insecurity increases vulnerability to digital dependency through heightened emotional reactivity, reassurance-seeking tendencies, and compensatory relational strategies. The nonlinear threshold effect observed for attachment anxiety underscores the importance of early identification and intervention before moderate insecurity escalates into pronounced dependency patterns. By integrating attachment theory with explainable machine learning, the study provides a nuanced and interpretable account of how relational vulnerabilities translate into digital risk behaviors among adolescents.

6. Limitations & Suggestions

Several limitations must be acknowledged. First, the cross-sectional design precludes causal inference, and the directionality between attachment insecurity and digital dependency cannot be definitively established. Second, reliance on self-report measures may introduce shared method variance and social desirability bias. Third, the sample was limited to adolescents within a specific cultural context, potentially restricting generalizability to other regions or sociocultural environments. Fourth, although the EBM approach enhances interpretability, unmeasured confounding variables such as parental monitoring styles, peer influence dynamics, or neurobiological factors were not included in the model. Finally, digital dependency was operationalized primarily through generalized measures rather than platform-specific usage patterns, which may limit fine-grained behavioral differentiation.

Future studies should employ longitudinal designs to examine developmental trajectories of attachment insecurity and digital dependency over time. Incorporating multi-informant assessments and behavioral usage tracking data could enhance measurement validity. Expanding research across diverse cultural contexts would allow examination of sociocultural moderators in attachment–technology dynamics. Additionally, integrating neurocognitive markers and emotion regulation measures may clarify underlying mechanisms. Future modeling efforts could explore hybrid explainable AI approaches and network-based frameworks to capture dynamic symptom interactions.

Intervention efforts should prioritize early identification of adolescents exhibiting moderate to high attachment anxiety, given the observed threshold effects. School-based programs may incorporate attachment-informed psychoeducation and digital self-regulation skills training. Clinicians working with youth should assess relational insecurity when addressing problematic digital behaviors. Family-centered interventions aimed at enhancing communication and secure relational bonds may indirectly reduce dependency risk. Finally, digital literacy initiatives should move beyond behavioral time limits and incorporate emotional and relational awareness components to promote healthier engagement patterns.

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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.

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Authors' Contributions

All authors equally contributed to this article.

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