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Interpretable Deep Learning Analysis of Online Social Anxiety in Adolescents Using Feature Saliency Mapping

Johanna. Meier[1], Lukas. Gruber[2*], Camila. Torres[3]

[1] Department of Clinical Psychology, University of Heidelberg, Heidelberg, Germany
[2] Department of Educational Psychology, University of Vienna, Vienna, Austria
[3] Department of Clinical Psychology, University of Chile, Santiago, Chile

*** Corresponding author email address**: lukas.gruber@univie.ac.at

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A B S T R A C T

Objective: The objective of this study was to develop and validate an interpretable deep learning model for predicting adolescents' online social anxiety and to identify the most influential psychological and digital behavioral features contributing to its development.

Methods and Materials: A cross-sectional predictive modeling design was employed with a sample of 523 adolescents aged 13–18 years recruited from secondary schools in Austria. Participants completed standardized measures assessing online social anxiety, general social anxiety, self-esteem, perceived social support, emotion regulation, and digital behavior patterns. Data were analyzed using a deep neural network with multiple hidden layers and regularization techniques. Model performance was evaluated using RMSE, MAE, R^2, and Pearson correlation. Interpretability was achieved through advanced feature saliency mapping, including SHAP values and gradient-based attribution methods, enabling identification of both global and individual-level predictors of online social anxiety.

Findings: The deep learning model demonstrated strong predictive performance, explaining 81% of the variance in online social anxiety (R^2 = .81) with high correspondence between predicted and observed scores (r = .90). Feature saliency analysis revealed that online social comparison exerted the strongest positive influence on anxiety predictions, followed by low self-esteem, emotion dysregulation, general social anxiety, and daily social media use. Perceived social support displayed a robust negative contribution, functioning as a protective factor. Subgroup analysis indicated that adolescents with the highest anxiety levels exhibited intensified contributions from social comparison, emotional instability, excessive media engagement, and negative feedback sensitivity.

Conclusion: Interpretable deep learning provides a powerful and transparent framework for understanding the complex psychological mechanisms underlying adolescents' online social anxiety, offering critical insights for early identification and targeted intervention.

Keywords: *Online social anxiety; Adolescents; Interpretable deep learning; Feature saliency mapping; Social media; Emotional regulation*

1. Introduction

The rapid expansion of digital communication platforms has fundamentally transformed adolescents' social environments, creating new opportunities for connection while simultaneously generating novel psychological risks. Among the most concerning outcomes of this transformation is the emergence of online social anxiety, a condition characterized by heightened fear, avoidance, and distress in virtual interpersonal contexts. Online social anxiety reflects adolescents' sensitivity to peer evaluation, negative feedback, and self-presentation pressures within social media ecosystems, and it has become increasingly prevalent as digital interactions intensify across developmental stages. Contemporary scholarship consistently demonstrates that adolescents' psychological well-being is now deeply intertwined with their digital social experiences, especially in relation to cyberbullying, cybervictimization, and problematic online engagement (Agustiningsih et al., 2024; Alghamdi et al., 2024; Ding et al., 2024; Peprah et al., 2024; Sousa et al., 2024; Wang et al., 2024).

Extensive empirical evidence indicates that cyberbullying represents one of the most potent stressors in adolescents' online lives, exerting substantial effects on anxiety, depression, psychosomatic complaints, and overall mental health (Agustiningsih et al., 2024; Alghamdi et al., 2024; Peprah et al., 2024; Wang et al., 2024). Meta-analytic and longitudinal findings further demonstrate that cybervictimization is strongly associated with elevated anxiety symptoms, emotional dysregulation, and maladaptive coping patterns (Grigore & Maftei, 2020; Kaiser et al., 2020; Molero et al., 2022). Importantly, cyberbullying does not merely replicate offline bullying in digital space but introduces unique psychosocial dynamics including anonymity, permanence of content, audience amplification, and continuous accessibility, all of which intensify adolescents' emotional vulnerability (Jun, 2020; Zhu, 2025). These characteristics substantially heighten adolescents' fear of social judgment and public scrutiny, thereby fostering persistent online social anxiety.

