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Influence of mobile learning app on secondary school students' mathematics motivation and engagement in Pakistan

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Muhammad Shehryar Rao[1], Komal Niazi[2], Dyana Wijayanti[3] and Fahad Alam[4]*

Department of Mathematics Education, School of Mathematical Sciences, East China Normal University, China[1]; LIAVH Laboratory for Integrated Archaeological Visualization and Heritage, Pratt Institute, USA[2]; Mathematics Education Department, Universitas Islam Sultan Agung, Indonesia[3]; School of Economics and Management, Tongji University, China[4]

For Correspondence: Email: *niazi.komal_leo@yahoo.com*; Phone: +8618930854447

Abstract

Mathematics education faces significant challenges, with students frequently experiencing anxiety and poor learning outcomes, particularly in developing countries like Pakistan. Mobile learning apps are promising tools for enhancing student engagement and motivation through interactive, personalized learning experiences. This study examines the influence of mobile learning app usage on the mathematics motivation and engagement of secondary school students in Pakistan and investigates how perceived barriers moderate these relationships. Using convenience sampling, 343 students were selected from 15 secondary schools in Sahiwal district. The study employed Partial Least Squares Structural Equation Modeling (PLS-SEM) to analyze the data. Results indicate that mobile learning app usage significantly influences students' mathematics motivation ($\beta = 0.557$, $p < 0.001$) and engagement ($\beta = 0.283$, $p < 0.001$), while mathematics motivation also significantly influences engagement ($\beta = 0.525$, $p < 0.001$). The model explained substantial variance ($R^2 = 0.460$ for motivation; $R^2 = 0.616$ for engagement). Moreover, barriers negatively moderated these relationships (motivation: $\beta = -0.125$, $p < 0.01$; engagement: $\beta = -0.052$, $p < 0.05$). These findings guide policymakers and app developers in developing contexts. By boosting students' motivation and engagement, mobile learning can reduce mathematics anxiety, build confidence, and support wellbeing and success. *(Afr J Reprod Health 2026; 30 [2]: 179-193).*

Keywords: Mathematics education; Mobile learning; Student motivation; Student engagement; Technology barriers; Pakistan

Résumé

L'enseignement des mathématiques est confronté à des défis importants, les élèves souffrant fréquemment d'anxiété et obtenant de faibles résultats scolaires, notamment dans les pays en développement comme le Pakistan. Les applications mobiles d'apprentissage constituent des outils prometteurs pour renforcer l'engagement et la motivation des élèves grâce à des expériences d'apprentissage interactives et personnalisées. Cette étude examine l'influence de l'utilisation d'applications mobiles d'apprentissage sur la motivation et l'engagement en mathématiques des élèves du secondaire au Pakistan et analyse comment les obstacles perçus modèrent ces relations. Un échantillon de 343 élèves issus de 15 établissements secondaires du district de Sahiwal a été sélectionné par échantillonnage de commodité. L'étude a utilisé la modélisation par équations structurelles aux moindres carrés partiels (PLS-SEM) pour analyser les données. Les résultats indiquent que l'utilisation d'applications mobiles d'apprentissage influence significativement la motivation ($\beta = 0.557$, $p < 0.001$) et l'engagement ($\beta = 0.283$, $p < 0.001$) des élèves en mathématiques, tandis que la motivation en mathématiques influence également significativement leur engagement ($\beta = 0.525$, $p < 0.001$). Le modèle explique une part importante de la variance ($R^2 = 0.460$ pour la motivation; $R^2 = 0.616$ pour l'engagement). De plus, les obstacles modèrent négativement ces relations (motivation: $\beta = -0.125$, $p < 0.01$; engagement: $\beta = -0.052$, $p < 0.05$). Ces résultats orientent les décideurs politiques et les développeurs d'applications dans l'élaboration de contextes d'apprentissage adaptés. En stimulant la motivation et l'engagement des élèves, l'apprentissage mobile peut réduire l'anxiété liée aux mathématiques, renforcer la confiance en soi et favoriser le bien-être et la réussite. *(Afr J Reprod Health 2026; 30 [2]: 179-193).*

Mots-clés: Enseignement des mathématiques; Apprentissage mobile; Motivation des élèves; Engagement des élèves; Obstacles technologiques; Pakistan

