Critical Public Health

ISSN: 0958-1596 (Print) 1469-3682 (Online) Journal homepage: www.tandfonline.com/journals/ccph20

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To cite this article: Ikram E. Khuda, Azeem Aftab, M. Umer Zia, Samar Ikram & Tao Huang (2025) Construction of physiological anxiety beyond individual pathology: integrating psychophysiological biomarkers and socio-digital contexts among university students in a post-pandemic world, Critical Public Health, 35:1, 2574960, DOI: 10.1080/09581596.2025.2574960

To link to this article: https://doi.org/10.1080/09581596.2025.2574960

Published online: 26 Oct 2025.

CRITICAL PUBLIC HEALTH
2025, VOL. 35, NO. 1, 2574960
https://doi.org/10.1080/09581596.2025.2574960

RESEARCH ARTICLE

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Construction of physiological anxiety beyond individual pathology: integrating psychophysiological biomarkers and socio-digital contexts among university students in a post-pandemic world

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ABSTRACT

As digital platforms increasingly mediate mental health care, a critical gap persists in understanding how digital engagement and social connectedness influence physiological anxiety, especially in contexts marked by structural inequality, cultural hierarchies and digital saturation, such as Pakistan. This study investigates how active versus passive social media use, combined with perceived social connectedness, affects heart rate variability (HRV), a physiological marker of stress, among university students. Using a biopsychosocial and political economy framework, we conducted real-time HRV monitoring during cognitive stress tasks via a mobile-based system. Results indicate that passive media use in low-connectedness settings is associated with significantly lower HRV, reflecting heightened physiological anxiety, whereas active use in socially embedded contexts predicts higher HRV and better autonomic regulation. These findings show that the emotional and physiological impacts of digital engagement are stratified by relational and sociotechnical factors. HRV emerges as a meaningful biomarker of anxiety when situated within broader social and digital ecologies. While empirically grounded in Pakistan, the findings reflect structural patterns across the Global South, where similar platform logics, infrastructural precarity, and sociocultural hierarchies shape digital mental health risks. The study contributes to critical public health by underscoring the need for equity-driven, context-sensitive digital mental health strategies.

ARTICLE HISTORY
Received 27 June 2025
Accepted 9 October 2025

KEYWORDS
Public mental health; digital technology; sustainable mental health; autonomic regulation; HRV

Introduction

Mental health concerns among university students have intensified globally, but the pressures faced by students in Pakistan are particularly acute due to the ongoing impacts of the COVID-19 pandemic, including the lasting effects of prolonged lockdowns and increased digital dependence. Although rising levels of depression, anxiety, and self-destructive behavior have been documented across diverse higher education contexts, Pakistan's rates often exceed global averages. This reflects the compounding effects of structural inequities, limited access to culturally appropriate mental health services, and the disruptive impact of public health emergencies. Recent studies, including Muneer et al. (2024), reported that 42.66% of Pakistani university students exhibit depressive symptoms. While social anxiety is widespread, it remains underexplored in local research and policy discourse. Wajid et al. (2024) highlighted a lack of culturally relevant interventions, and Khuda et al. (2024) observed a marked post-pandemic surge in social anxiety linked to inadequate policy response.

Despite these urgent patterns, prevailing interpretations reduce student distress to individual pathology, overlooking how broader socio-political systems structure mental health. In Pakistan, as in many Global South contexts, mental health infrastructures remain shaped by colonial legacies, donor-driven priorities, and economic uncertainty. Within this landscape, digital platforms are

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

increasingly promoted as scalable solutions to the mental health crisis, yet they often serve to obscure rather than address underlying structural determinants. These platforms operate within algorithmic and market-driven logics that commodify emotional distress and promote individualized, technologically mediated interventions (Mills & Hilberg, 2020). This risks reproducing a form of "digital care" that substitutes for meaningful investment in social infrastructure while depoliticizing the roots of emotional suffering.

The pandemic accelerated students' reliance on digital platforms for education, social connection, and mental health support. While these platforms offered continuity during crisis, they simultaneously entrenched passive digital consumption, algorithmic control, and psychosocial harm. Emerging scholarship shows that passive use of social media correlates strongly with anxiety and social withdrawal (Lim et al., 2021; Yue et al., 2022). Furthermore, its effects are amplified by race, gender, and economic inequality (Chhatwani et al., 2023). However, these patterns are insufficiently understood within the Pakistani context, where social hierarchies, limited access, and surveillance infrastructures reshape how digital mental health is experienced.

Critically, digital mental health interventions are embedded in broader architectures of surveillance capitalism (Smith et al., 2021). They commodify emotional states, extract behavioral data, and prioritize efficiency over ethics. In countries like Pakistan, where mental health services are underfunded, fragmented, and stigmatized, these platforms are often positioned as innovative solutions. Yet their use may deepen inequities by redirecting attention away from collective, structural responses to distress.

Research increasingly demonstrates that it is not merely the quantity, but the quality and structure of digital engagement that shapes mental health outcomes. Passive behaviors such as scrolling are associated with heightened loneliness, anxiety, and emotional dysregulation, whereas active, relational engagement tends to support psychological well-being (Lim et al., 2021). However, algorithmically curated digital spaces complicate this dichotomy by creating affective echo chambers that selectively amplify emotionally charged content and reinforce existing vulnerabilities. By narrowing psychological distance and selectively amplifying content aligned with existing behaviors or vulnerabilities, these platforms heighten emotional reactivity while limiting exposure to relational nuance or dissenting perspectives (Lee et al., 2021). For university students already navigating social fragmentation and limited offline relational infrastructure, such curated environments exacerbate feelings of disconnection and entrench maladaptive patterns of digital engagement.

Anchored on this, the legacy of pandemic-era digital dependence continues to affect students' psychosocial functioning, exacerbating anxiety in face-to-face interactions and impairing academic engagement (Powell & Martin, 2023). These effects are especially pronounced among students with limited relational infrastructure. Chelidoni et al. (2023) and Tatlı and Karadağ (2024) has repeatedly reported rising fear of public speaking and in-person engagement in the post-pandemic period. Yet these relational disruptions remain peripheral to dominant mental health models, which continue to pathologize students while ignoring the digital architectures that shape their distress.

To better conceptualize anxiety in digitized academic contexts, we turn to integrative theoretical models, which explains and raionalize our observations. The Stimulus-Organism-Response (SOR) framework (Mehrabian & Russell, 1974) provides a foundational lens, suggesting that environmental inputs, such as platform algorithms or digital isolation, elicit internal cognitive, affective, and physiological responses. Neurobiological pathways, including the amygdala-HPA axis, mediate these responses, triggering somatic markers like increased heart rate, muscular tension, and digestive irregularities (Kim et al., 2025). Complementing this, Construal Level Theory explained how reduced psychological distance in digital environments intensifies emotional arousal and avoidance behavior (Trope & Liberman, 2010).