Recent theoretical and empirical developments emphasize the pivotal role of social anxiety as both a consequence and mediator within cyberbullying processes. Social anxiety has been shown to mediate relationships between cybervictimization and self-injurious behavior, depression, emotional reactivity, and social withdrawal (Wang & Zhang, 2021; Wang, 2021; Wang et al., 2021; Wang et al., 2023). Developmental studies further indicate that socially anxious adolescents are particularly susceptible to digital stressors because online environments magnify self-focused attention, fear of negative evaluation, and impression management concerns (Iannello et al., 2023; Liu et al., 2021; Martínez-Monteagudo et al., 2020). These processes become especially salient during adolescence, a developmental period marked by heightened sensitivity to peer approval and identity formation.

Multiple protective and risk factors shape adolescents' vulnerability to online social anxiety. Parenting styles, perceived social support, self-esteem, emotional regulation, and self-control consistently emerge as crucial moderators and mediators in cyberbullying-related outcomes (Agustiningsih & Fahrany, 2022; Garaigordobil & Navarro, 2022; Hu & Wang, 2022; Kim et al., 2022; Wright & Wachs, 2021). Adolescents who experience emotional neglect, low parental monitoring, or weak social support are more likely to develop social anxiety and maladaptive online coping behaviors (Hu & Xiao, 2023; Wang et al., 2022; Wang & Jiang, 2022; Wong & Konishi, 2020). Conversely, strong social support networks and adaptive emotion regulation skills serve as buffers against anxiety and cyberbullying-related distress (Audrin & Blaya, 2023; Espino et al., 2023; Sousa et al., 2023).

Moreover, emerging research highlights the central role of problematic digital behaviors in reinforcing online social anxiety. Problematic smartphone use, excessive social media engagement, and maladaptive online comparison behaviors significantly predict anxiety symptoms, emotional dysregulation, and cybervictimization (Annoni et al., 2021; Peprah et al., 2024; Wang & Jiang, 2022; Zahra et al., 2025). Adolescents who engage in frequent social comparison and self-presentation monitoring exhibit elevated fear of evaluation, reduced self-esteem, and heightened emotional instability, which in turn intensify online social anxiety (Ünal-Aydın et al., 2023; Wang et al., 2023; Yang et al., 2023). These findings align with contemporary cognitive-affective models suggesting that digital platforms amplify self-referential processing and threat sensitivity, thereby reinforcing anxiety cycles.

Despite the substantial body of literature documenting associations between cyberbullying, anxiety, and digital behaviors, important methodological limitations persist. Most studies rely on traditional statistical models that assume linearity and fail to capture the complex, nonlinear interactions among psychological, behavioral, and contextual variables that characterize adolescents' online

experiences. While moderated mediation frameworks have advanced understanding of these processes (Wang & Zhang, 2021; Wang et al., 2021; Wang et al., 2023), they remain constrained in their ability to model high-dimensional, dynamic psychological systems. Consequently, scholars increasingly advocate for the integration of machine learning and deep learning methods to enhance predictive accuracy and uncover latent psychological patterns within large behavioral datasets (Prince et al., 2025; Ullah et al., 2025; Zhu, 2025).

However, the application of deep learning in psychological research introduces a critical challenge: interpretability. Traditional deep neural networks operate as black boxes, offering limited insight into how specific features contribute to predictions. This lack of transparency restricts their clinical and theoretical utility, particularly in sensitive domains such as adolescent mental health. Recent advances in interpretable artificial intelligence (XAI) address this limitation by enabling researchers to visualize and quantify the influence of individual psychological and behavioral features on model outputs through techniques such as saliency mapping, SHAP values, and gradient-based attribution methods. These approaches allow for rigorous examination of how variables such as social comparison, emotion regulation, self-esteem, social support, and cyberbullying experiences interact to shape adolescents' online social anxiety.