Introduction

The global mathematics education crisis has reached unprecedented proportions, with more than half of children and adolescents worldwide failing to achieve minimum proficiency levels in mathematics.[1] This crisis is particularly acute in Pakistan, where mathematics consistently ranks among the most challenging subjects for secondary school students, which often results in student anxiety and poor learning outcomes.[2] The Annual Status of Education Report (ASER) 2023 reveals that mathematics performance remains critically low across Pakistani secondary schools, with rural students demonstrating particularly weak foundational skills in basic mathematical operations.[2] These persistent learning gaps, combined with limited access to qualified mathematics teachers in rural areas, underscore the urgent need for innovative pedagogical approaches that can reach students beyond traditional classroom constraints.[2] Traditional instruction methods often fail to enhance student motivation and engagement, which are considered the critical psychological constructs that drive effective mathematical learning. In this study, wellbeing is conceptualized not in a broad psychological sense, but in terms of students' educational wellbeing, notably reduced mathematics anxiety, enhanced feelings of competence, and increased confidence that emerge through motivation and engagement. Mobile learning apps have emerged as promising solutions, offering interactive experiences that can transform mathematical understanding through personalized, accessible learning environments.[3] Pakistan presents a compelling research context, with internet users projected to reach 116.0 million in 2025, representing 45.7% of the population.[4] This unique combination of significant mathematics learning challenges and growing mobile technology access creates an ideal setting for investigating mobile learning effectiveness in resource-constrained educational environments. However, realizing this potential requires addressing significant barriers, including technological limitations, economic constraints, cultural factors, and pedagogical challenges.[5,6]

Existing research suffers from geographical bias, with 85% of mobile learning studies originating from developed countries.[7,8] Furthermore, theoretical frameworks inadequately capture mobile learning's complexity by treating technology adoption and learning motivation as separate phenomena, while the moderating role of barriers remains unexplored. This study addresses these gaps by investigating three key research questions: (1) How does mobile learning app usage influence students' mathematics motivation and engagement among secondary school students in Pakistan? (2) To what extent do perceived barriers moderate these relationships? (3) What is the mediating role of students' mathematics motivation between app usage and engagement? This study uses both the Technology Acceptance Model (TAM) and Self-Determination Theory (SDT), and incorporates them into a barrier-moderated framework to offer a complete account of mobile learning effectiveness in resource-limited settings, providing both theoretical insights and practical guidance to inform educational stakeholders.

Literature review

Technology acceptance model (TAM)

The Technology Acceptance Model, developed by Davis[9], represents one of the most widely applied frameworks for understanding technology adoption in educational contexts. TAM proposes that technology acceptance is primarily determined by two factors: perceived usefulness (PU) and perceived ease of use (PEOU). These factors together influence behavioral intention to adopt new technologies.[10] Meta-analytical evidence confirms TAM's strong predictive validity in mobile learning contexts.[11]

In mathematics education, TAM has proven particularly relevant as students' perceptions of usefulness directly relate to mathematical self-efficacy and learning outcomes. However, TAM's focus on technological aspects while neglecting motivational factors crucial for sustained educational use represents a significant limitation.[12] Extended TAM models have successfully integrated motivational variables, enhancing their explanatory power in academic contexts.[13] Importantly, TAM's perceived usefulness aligns with SDT's competence satisfaction, while perceived ease of use supports autonomy needs, though TAM's adoption focus requires motivational theory to explain sustained engagement.

Mobile learning apps

Mobile learning apps offer structured, pedagogical experiences that differ from general mobile technologies. Research demonstrates significant effectiveness across mathematical domains, including algebra, geometry, and probability.[14-16] Gamified elements are particularly effective in STEM subjects for increasing engagement and motivation.[17] Apps enhance learning through collaborative features, adaptive difficulty algorithms, immediate feedback mechanisms, and progress visualization systems.[18]

The ubiquitous nature of mobile apps enables anytime, anywhere learning, while touch interfaces provide intuitive interaction modalities that are particularly suited to mathematical content manipulation.[8] However, mobile learning app research suffers from geographical bias toward developed countries, while research in resource-constrained environments remains limited.[19] In developing contexts, apps must address unique challenges, including limited connectivity, diverse device capabilities, and varying digital literacy levels. Most effectiveness studies suffer from duration limitations, with interventions lasting less than one month. This raises questions about sustained effectiveness beyond initial novelty effects. The educational impact of these technological features ultimately depends on their ability to satisfy the psychological needs that drive sustained learning motivation.

Mathematics motivation and self-determination theory

Mathematics motivation serves as the psychological catalyst that transforms technology access into active learning experiences.[20] SDT provides a comprehensive framework through three basic psychological needs: autonomy (feeling volitional), competence (feeling effective), and relatedness (feeling connected to others).[21] Research demonstrates that competence satisfaction most strongly predicts mathematics achievement, with autonomous motivation consistently outperforming controlled motivation in educational outcomes.[22]

Mobile learning apps can facilitate psychological need satisfaction through specific design features. Self-paced learning environments support autonomy needs, adaptive challenge algorithms enhance competence satisfaction through appropriately difficult tasks, and collaborative features address relatedness needs by connecting students with peers and mathematical communities.[23,24] However, SDT remains underutilized in mobile learning research, with limited validation in technology-enhanced mathematics contexts, despite its strong explanatory power for educational motivation.[25] SDT’s psychological needs are directly supported by TAM’s adoption factors: autonomy through ease of use, competence through perceived usefulness, and relatedness through collaborative features.