While these models help explain anxiety mechanisms, they must be situated within the critique of political economy. The conditions that shape student distress, including digital infrastructure, institutional neglect, and algorithmic governance, are neither neutral nor inevitable. They reflect choices about which well-being is prioritized and how mental health is governed (Mills & Hilberg, 2020; Smith et al., 2021).

Recent evidence underscores that mental health is co-produced by individual, relational, and structural forces. Xia et al. (2025), recently linked mental health literacy gaps to social and digital conditions.

Chudzicka-Czupała et al. (2025) emphasized that social support is a stronger predictor of student well-being than individual coping alone. These insights demand a public health response that foregrounds equity, critiques technocratic care models, and resists the neoliberal commodification of emotional life.

Problem definition

Social anxiety among university students in Pakistan, and comparable Global South contexts, is no longer adequately explained through individual-centered frameworks. Our review identifies a critical gap in mental health research: the failure to integrate relational and physiological dimensions of anxiety with macro-level social contexts. While students increasingly rely on digital platforms for emotional support, these infrastructures shape distress through mechanisms of surveillance, commodification, and social disconnection. Prevailing mental health frameworks often overlook the broader systemic conditions shaping emotional distress, framing anxiety primarily as an individual clinical issue. This perspective neglects the intertwined effects of passive digital engagement, weakened social relationships, and commodified models of care that collectively contribute to the production of emotional suffering. This study responds by proposing a biopsychosocial and postcolonial framework that combines physiological anxiety markers, specifically heart rate variability (HRV), with measures of digital and relational engagement.

To address these gaps, this study is guided by the following questions:

Research questions (RQ)

1. How does the quality of digital engagement (active vs. passive) interact with perceived social connectedness to influence physiological markers of anxiety among university students in Pakistan?
2. To what extent can HRV serve as a meaningful biomarker of social anxiety when contextualized within broader sociotechnical environments?
3. How can affective computing and digital mental health interventions incorporate political-economic critique to address structural inequities in mental health governance?

Materials and methods

Study design and participants

This cross-sectional observational study employed a technology-enhanced assessment design to investigate the interplay between digital behavior, physiological stress, and social anxiety among university students in Pakistan. A total of 156 undergraduate students (final analytic sample: $N = 156$; age range: 18–25 years; with frequency of 83 males (~53%) and 73 females (~47%)) were recruited through convenience sampling from public and private universities across three metropolitan cities in Pakistan between February and April 2025. This count of the participants satisfied the inclusion criteria of our study.

Participants were eligible if they (i) were currently enrolled full-time in an undergraduate degree program, (ii) had no history of psychiatric diagnosis, and (iii) provided informed digital consent. Exclusion criteria included a self-reported history of psychiatric disorders, invalid heart rate variability (HRV) signals due to sensor artifacts, or signal loss exceeding 20% during task performance. Additionally, only participants aged 18–25 were included to control for age-related variability in HRV. Since SDNN values typically decline with age due to reductions in parasympathetic activity and baroreflex sensitivity, restricting the age range helped ensure that variations in HRV more accurately reflected psychological and contextual differences rather than age-related autonomic decline. This criterion strengthened the internal validity of the study by minimizing physiological confounds.

Primary data were collected through a custom mobile app featuring demographic items, gamified cognitive-behavioral tasks, and real-time HRV monitoring via eSense Pulse.

This study was approved by the Institutional Review Board of Iqra University (Ref: ERB#03-04-01). All participants provided voluntary, written informed consent via the mobile application designed for this study.

Participants were informed about the purpose of the research, the procedures involved, and their right to withdraw at any stage without any consequences. Confidentiality and anonymity were ensured throughout the study, and all data were securely stored in compliance with institutional and ethical guidelines.

Measures

Collected measures used in this study are shown in Table 1.

Demographics

Demographic information collected included age and gender via our mobile app.

Standardized anxiety screening

To enhance clinical relevance and enable comparison with global data, the Generalized Anxiety Disorder 7-item scale (GAD-7) was administered before task initiation to screen for self-reported anxiety symptoms. Cronbach's alpha for the GAD-7 in this sample was 0.89. GAD-7 screening was performed using our mobile app.

Cognitive behavioral tasks

To assess the psychophysiological markers associated with anxiety, two gamified cognitive behavioral tasks were administered on a mobile-based interface (Table 2).

1. Tap Test**:** A modified Go/No-Go task assessing impulse control and response inhibition, inspired by the Stroop test (Stroop, 1935).
2. Match Test**:** Cognitive speed and visual perception (Zubin, 1933).

Table 1. Demographic information variables used in the mobile app.

Variable name	Description	Variable and response type
History	Requires if a participant has any anxiety/psychiatric disease diagnosed previously	Categorical (Yes or No)
Heart Disease	Requires if a participant has any heart disease diagnosed previously	Categorical (Yes or No)
Undergraduate university student	Requires if currently enrolled in undergraduate university program	Categorical (Yes or No)
Gender	Requires gender information	Categorical (Male, Female or Other)
Age	Requires age information	Ordinal $(18-25, 26-33, 34-41, other)$
GAD	Requires participant to fill GAD-7 questionnaire and in the end anxiety level is identified using GAD-7 scoring on the mobile app.	Categorical
Tap_Test	Cognitive behavioral task based on response inhibition and results in corrected taps	Discrete
Match_Test	Cognitive behavioral task based on evaluation of cognitive speed under time constraints. It results no. correct matches.	Discrete
SM_Usage	Social Media Usage. Requires information regarding social media usage	Categorical (Active or Passive)
S_Conn	Social Connectedness. Requires the information regarding daily social connectedness.	Categorical 1 hour or less => low 2 to 3 hours => Medium More than 3 hours => High
SDNN	Provides the information on HRV in time domain as standard deviation of NN intervals in a regular ECG	Continuous data

Table 2. Functions performed in the mobile app.

S. No	Tasks	Duration (s)
1	Demographic information	–
2	Tap test normal	120
3	Refresh time	10
4	Match test	120
5	Refresh time	10

All of these tasks were performed by the participating students in a quiet room but in the presence of their friends/classmates. In this way, these tasks were designed to reflect the cognitive challenges that socially anxious individuals face in tech-saturated environments and academic settings, aligning with the study's broader aim of ecologically valid and digitally relevant measurements.

Social context variables

To assess participants' real-life social interaction and digital habits:

a. Social Media Use
   Participants were categorized based on self-reported engagement as active (e.g., posting, messaging) or passive (e.g., scrolling, lurking) users (Table 1).
b. Social Connectedness
   Social connectedness was measured through a brief index that classified participants into low, medium, or high perceived physical social connection levels (Table 1). This social connectedness strictly reflected the participants' physical interactions with friends, colleagues, and so on, thus not using social media.