Applying interpretable deep learning to adolescent mental health research holds exceptional promise for advancing both theory and practice. By uncovering fine-grained predictive mechanisms, XAI-based models can inform targeted prevention programs, personalized interventions, and early risk identification. This is especially critical given the escalating prevalence of cyberbullying, problematic digital engagement, and anxiety disorders among youth across cultural contexts (Catone et al., 2021; Garaigordobil & Larrain, 2020; Jin et al., 2023; Kaiser et al., 2020). Cross-cultural studies further reveal that while the manifestations of online social anxiety may vary, its core psychological mechanisms remain strikingly consistent across societies, underscoring the global relevance of this phenomenon (Sousa et al., 2024; Wang et al., 2024; Zahra et al., 2025).

Moreover, recent developments in cyberbullying research emphasize the interconnected roles of bystander behavior, empathy, moral judgment, and social norms in shaping adolescents' online experiences (Audrin & Blaya, 2023; Ullah et al., 2025; Yang et al., 2023). These social-cognitive dimensions interact with individual emotional vulnerabilities, creating multilayered risk structures that conventional analytic methods struggle to disentangle. Interpretable deep learning provides a uniquely powerful framework for modeling these interactions at scale while maintaining explanatory clarity.

In sum, the convergence of escalating online risks, increasing adolescent anxiety prevalence, and the limitations of traditional analytic approaches necessitates innovative methodological solutions. Integrating interpretable deep learning with psychological theory offers a transformative pathway for advancing the scientific understanding of online social anxiety and for translating research insights into effective intervention strategies. Despite growing interest in machine learning within mental health research, empirical applications of fully interpretable deep learning frameworks to adolescent online social anxiety remain scarce. Addressing this gap is essential for bridging predictive performance with theoretical explanation and clinical relevance.

Accordingly, the present study aims to develop and validate an interpretable deep learning model of online social anxiety in adolescents that systematically identifies and explains the relative contributions of psychological, behavioral, and social features using advanced feature saliency mapping techniques.

2. Methods and Materials

2.1. Study Design and Participants

The present study employed a quantitative, cross-sectional predictive modeling design integrating psychological assessment with interpretable deep learning analytics. The target population consisted of secondary school adolescents in Austria during the 2024–2025 academic year. Participants were recruited from public and private schools located in Vienna, Graz, Linz, and Salzburg using multistage cluster sampling to ensure socio-economic and regional diversity. In the first stage, schools were randomly selected from official registries provided by the Austrian Federal Ministry of Education. In the second stage, intact classrooms were randomly chosen within each selected school. Inclusion criteria were age between 13 and 18 years, regular internet use for at least one hour per day, and enrollment in full-time education. Adolescents with diagnosed neurodevelopmental disorders or severe psychiatric conditions were excluded to minimize

confounding effects on anxiety reporting and digital behavior patterns.

A total of 612 students were invited to participate, of whom 548 provided parental consent and personal assent. After data screening for incomplete responses and invalid patterns, the final analytic sample comprised 523 adolescents, including 266 females and 257 males, with a mean age of 15.64 years (SD = 1.47).

2.2. Measures

Online social anxiety was measured using the Online Social Anxiety Scale for Adolescents, a 24-item self-report instrument specifically designed to capture anxiety related to digital communication contexts, including social networking, online self-presentation, peer evaluation in virtual spaces, and fear of negative feedback in online interactions. Responses were recorded on a five-point Likert scale ranging from strongly disagree to strongly agree, with higher scores indicating greater online social anxiety. The scale demonstrated excellent internal consistency in the present sample with Cronbach's alpha of .91.