Mathematics engagement

Mathematics engagement represents the observable manifestation of motivation across three interconnected dimensions: behavioral (participation, persistence, and effort), emotional (enjoyment, interest, and reduced anxiety), and cognitive (deep learning strategies, metacognition, and self-regulation).[26] These dimensions operate synergistically, with emotionally connected students employing more sophisticated cognitive strategies and demonstrating greater persistence through mathematical challenges.

Mobile learning engagement differs from traditional classroom engagement through asynchronous behavioral patterns and individualized experiences. These features may enhance emotional engagement by providing personalized feedback and reducing social comparison anxiety. Mobile apps can enhance behavioral engagement through interactive content and progress tracking. They can improve emotional engagement through gamification elements and success experiences, and cognitive engagement through multiple problem-solving strategies and metacognitive support.[25,27] Student engagement in technology-mediated environments requires satisfaction of SDT’s three basic psychological needs for optimal development.[28]

Role of barriers as moderators

Traditional mobile learning research treats barriers as implementation obstacles rather than theoretical moderators of learning relationships. However, meta-analytical evidence reveals that contextual factors, including education level, region, and culture, systematically moderate mobile learning acceptance relationships.[7] This suggests barriers function as critical boundary conditions that determine when and how mobile learning achieves theoretical benefits rather than simply impeding access. Four barrier types systematically moderate mobile learning effectiveness: technological (connectivity, device limitations), economic (costs, affordability), cultural (family attitudes, gender restrictions), and pedagogical (teacher support, curriculum alignment). These barriers create complex interaction effects that may fundamentally alter technology-learning relationships by disrupting feedback loops that are essential for maintaining motivation and competence satisfaction.[29] The research indicates that the presence of epistemological, security, and social barriers influences the self-efficacy and locus of control of learners substantially implying that barriers have a psychological operation through which they impede the process of motivation that learners heavily rely on in engaging in prolonged performance.[30]

Theoretical integration

This paper fills these gaps by combining both TAM and SDT. TAM observes that early adoption of technology based on perceived usefulness and easy use, whereas SDT explains continued use based on satisfaction of psychological needs and motivational processes. The integration addresses critical gaps: TAM's adoption focus provides insufficient explanation for sustained educational technology use, while SDT's motivational focus lacks consideration of initial technology acceptance factors. Although studies have separately related SDT to information technology and TAM to educational contexts, research investigating mobile learning effectiveness using integrated TAM-SDT frameworks in mathematics education remains limited.[13,31] This integration is particularly decisive in developing contexts where both technology adoption and sustained motivation face significant challenges due to contextual barriers.

Hypothesis development

Based on the theoretical foundations and empirical evidence presented, this study proposes an integrated TAM-SDT framework with barrier moderation to address identified research gaps.

Direct effects

The established relationships between technology acceptance, psychological need satisfaction, and educational outcomes provide the foundation for three direct-effect hypotheses:

H1: Mobile learning app usage positively influences students' mathematics motivation.

H2: Mobile learning app usage positively influences students' mathematics engagement.

H3: Mathematics motivation positively influences students' mathematics engagement.

These relationships reflect the theoretical integration where TAM's perceived usefulness and ease of use facilitate initial app adoption, while SDT's psychological need satisfaction mechanisms (autonomy, competence, relatedness) explain motivational development. The established three-dimensional engagement framework (behavioral, emotional, and cognitive) provides the outcome structure, with motivation serving as the psychological catalyst that transforms technology interaction into sustained learning engagement.

Moderation effects

The barrier literature establishes contextual factors as critical boundary conditions rather than simple obstacles, which leads to two moderation hypotheses:

H4: Barriers negatively moderate the relationship between mobile app usage and students' mathematics motivation.

H5: Barriers negatively moderate the relationship between mobile app usage and students' mathematics engagement.