Physiological stress reflected anxiety (HRV)

Physiological stress was operationalized using heart rate variability (HRV**)** recorded via a validated Bluetooth-based wireless sensor (eSense Pulse, Mindfield GmbH, Germany) connected to an Android application. The standard deviation of normal-to-normal intervals (SDNN) was extracted as a time-domain measure of HRV, capturing the autonomic nervous system reactivity. HRV was recorded continuously during a battery of interactive tasks designed to induce mild cognitive and social stress in cognitive-behavioral tasks. HRV values as SDNN vary within the range of 10*ms* to 250*ms*, indicating physiological plausibility (Shaffer & Ginsberg, 2017).

While several HRV indices exist, this study specifically employed SDNN (Standard Deviation of Normal-to-Normal Intervals) as a global marker of autonomic variability due to its robust sensitivity to both sympathetic and parasympathetic influences under stress conditions. SDNN provides an integrative measure of overall autonomic flexibility, making it well-suited for assessing physiological anxiety in young adult populations exposed to fluctuating psychosocial environments, such as university settings. Prior research has consistently validated SDNN as a reliable biomarker for stress-related autonomic dysregulation. For example, Kim et al. (2018) demonstrated through meta-analysis that lower SDNN values are significantly associated with elevated psychological stress across diverse populations. More recently, Kazdagli et al. (2024) confirmed SDNN's utility in detecting exam-induced stress responses among health sciences students, a cohort demographically comparable to our sample. Given its non-invasiveness, interpretability, and relevance in short-term recordings, SDNN was chosen as the principal HRV index to quantify autonomic anxiety regulation in this study.

Tap Test (impulse control and inhibition)

The Tap Test we developed and used was a modified version of the well-known Go/No-Go psychological task intended to measure impulse control and response inhibition. Participants were instructed to tap quickly in response to the target stimuli and withhold their responses to distractor stimuli. This task operationalized a core feature of anxiety, assessing impaired cognitive control in the contexts of ambiguity, threat, or evaluation. Given the relationship between social anxiety and difficulty in suppressing proponent responses in socially evaluative situations, the task offered a behavioral proxy for inhibition-related deficits common in socially anxious individuals.

Match Test (cognitive speed and visual perception)

The Match Test assesses cognitive speed and visual processing by requiring participants to identify matching letters or symbols under time constraints. This task mirrored the demand for rapid information

filtering and interpretation in over-stimulating digital environments. Slower response times or increased error rates have been interpreted as indicators of cognitive inefficiency and perceptual vigilance, often seen in anxious individuals, particularly in the context of social information processing.

Justification, theoretical integration and HRV

These tasks were chosen for their psychometric rigor and ecological validity within the study's conceptual model. In algorithmically saturated digital environments, socially anxious individuals experience impaired inhibition and attention. The Tap and Match Tests captured these cognitive disruptions, linking digital engagement, self-regulation, and anxiety through psychophysiological grounded assessment.

Physiological arousal while performing cognitive behavioral tasks was indexed by HRV, measured in real time using an eSense Pulse sensor (Mindfield Biomedical, Germany/USA). The device recorded inter-beat intervals (IBI) of the electrocardiogram (ECG signal) and transmitted them to our mobile app wirelessly via Bluetooth during each task performance. The primary HRV metric used was SDNN (Standard Deviation of NN intervals), with cutoffs of $<50ms$ (unhealthy/high anxiety), $50-100ms$ (compromised/medium anxiety), $>100ms$ (healthy/low anxiety), based on (Shaffer & Ginsberg, 2017). SDNN was selected for its well-established sensitivity to parasympathetic and sympathetic modulation, making it a powerful psychophysiological index for assessing stress-related autonomic flexibility in dynamic digital environments.

Procedure

The participants were guided by trained research assistants on how to use the mobile app and the HRV sensor. Tasks were performed individually but in the presence of peer groups in a controlled laboratory environment to simulate various social contexts. Baseline HRV was recorded during a 1-minute rest period before task onset.

Data processing and analysis

All the variables included in the analysis are summarized in Table 1. Data preprocessing followed rigorous artificial intelligence and psychophysiological research standards to ensure transparency, reliability, and reproducibility. Outliers were identified and addressed, and missing values were managed using mean imputation to preserve the data integrity in this moderate-sized sample. The primary outcome variable, the standard deviation of normal-to-normal intervals (SDNN), was derived from real-time heart rate variability (HRV) data collected during cognitive tasks using the eSense biofeedback app. This tool employs edge-AI-like signal processing to achieve precise low-noise extraction of short-term HRV measures. Independent variables, social media use modality (active vs. passive), and social connectedness (low, medium, high) were selected to model interactions between digital engagement and the psychosocial context. A Generalized Linear Model (GLM) were applied to capture complex, non-additive effects on SDNN, with univariate tests confirming significant interactions. This analysis critically illuminates how algorithmically mediated, inequitable digital infrastructure co-produces embodied anxiety, informing systemic, equity-focused interventions in Pakistan and beyond.

Given the use of real-time biometric monitoring and mobile app-based data collection in a low-resource, digitally uneven setting, this research also foregrounds important ethical considerations. While the study was reviewed and approved by the Institutional Review Board of Iqra University (Ref: ERB#03-04-01), and informed consent was obtained through a secure digital platform, we recognize that procedural compliance alone is insufficient in contexts marked by asymmetries in digital literacy and power. Participants were fully informed of their rights, including voluntary participation and withdrawal, and all data were anonymized and encrypted in accordance with international standards. Still, we acknowledge the ethical imperative to situate such research within frameworks that resist extractive data practices, prioritize relational accountability, and safeguard participant autonomy in digitally mediated environments.

Results

Following data preprocessing, we conducted descriptive analyses to explore the frequency distributions of the independent variables: social media usage *SM_Usage* and social connectedness *S_Conn* summarized in Figure 1 and Table 3. The descriptive statistics for the outcome variable *SDNN* are reported in Table 4. The estimated population mean μ_{SDNN} of the SDNN with 95% confidence intervals is shown in Table 5. These estimates suggest that the average level of physiological anxiety, as indexed by *SDNN*, falls within the moderate range according to established clinical thresholds.

In order to address RQ1, we proceeded by modeling associations between psychosocial variables and physiological stress. We used statistical procedures utilizing General Linear Model (GLM) to investigate how the interaction between active vs. passive social media usage and levels of social connectedness influences SDNN. *SM_Usage* was coded as active or passive, while *S_Conn* was classified as low, medium, or high. The GLM incorporated main effects and interaction terms to model the combined influence of digital and social variables. The full model was executed using SPSS with a 95% confidence interval.