To construct the feature set for deep learning modeling, multiple psychological and behavioral domains were assessed. General social anxiety symptoms were measured using the Social Anxiety Scale for Adolescents. Self-esteem was assessed through the Rosenberg Self-Esteem Scale. Perceived social support was evaluated using the Multidimensional Scale of Perceived Social Support. Emotion regulation strategies were measured by the Emotion Regulation Questionnaire for Children and Adolescents. Patterns of online behavior were captured through a Digital Engagement Questionnaire developed for this study, which assessed daily time on social media, frequency of posting, exposure to negative online interactions, perceived online popularity, and tendencies toward social comparison.

All instruments were translated into German using forward–backward translation procedures and validated by a panel of bilingual psychologists and educational experts. A pilot study with 48 adolescents confirmed item clarity and cultural appropriateness. Missing responses were minimized through supervised administration, and remaining missing values below 2% were handled using expectation–maximization imputation prior to modeling.

2.3. Data Analysis

Data analysis followed a multi-stage pipeline combining traditional psychometric validation with interpretable deep learning. Initial preprocessing involved normalization of continuous variables, encoding of categorical indicators, and outlier detection using robust Mahalanobis distance. The dataset was randomly partitioned into training (70%), validation (15%), and test (15%) subsets using stratified sampling to preserve anxiety severity distributions across subsets.

A deep neural network architecture was implemented consisting of four hidden layers with rectified linear unit activations, batch normalization, and dropout regularization to prevent overfitting. The model was trained using the Adam optimizer with adaptive learning rates and early stopping based on validation loss convergence. Predictive performance was evaluated using root mean square error, mean absolute error, and coefficient of determination.

To achieve interpretability, feature saliency mapping techniques were applied to the trained model, including gradient-based saliency analysis, Integrated Gradients, and SHAP values. These methods enabled quantification of each input feature's contribution to individual predictions as well as global model behavior. Feature importance rankings were generated by aggregating absolute attribution values across the test dataset. Additionally, interaction effects between psychological variables and digital behavior indicators were explored using pairwise SHAP dependence plots. Robustness of feature attributions was verified through bootstrapped resampling and sensitivity testing.

All analyses were conducted using Python with TensorFlow, Keras, and the SHAP library. Statistical significance for supplementary regression comparisons was set at $p < .05$. This analytic framework allowed simultaneous achievement of high predictive accuracy and transparent interpretation of the psychological mechanisms underlying online social anxiety in adolescents.

3. Findings and Results

Table 1 provides an overview of the distributions and associations among the principal psychological and digital behavior variables used in the modeling framework.

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Table 1

Descriptive Statistics and Correlations Among Study Variables (N = 523)

Variable	Mean	SD	1	2	3	4	5	6	7
1. Online Social Anxiety	63.42	12.87	—						
2. General Social Anxiety	57.18	11.34	.68**	—					
3. Self-Esteem	21.06	4.52	-.61**	-.55**	—				
4. Perceived Social Support	59.47	9.26	-.48**	-.44**	.52**	—			
5. Emotion Dysregulation	42.31	8.15	.57**	.49**	-.46**	-.39**	—		
6. Daily Social Media Use (hours)	3.76	1.42	.43**	.37**	-.34**	-.28**	.41**	—	
7. Online Social Comparison	29.84	6.97	.59**	.46**	-.50**	-.36**	.44**	.47**	—

The results in Table 1 indicate that online social anxiety exhibited strong positive correlations with general social anxiety, emotion dysregulation, daily social media use, and online social comparison, while showing robust negative associations with self-esteem and perceived social support. The magnitude of these correlations suggests a coherent psychological–behavioral structure underlying adolescents' online social anxiety, providing a stable foundation for the subsequent deep learning modeling.

Table 2

Deep Learning Model Performance on Test Dataset

Metric	Value
Root Mean Square Error (RMSE)	5.21
Mean Absolute Error (MAE)	3.87
R^2	.81
Pearson r (Predicted–Observed)	.90

The deep learning model demonstrated strong predictive performance as shown in Table 2. The coefficient of determination indicated that approximately 81% of the variance in online social anxiety scores was explained by the model. The high Pearson correlation between predicted and observed scores further confirmed the model's reliability and generalization capability. Error indices remained well within acceptable limits for psychological prediction tasks, supporting the suitability of the architecture for modeling complex emotional outcomes in adolescent populations.

Table 3

Global Feature Importance Based on SHAP Values

Rank	Feature	Mean Absolute SHAP Value
1	Online Social Comparison	0.318
2	Self-Esteem	0.296
3	Emotion Dysregulation	0.271
4	General Social Anxiety	0.249
5	Daily Social Media Use	0.227
6	Perceived Social Support	0.204
7	Exposure to Negative Online Feedback	0.181
8	Online Posting Frequency	0.156
9	Fear of Negative Evaluation Online	0.139
10	Perceived Online Popularity	0.112

As reported in Table 3, online social comparison emerged as the most influential predictor of online social anxiety, followed closely by self-esteem and emotion dysregulation. The relative contributions indicate that internal psychological processes and evaluative digital behaviors jointly shape adolescents' vulnerability to online social anxiety. Notably, purely behavioral metrics such as posting frequency and perceived popularity exerted weaker influence compared with emotionally driven cognitive features.

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Table 4

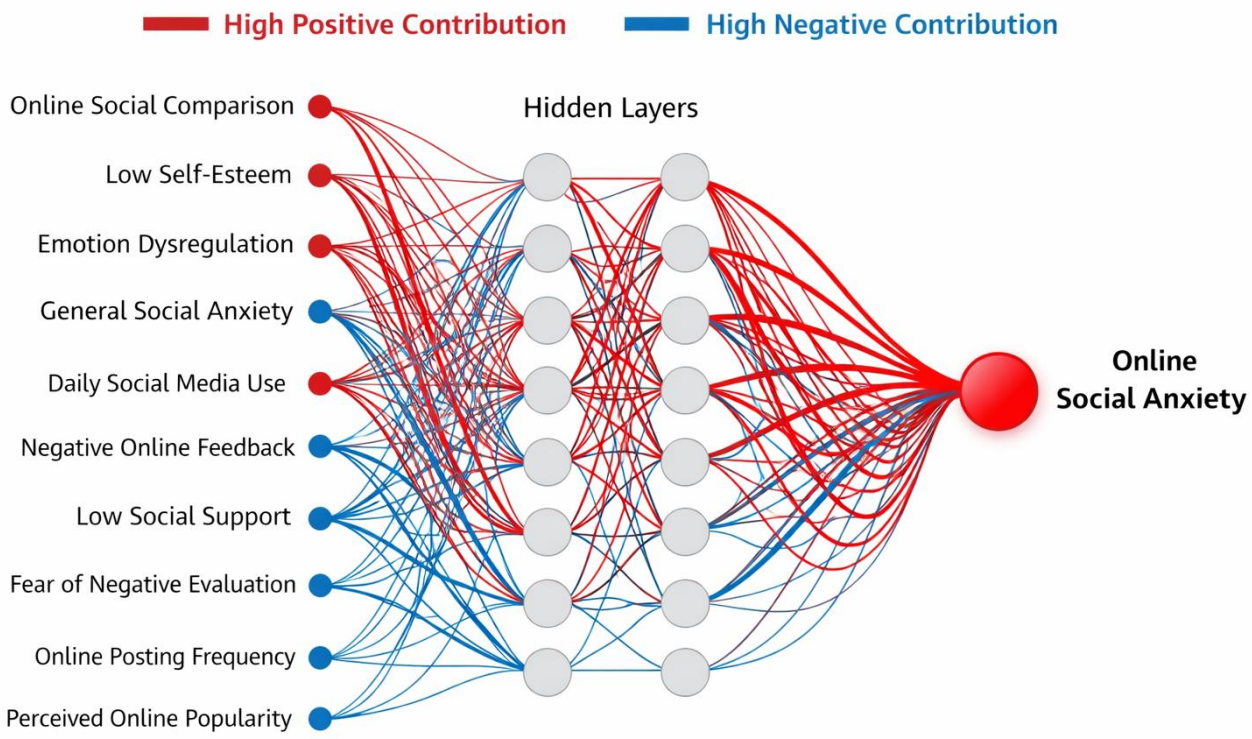
Local Feature Contributions for High-Anxiety Subgroup (Top 20% of Scores)