The GLM was structured with two categorical predictors, *S_Conn* (Low, Medium, High) and *SM_Usage* (Active and Passive), coded as dichotomous, to examine their effects on the continuous outcome variable, *SDNN*. The codes used for dichotomous predictors are listed in Table 6.

The resultant, fitted GLM is represented as:

$$SDNN_i = b_o + b_1 S\_Conn_{1i} + b_2 S\_Conn_{2i} + b_3 SM\_Usage_i + b_4 Int_{1i} + b_5 Int_{2i} + \varepsilon_i \quad (1)$$

The interaction term (*Int*) represents the combined effect of categorical predictors, and mathematically shows their multiplication. The first interaction compared passive vs. active social media use in low-vs. medium-connected groups, and the second compared passive vs. active use in low-vs. high-connected groups. Model fit statistics, shown in Table 7, indicate that 59.3% of the variance in *SDNN* was accounted for ($R^2 = 0.593, p < 0.001$), confirming strong explanatory power. Analysis of Variance (ANOVA) decomposed

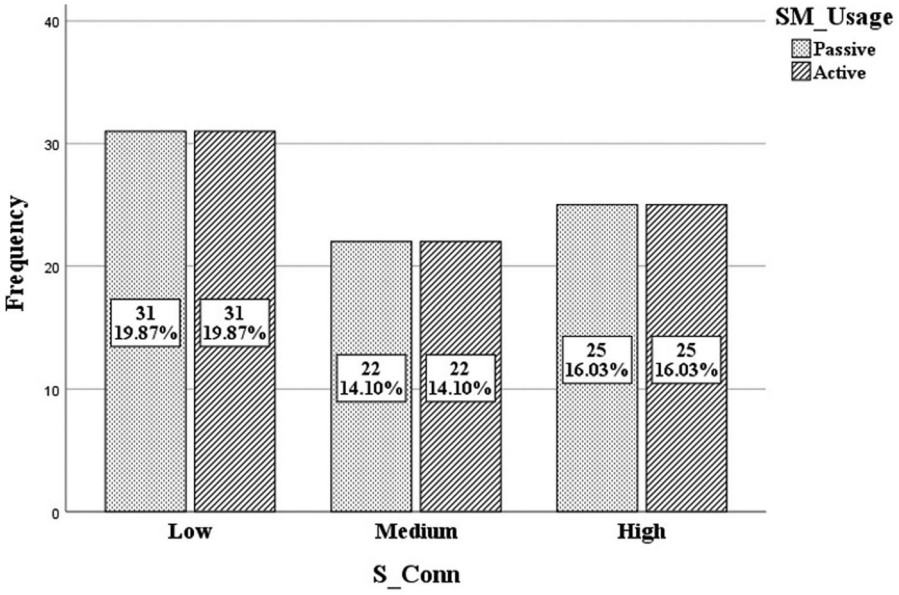

Figure 1. Frequency distribution of social connectedness (*S_Conn*) and social media usage (*SM_Usage*) in the sample.

Table 3. Frequency distribution of social connectedness (S_conn) and social media usage (SM_usage) in the sample.

		Social connectedness (S_conn)			
		Low	Medium	High	Total frequency
SM_Usage	Passive	31	22	25	78
	Active	31	22	25	78
Total frequency		62	44	50	156

Table 4. Descriptive statistics of standard Deviation of NN intervals (SDNN).

Social connectedness	Social media use	N	Mean	Standard deviation	Variance
Low	Passive	31	28.28	15.45	238.66
	Active	31	55.82	21.61	467.09
Medium	Passive	22	47.99	37.81	1429.85
	Active	22	101.88	46.98	2206.83
High	Passive	25	24.45	15.12	228.66
	Active	25	123.36	39.73	1578.18
Grand Total		156	61.54	47.24	2232.05

Table 5. Mean estimation Standard Deviation of NN interval (SDNN) in the population.

				95% confidence interval	
	t	df	Sig.	Lower	Upper
SDNN	16.268	155	0.000	54.0648	69.0089

t is t statistics for sample mean.
df is the degree of freedom for population mean estimation.
Sig is the significance value (p value) at 0.05 level of significance.

Table 6. Coding used in the developed generalized linear model (GLM) of (2).

Social connectedness (S_conn)	Social media usage (SM_usage)	S_Conn_1	S_Conn_2	SM_Usage	Int_1	Int_2	*Mean*
Low	Passive	0	0	0	0	0	28.2806
Low	Active	0	0	1	0	0	55.8242
Medium	Passive	0	1	0	0	0	47.9973
Medium	Active	0	1	1	1	0	101.8770
High	Passive	1	0	0	0	0	24.4520
High	Active	1	0	1	0	1	123.3580

S_Conn_1 and S_Conn_2 are dummy variables for Social Connectedness levels.
SM_Usage is dichotomous and indicates social media usage levels.
Int_1 and Int_2 are the interaction variables between social connectedness and social media usage.

Table 7. Model summary for the GLM (1).

					Change statistics				
Model	R	R square	Adjusted R square	Std. Error of the estimate	R square change	*F* change	df_1	df_2	*p-value* change
1	0.770[a]	0.593	0.579	30.64931	.593	43.659	5	150	0.000

R is the Pearson correlation coefficient.
$df_1$and df_2 are degree of freedoms for the GLM (1) and errors respectively.

this variance into components attributable to social connectedness, social media usage, and their interaction. Table 8 presents the results of ANOVA, detailing the distribution of the total sum of squares (SST), partitioned into explained variance (SSR) and residual variance (SSE). The explained variance (SSR) was decomposed into three components: SSA (attributable to Social Connectedness, S_Conn), SSB (attributable to Social Media Usage, SM_Usage), and SSI (interaction effect between S_Conn and SM_Usage), as illustrated in Figure 2.

The regression coefficients and their significance levels obtained by executing GLM are presented in Table 9. All predictors are statistically significant, except for the dummy variable representing high Social Connectedness (S_Conn_2). However, the interaction between S_Conn_2 and the active state of SM_Usage was significant, suggesting that, while high social connectedness alone did not significantly affect *SDNN* , its interaction with active social media use exerted a meaningful influence on the outcome variable. Using these results, our GLM model that best fits the data and describes the changing effects of variables on social anxiety, measured as *SDNN* is as follows:

$$SDNN_i = 28.281 - 3.829 \times S_{Conn1i} + 19.717 \times S_{Conn2i} + 27.544 \times SM_{Usagei} + 26.337 \times Int_{1i} + 71.362 \times Int_{2i} + \varepsilon_i \quad (2)$$

Further in explaining RQ1, the GLM analysis revealed distinct psychophysiological profiles across social connectedness and social media usage groups among the university students in Pakistan. Firstly, the

Table 8. Analysis of variances (ANOVA) table for model fitness.

Model	Sum of squares (SS)	df	Mean square	F	Sig.
Regression (SSR)	205060.959	5	41012.192	43.659	0.000
Residual (SSE)	140907.063	150	939.380		
Total (SST)	345968.022	155			

SSR indicates Sum of Square Regression.
SSE indicates Sum of Square Errors.
SST indicates Sum of Squares Total.
df indicates degree of freedoms for SSR, SSE and SST.
F shows F ratio between mean squares of SSR and SSE.
Sig is the significance value (p value) at 0.05 level of significance.

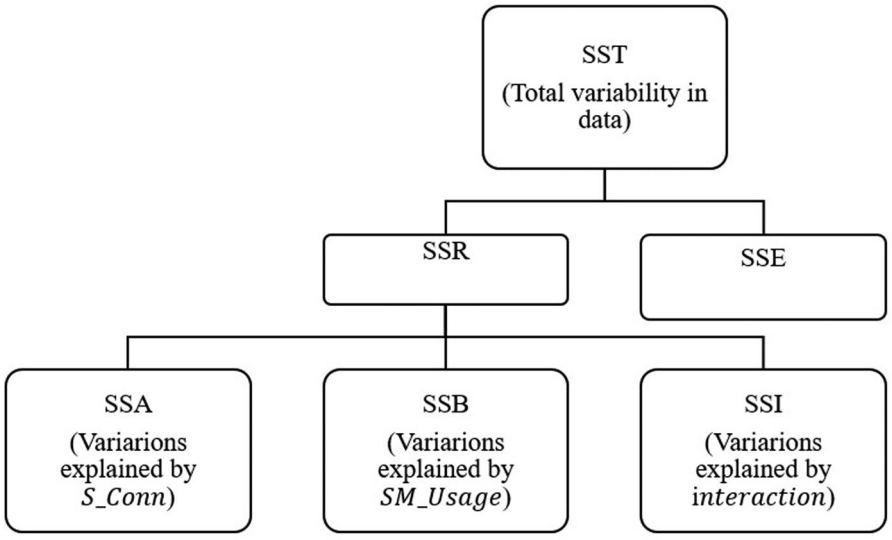

Figure 2. The distributions of variations in data and model.

Table 9. Regression coefficient (b) and estimates of the developed GLM model at 0.05 Level of significance for (1).

	Unstandardized coefficients		Standardized coefficients			95.0% confidence interval for *b*	
Model	*b*	Std. error	Beta	t	Sig.	Lower bound	Upper bound
(Constant)	28.281	5.505		5.137	0.000	17.404	39.158
SM_Usage	27.544	7.785	0.292	3.538	0.001	12.161	42.926
S_Conn_1	−3.829	8.239	−0.038	−0.465	0.643	−20.108	12.450
S_Conn_2	19.717	8.544	0.188	2.308	0.022	2.834	36.599
Int_1	26.337	12.083	0.195	2.180	0.031	2.462	50.212
Int_2	71.362	11.651	0.556	6.125	0.000	48.340	94.385

S_Conn_1 and S_Conn_2 are dummy variables for Social Connectedness levels.
SM_Usage is dichotomous and indicates social media usage levels.
Int_1 and Int_2 are the interaction variables between social connectedness and social media usage.

baseline group, that is, low social connectedness with passive media use, showed the lowest *SDNN* ($b0 = 28.28 ms$), indicating it is linked to higher physiological stress and heightened anxiety. Secondly, active social media use with low social connectedness significantly elevated *SDNN* ($b3 = 27.54 ms$), suggesting it is associated with lower anxiety through increased digital engagement; hence, the latter proved a buffering effect of digital engagement. Thirdly, medium social connectedness ($b2 = 19.71 ms$) independently improved *SDNN*, reflecting the stabilizing role of interpersonal ties. Fourthly, the combined effect of medium connectedness and active use ($b4 = 26.34 ms$) demonstrated additive benefits, underscoring the biopsychosocial synergy between the social environment and digital behavior, and hence autonomic regulation. Conversely, high connectedness combined with passive use was associated with a non-significant decrease in *SDNN* ($b1 = -3.83 ms$), implying potential stress amplification and linked to heightened anxiety

in disengaged individuals despite strong social networks. Finally, however, high connectedness paired with active media use was found to be associated with highest *SDNN* increase ($b5 = 71.36\,ms$), highlighting the critical role of active social engagement within robust social environments for optimal autonomic regulation. These findings emphasize the nuanced interplay between digital behavior and the social context in modulating physiological stress responses, with clear implications for public health interventions targeting anxiety and well-being.

To further investigate the extent to which HRV, operationalized as SDNN, functions as a meaningful biomarker of social anxiety within broader sociotechnical environments (RQ2), we conducted a univariate between-subjects factorial ANOVA. While the General Linear Model captured multifactorial interactions, this approach provided a focused lens on the independent and combined effects of social connectedness (*S_Conn*) and social media usage (*SM_Usage*) on psychophysiological responses. By examining mean differences in *SDNN* across these categorical variables, we assessed how anxiety-related autonomic activity is patterned by digital engagement and relational embeddedness, two key dimensions of sociotechnical context. Additionally, as shown in Table 5, a one-sample t-test revealed that the sample's mean SDNN significantly deviated from normative expectations ($t = 16.27$, $p < 0.001$), with a 95% confidence interval ranging from 54.06 to 69.01 ms. This provides further support for HRV as a meaningful and sensitive biomarker of social anxiety within the particular sociotechnical and educational conditions characterizing this population.

Figures 3 and 4 demonstrated significant main effects of low connectedness and passive media use on SDNN, while Table 10 confirmed robust interaction effects. As visualized in Figure 5, students with higher social connectedness and active media use exhibited elevated *SDNN*, indicative of lower physiological anxiety, whereas those with low connectedness and passive use showed significantly lower association with *SDNN*.

To unpack these interactions, a simple effects analysis was conducted. The results showed that active users consistently demonstrated higher *SDNN* across all connectedness levels, while passive users, especially those with low social ties, exhibited elevated psychophysiological stress. As shown in Figure 6 and Table 11, non-overlapping error bars and statistically significant within-group variance affirmed the moderating role of social context.