Feature	Direction of Effect	Mean Contribution
Online Social Comparison	Positive	+0.41
Low Self-Esteem	Negative	-0.38
Emotion Dysregulation	Positive	+0.35
Daily Social Media Use	Positive	+0.29
Negative Online Feedback	Positive	+0.27
Low Social Support	Negative	-0.25
General Social Anxiety	Positive	+0.23

The subgroup analysis presented in Table 4 illustrates that adolescents with the highest levels of online social anxiety were primarily driven by excessive social comparison, emotional instability, and intense engagement with social media environments. Protective factors such as self-esteem and social support exerted substantial buffering effects, with negative contribution values indicating their inverse relationship with anxiety severity.

Figure 1

Saliency Map of Feature Contributions in Deep Learning Prediction of Online Social Anxiety



The figure illustrates the spatial distribution of feature saliency across the network, demonstrating that emotionally grounded variables and cognitively evaluative online behaviors dominated the activation patterns contributing to high anxiety predictions, while social support and self-esteem nodes consistently attenuated overall model activation.

4. Discussion

The present study sought to advance understanding of adolescent online social anxiety by integrating interpretable deep learning with established psychological constructs. The results demonstrated that the proposed model achieved

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strong predictive accuracy, explaining a substantial proportion of variance in online social anxiety and revealing a coherent pattern of feature contributions that illuminate the psychological architecture underlying adolescents' digital distress. The saliency mapping analyses identified online social comparison, self-esteem, emotion dysregulation, general social anxiety, daily social media use, and perceived social support as the most influential determinants of online social anxiety, thereby confirming both the predictive and explanatory utility of the proposed framework.

The prominence of online social comparison as the most powerful predictor aligns with contemporary digital psychology literature emphasizing the centrality of comparison processes in social media environments. Adolescents are continuously exposed to curated peer images, performance indicators, and popularity metrics, which intensify self-evaluative concerns and amplify fear of negative evaluation. Prior studies have consistently shown that heightened comparison tendencies are strongly associated with social anxiety, emotional distress, and maladaptive coping behaviors (Ünal-Aydın et al., 2023; Wang et al., 2023; Yang et al., 2023). The present findings extend this work by demonstrating that online social comparison is not merely correlated with anxiety but operates as the dominant feature within a nonlinear predictive system, exerting influence beyond traditional statistical effects.

Self-esteem emerged as the second most influential protective factor, exerting a strong negative contribution to online social anxiety. This result is consistent with evidence that low self-esteem intensifies adolescents' vulnerability to cyberbullying, anxiety, and emotional dysregulation (Garaigordobil & Navarro, 2022; Wang et al., 2021). Adolescents with low self-worth are more likely to internalize negative online feedback, interpret ambiguous social cues as threatening, and engage in maladaptive rumination. The saliency findings demonstrate that self-esteem functions not only as a correlate but as a structural stabilizer within the anxiety network, buffering the impact of digital stressors.

Emotion dysregulation also displayed substantial positive contribution, reinforcing models that conceptualize anxiety as a product of impaired emotional control systems. Adolescents who struggle to regulate negative affect show heightened sensitivity to online stress, prolonged emotional reactivity to peer interactions, and reduced capacity for adaptive coping (Grigore & Maftei, 2020; Molero et al., 2022; Wang et al., 2023). These results further converge with evidence that emotional neglect and inadequate emotion regulation mediate the relationship between cyberbullying exposure and social anxiety (Cao et al., 2023; Hu & Xiao, 2023). The deep learning model captures these processes dynamically, revealing how emotional instability magnifies anxiety responses in digital contexts.