To quantify the practical significance of these patterns, effect sizes were computed from *F*-values using the transformation:

$$r = \sqrt{\frac{F(1, df_R)}{F(1, df_R) + df_R}} \tag{3}$$

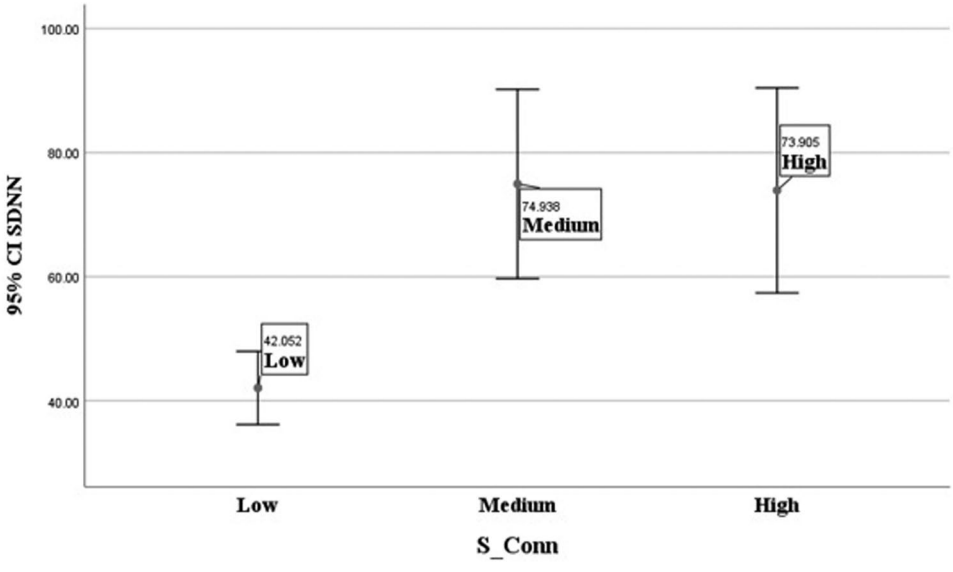

Figure 3. Between subjects effect of social connectedness (*S_Conn*) on SDNN.

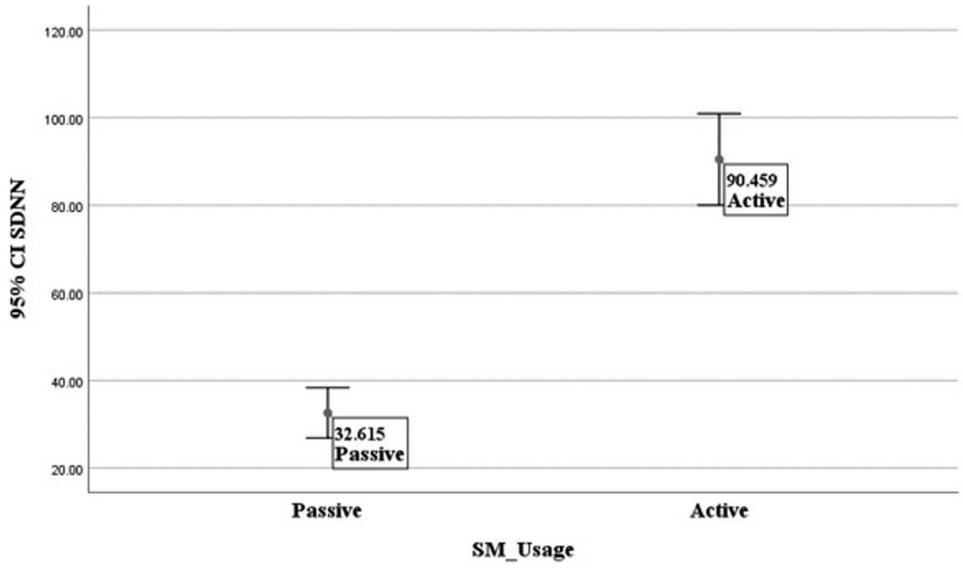

Figure 4. Between subjects effect of social media usage (*SM_Usage*) on SDNN.

Table 10. Tests of between-subjects effects.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected Model	205060.959[a]	5	41012.192	43.659	0.000
Intercept	619149.813	1	619149.813	659.104	0.000
S_Conn	39087.832	2	19543.916	20.805	0.000
SM_Usage	138128.404	1	138128.404	147.042	0.000
*S_Conn*SM_Usage*	35479.724	2	17739.862	18.885	0.000
Error	140907.063	150	939.380		
Total	936706.484	156			
Corrected Total	345968.022	155			

a. R Squared = .593 (Adjusted R Squared = 0.579).

S_Conn indicates social connectedness.

SM_Usage indicates social media usage.

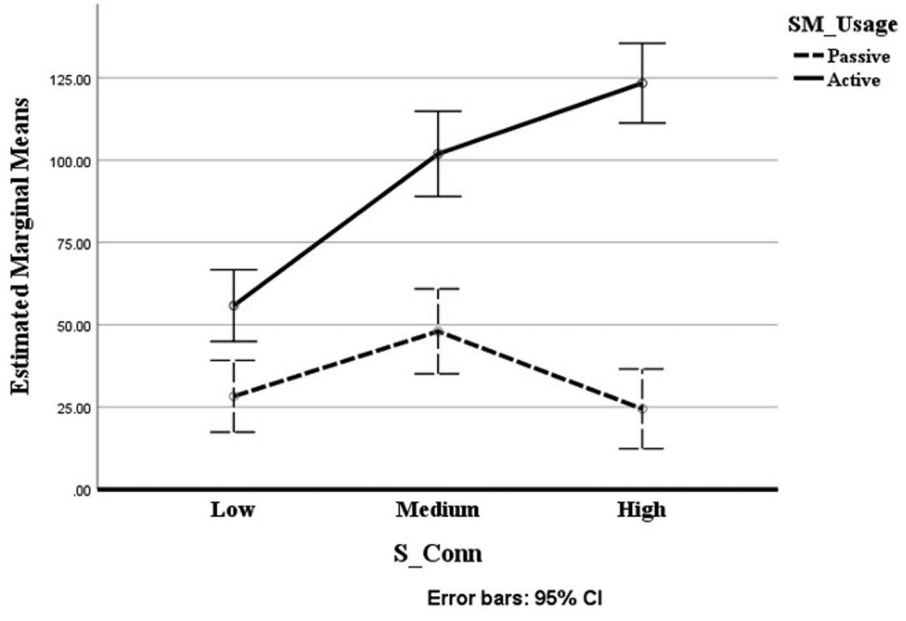

Figure 5. Visualization of interaction.