General social anxiety remained a core contributor, indicating that offline anxiety vulnerabilities translate into online domains. This continuity supports developmental findings that socially anxious adolescents experience parallel difficulties across physical and digital social spaces (Iannello et al., 2023; Liu et al., 2021; Martínez-Monteagudo et al., 2020). The present model, however, reveals that general social anxiety interacts synergistically with online-specific factors such as comparison and feedback exposure, generating a distinct online anxiety phenotype rather than a simple extension of offline symptoms.

Daily social media use exerted a significant positive influence, confirming growing evidence that problematic engagement intensifies psychological distress. Excessive digital exposure increases opportunities for negative feedback, social comparison, and cybervictimization, thereby reinforcing anxiety cycles (Annoni et al., 2021; Peprah et al., 2024; Wang & Jiang, 2022). The current findings demonstrate that usage intensity amplifies the effects of cognitive and emotional vulnerabilities, suggesting that behavioral regulation remains a critical intervention target.

Perceived social support emerged as a robust protective factor, substantially reducing predicted anxiety levels. This finding aligns with extensive research demonstrating that supportive relationships mitigate the psychological harm of cyberbullying and digital stress (Espino et al., 2023; Sousa et al., 2023; Wright & Wachs, 2021). Adolescents who perceive strong familial and peer support exhibit greater resilience, more adaptive coping strategies, and lower anxiety reactivity when confronted with online challenges. The saliency patterns reveal that social support actively dampens anxiety pathways within the model, reinforcing its central protective role.

The subgroup analysis further clarified the structure of high-risk profiles. Adolescents in the highest anxiety percentile exhibited pronounced activation of social comparison, emotional dysregulation, excessive media use, and negative feedback sensitivity, coupled with suppressed contributions from self-esteem and social support. This constellation mirrors the psychological profile described in cyberbullying and anxiety literature, where vulnerability

accumulates across cognitive, emotional, and social domains (Agustiningsih et al., 2024; Sousa et al., 2024; Wang et al., 2024; Zhu, 2025). Importantly, the interpretable deep learning approach allowed these profiles to be detected with precision, providing actionable insights for targeted intervention design.

5. Conclusion

These findings have significant theoretical implications. They support integrative models that conceptualize online social anxiety as an emergent property of interacting emotional, cognitive, behavioral, and social systems rather than as an isolated symptom cluster. The results also highlight the necessity of moving beyond linear analytic frameworks toward nonlinear, high-dimensional models capable of capturing the complexity of adolescent psychological development in digital ecologies. From a methodological perspective, the study demonstrates that interpretable deep learning can achieve high predictive accuracy while maintaining explanatory transparency, addressing longstanding concerns about the clinical applicability of artificial intelligence in mental health research (Prince et al., 2025; Ullah et al., 2025).

6. Limitations & Suggestions

Several limitations should be acknowledged. First, the cross-sectional design restricts causal inference regarding the developmental sequencing of psychological and digital factors. Second, reliance on self-report measures introduces potential reporting bias. Third, although the sample was demographically diverse, cultural specificity limits generalization to non-European populations. Finally, while the model demonstrated strong performance, additional longitudinal validation is required to assess stability across developmental stages.

Future studies should employ longitudinal and experimental designs to examine temporal dynamics and causal pathways underlying online social anxiety. Integration of physiological markers, behavioral tracking data, and ecological momentary assessment would further strengthen predictive modeling. Expanding cross-cultural samples and incorporating network-based analytic frameworks could provide deeper insight into sociocultural moderators and developmental trajectories.

The findings underscore the importance of early screening for social comparison tendencies, emotional regulation difficulties, and problematic digital behaviors in adolescents. School-based mental health programs should integrate emotional skills training, self-esteem enhancement, and digital literacy education. Clinicians and educators should collaborate with families to strengthen social support networks and promote healthy online 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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