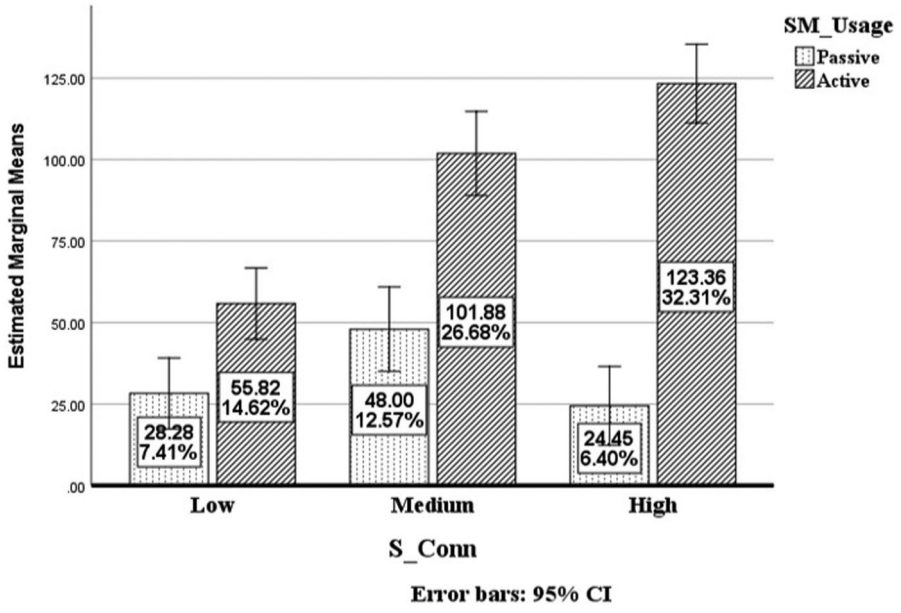

Figure 6. Results of simple effect analysis.

Table 11. Results of simple effect analysis.

Social connectedness (S_{Conn})		Sum of squares	df	Mean square	F	Sig.
Low	Contrast	11759.029	1	11759.029	12.518	0.001
	Error	140907.063	150	939.380		
Medium	Contrast	31934.137	1	31934.137	33.995	0.000
	Error	140907.063	150	939.380		
High	Contrast	122279.960	1	122279.960	130.171	0.000
	Error	140907.063	150	939.380		

Resulting values were,

$$r_{SM\_Usage(Low)} = 0.2275 \Rightarrow low\ effect\ size$$

$$r_{SM\_Usage(Medium)} = 0.4298 \Rightarrow large\ effect\ size$$

$$r_{SM\_Usage(High)} = 0.6816 \Rightarrow large\ effect\ size$$

The results of this study provide critical empirical grounding for addressing RQ3 by demonstrating that heart rate variability (HRV), a physiological marker of anxiety, responds unequally to digital engagement based on levels of social connectedness, a proxy for embeddedness in relational infrastructure. Specifically, the effect sizes associated with active versus passive media use were markedly larger at medium and high levels of social connectedness, indicating that digital engagement's psychophysiological impact is not universally experienced but is instead stratified along social-relational lines. Students with stronger relational ties benefited from active engagement (as seen in elevated SDNN), suggesting a buffering effect, while those with low social connectedness exhibited low association with SDNN when passively consuming content, evidence of heightened autonomic stress. These disparities cannot be meaningfully interpreted without considering the broader sociotechnical systems in which they occur. Algorithmically curated digital environments, designed to maximize engagement rather than care, amplified emotional reactivity and disproportionately burden structurally disadvantaged groups. Thus, affective computing and digital psychiatry must be conceptualized to account for the political economy of distress, where psychophysiological signals like HRV are not

merely biological indicators but are shaped by platform governance, social precarity, and systemic inequality. Embedding such critique enables more just, context-sensitive, and equity-informed mental health interventions.

Discussion

This study critically advances our understanding of how digital engagement and social connectedness jointly shape physiological stress regulation among university students in Pakistan, a context marked by digital saturation, structural inequality, and fragmented mental health infrastructure. Drawing on a biopsychosocial and political economy framework, we explored how different modalities of social media use, active versus passive, interacted with perceived social connectedness to affect heart rate variability (HRV), a non-invasive and objective biomarker of autonomic anxiety regulation. The findings offer significant implications not only for public health in the Global South but also for global discourses in affective computing and digital mental health.

Addressing RQ1: the interaction between digital behavior and social connectedness

The results revealed that passive social media use in conjunction with low social connectedness yielded the lowest SDNN values, indicating heightened physiological anxiety. These findings are consistent with existing literature that links passive digital consumption to emotional dysregulation, social withdrawal, and increased anxiety (Lim et al., 2021; Yue et al., 2022). However, our analysis extends these insights by situating them within broader sociotechnical and political-economic systems. Algorithmically curated digital environments reinforce echo chambers, amplify emotional reactivity, and narrow psychological distance, design effects that intensify distress, especially among already isolated users (Lee et al., 2021; Smith et al., 2021). These platforms, governed by platform capitalism and neoliberal logics, commodify attention and emotional labor, turning student distress into extractable data and monetizable engagement (Mills & Hilberg, 2020).

Conversely, active social media use, particularly when embedded in contexts of medium to high social connectedness, was associated with significantly higher SDNN values, suggesting a more regulated autonomic profile and lower anxiety. This supports prior findings that highlight the buffering effects of relational digital engagement (Chudzicka-Czupała et al., 2025). However we show that such benefits are not universally accessible. Rather, they are conditioned by social infrastructure, revealing the layered nature of digital precarity. Students embedded in strong social networks may experience digital tools as augmentative, while those facing structural disconnection, due to socioeconomic barriers, geographic isolation, or cultural constraints, remain vulnerable to the psychophysiological harms of passive engagement.

These findings must be interpreted within the cultural and educational realities of Pakistan, where collectivist norms traditionally emphasize embodied, in-person relationality, yet students face increasing social disconnection due to competitive academic structures, urban migration, and limited institutional investment in student well-being.

Addressing RQ2: HRV as a contextualized biomarker of anxiety

The second research question probed the extent to which HRV could serve as a meaningful biomarker of social anxiety when situated within broader sociotechnical environments. Our results demonstrate that HRV, specifically SDNN, effectively captured the differential physiological impact of digital engagement patterns across social contexts in the university students. This affirms its utility as a sensitive indicator of embodied stress but underscores the necessity of interpreting HRV within ecological and relational frameworks. The simple effects analysis showed that active users consistently exhibited higher HRV than passive users across all connectedness levels, with effect sizes increasing at medium and high levels of social connectedness ($r = 0.43 - 0.68$), indicating large, practically meaningful effects. These findings support a biopsychosocial interpretation of HRV as not just a biological signal but a socially patterned marker of lived experience (Kim et al., 2025; Xia et al., 2025).

This reinforces the importance of integrating physiological data with relational and behavioral variables, as advocated in emerging digital psychiatry and critical public health frameworks (Skeggs & Orben, 2025). HRV, in this view, becomes not only a diagnostic metric but a lens through which to understand how algorithmic infrastructures and social environments co-construct emotional health. Such contextualization is especially vital in the Global South, where physiological data are often interpreted through Western biomedical models without accounting for local sociopolitical realities. This is especially relevant in Pakistan, where stigma often deters self-reporting of emotional distress, and HRV offers a non-verbal, real-time indicator that can capture hidden burdens of mental ill-health.

While this study focused on students aged 18–25 to minimize age-related confounds in HRV, this deliberate age restriction may limit the generalizability of the findings to older or non-student populations. Gender data were collected during recruitment; however, initial analysis showed no statistically significant differences in HRV (SDNN) between male and female participants, likely due to limited sample size. These demographic constraints, while necessary for experimental control, warrant caution in extrapolating the results more broadly, especially in light of Pakistan's gendered digital access landscape and generational differences in online behavior.

Addressing RQ3: toward a politically conscious affective computing

Finally, our third research question asked how affective computing and digital mental health interventions might incorporate political-economic critique to address structural inequities. The differentiated effect sizes in our study, whereby digital engagement yielded significant stress relief only among students with strong social ties, highlight the urgent need to move beyond techno-solutionist models of digital mental health. These disparities are not merely behavioral artifacts; they are the physiological imprints of unequal access to social, emotional, and digital resources. As such, affective computing systems that rely solely on physiological inputs without accounting for structural embeddedness, risk reproducing and amplifying existing inequalities. In the Pakistani context, these inequities intersect with class, gender, and language access, where English-medium digital platforms may alienate rural or Urdu-speaking populations, and patriarchal norms may constrain online engagement for female students.

Our findings call for a paradigm shift: digital mental health interventions must be designed with an awareness of the broader conditions of platform governance, algorithmic harm, and relational exclusion. This means not only embedding physiological markers like HRV into platforms, but also ensuring that such systems are ethically governed, relationally informed, and responsive to the structural determinants of distress. Public health responses, particularly in resource-constrained settings like Pakistan, must resist the trend of outsourcing care to technology without addressing the underlying causes of disconnection, including underfunded mental health services, socio-cultural stigma, and digital stratification.

Conclusion

This study demonstrates that physiological anxiety among university students is not only a function of individual behavior but a reflection of deeper socio-technical entanglements. Active digital engagement can buffer against stress, but only when embedded in strong relational ecologies. HRV offers a promising biomarker of this interaction, but its interpretation must be grounded in critical, context-sensitive frameworks. By bridging physiological data with political economy critique, our work contributes to the emerging field of critical digital psychiatry and reaffirms the value of equity-driven, relationally aware approaches to mental health governance in the Global South.

Implications

This study offers critical implications for affective computing, digital psychiatry, and public health in the Global South. It demonstrates that HRV, specifically SDNN, serves as a meaningful biomarker of social anxiety when interpreted within relational and digital contexts. The interaction between social connectedness and digital engagement highlights how the psychophysiological impact of technology is socially stratified, cautioning against one-size-fits-all digital mental health interventions. In under-resourced

settings like Pakistan, reliance on digital tools without structural support may exacerbate inequality. The findings call for equity-focused, context-sensitive designs in affective computing that incorporate political-economic critique, recognizing how social platforms, data commodification, and algorithmic governance shape distress. By integrating bio-signals with sociotechnical variables, this research challenges biomedical reductionism and offers a model for ethically grounded, socially responsive mental health technologies and policies.

Limitations

This study has some limitations which should be considered as part of this study. The sample was restricted to undergraduate students aged 18–25 in Pakistan, which may limit generalizability across age groups, educational levels, or cultural contexts. Gender was not included as a comparative factor, and the cross-sectional design precludes causal inference. While HRV (SDNN) offers a reliable index of autonomic anxiety regulation, it is sensitive to extraneous influences such as physical fitness and circadian variation, which were not fully controlled.

Given the cross-sectional design of this study, causal relationships between digital engagement, social connectedness, and HRV cannot be inferred. All interpretations are framed to reflect correlational associations, and future longitudinal research is recommended to establish causal pathways.

This study's use of convenience sampling from three cities in Pakistan limits the generalizability of findings. Students from rural or marginalized backgrounds may exhibit different patterns of digital engagement and anxiety. Future studies should adopt more representative, stratified sampling to capture diverse sociocultural and institutional contexts.

Our operationalization of social connectedness as time spent in physical interaction reflects both practical considerations and the sociocultural context of Pakistan. While this behavioral proxy is established in prior studies, we recognize it may not capture the emotional or qualitative depth of relationships. In Pakistan's collectivist society, embodied interactions are central to relational life. Yet, factors like urban migration, academic pressures, and limited campus mental health resources, like trained counselors, quiet spaces for stress relief, or regular workshops on mental well-being, have led to social fragmentation and fraying of social ties. Students increasingly turn to digital platforms for connection, but infrastructural disparities, platform language biases, and gendered access restrictions shape their engagement. These contextual limitations complicate both the experience and measurement of connectedness. We acknowledge this constraint and suggest that future studies incorporate richer, multidimensional measures that capture the affective and relational complexity of social connectedness.

Future research and recommendations

Future research should adopt longitudinal and mixed-methods designs to examine the causal dynamics between digital engagement, social connectedness, and physiological anxiety over time. Expanding the sample to include diverse age groups, educational backgrounds, and geographic contexts would enhance generalizability. Future studies should also explore gendered and intersectional patterns of digital precarity, as well as the moderating effects of socioeconomic status on HRV and anxiety. Incorporating qualitative approaches, such as interviews or ethnographic observation, can deepen understanding of how students interpret and navigate algorithmically curated digital spaces. Finally, researchers and policymakers should prioritize the development of equitable, culturally grounded digital mental health interventions that integrate affective computing with structural critique, ensuring that technology supports relational resilience rather than exacerbating existing disparities.

Author contributions

All authors meet the requirements of International Committee of Medical Journal Editors (ICMJE) for authorship. All authors meet the requirements of Taylor & Francis authorship criteria. Ikram E Khuda: Conceptualization, resources, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, visualization, writing-original draft, writing-review & editing, validation, supervision. Azeem Aftab: Methodology, funding

acquisition, data curation and writing-original draft. M. Umer Zia: Data curation, writing-original draft, writing-review & editing. Samar Ikram: Investigation, data curation, writing-review & editing. Tao Huang: Supervision, project administration, validation. All authors approved the final version to be published.

Disclosure statement

The authors report there are no competing interests to declare.

Health and safety statement

All mandatory health and safety procedures were fully complied during the course of this research. The study did not involve any hazardous materials, equipment, or procedures, and therefore no specific safety warnings are applicable.

Funding

The research work presented is part of the HEC Pakistan awarded research project in the category of the National Research Program for Universities (NRPU) to Iqra University, Karachi, Pakistan. The grant number is: 20-15283/NRPU/R&D/HEC/2021.

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Data availability statement

Datasets cannot be shared due to ethical and privacy concerns.

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