These hypotheses extend Baron and Kenny's[32] moderation framework to developing educational

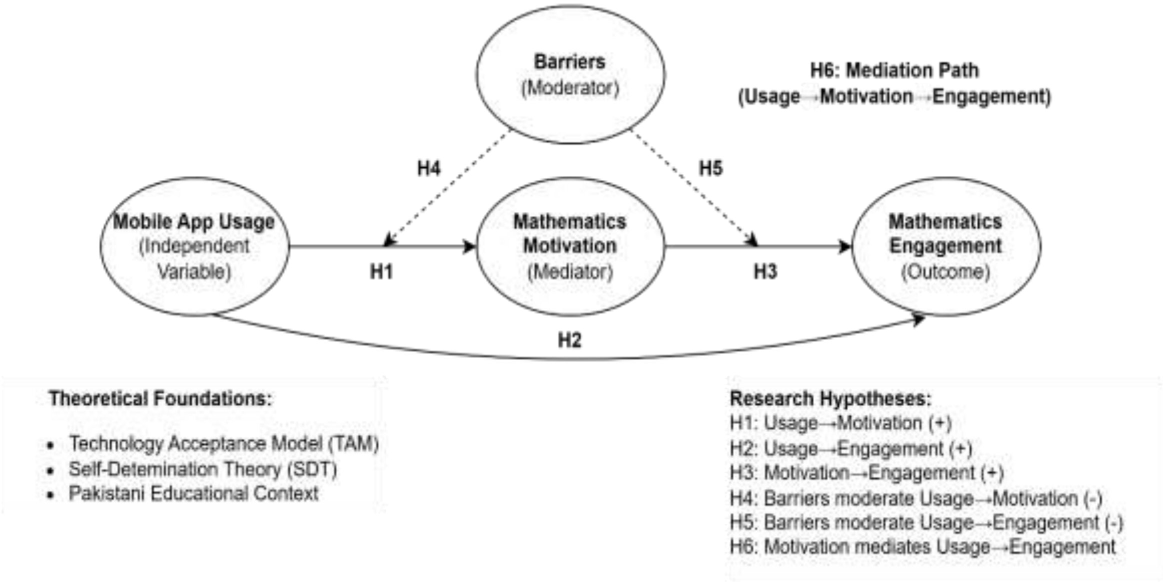

Figure 1: Integrated TAM-SDT framework with barrier moderation (researcher framework)

contexts, where barriers may disrupt psychological mechanisms essential for sustained motivation and engagement.

Mediation effect

The theoretical integration and SDT literature support a mediation relationship:
H6: Mathematics motivation mediates the relationship between mobile app usage and students' mathematics engagement.

This hypothesis reflects SDT's proposition that environmental factors influence behaviors through motivational processes. While apps may directly influence certain engagement behaviors, their primary impact occurs through the satisfaction of psychological needs, leading to increased intrinsic motivation.

Methods

Research design and participants

This study examined relationships between mobile learning app usage, students' mathematics motivation, engagement, and perceived barriers among secondary school students in Pakistan. Following Churchill's[33] and DeVellis's[34] scale development guidelines to ensure psychometric rigor when adapting existing scales to new contexts, instruments underwent expert review by three education technology researchers and two mathematics education specialists.

Due to practical constraints of school access and institutional permissions in the Pakistani educational system, particularly for girls' schools, this study employed convenience sampling. Schools were selected based on accessibility and willingness to participate, with 15 secondary schools from Sahiwal District ultimately agreeing to participate in the research. A total of 343 students from 15 secondary schools in Sahiwal district participated in the study. The students were in grades 9-10 (ages 14-17), with balanced representation: 56% male, 44% female, 45% from urban schools, and 55% rural schools. Smartphone access varied: 38% always, 41% sometimes, 15% often, and 6% rarely (see Table 1). This final sample size exceeds all recommended thresholds: (1) power analysis requirement of minimum 300 for medium effect sizes ($f^2 = 0.15$) in moderation analysis with 80% power;[35] (2) PLS-SEM requirement of 10 times the most significant number of formative indicators,[36] requiring minimum 120; and (3) Westland's[37] algorithm for SEM indicating minimum 250 for our model complexity. While this sampling approach

Table 1: Demographic information

Demographic characteristic		%
Student Gender	Male	56
	Female	44
Age	14 to 15 years	60
	16 to 17 years	40
Grade	Grade 9	52
	Grade 10	48
School location	Urban	45
	Rural/Village Area	55
Smartphone access	Always	38
	Sometimes	41
	Often	15
	Rarely	6

facilitated data collection in a challenging research environment, it limits the generalizability of findings beyond similar rural Pakistani contexts. The findings should be interpreted with caution when extending to urban areas or other developing country contexts with different technological and cultural characteristics. As such, the reliance on convenience sampling should be considered an important limitation of the study.

Instrument development

All constructs used 5-point Likert scales, ranging from 1 (strongly disagree) to 5 (strongly agree). Mobile Learning App Usage (6 items): Adapted from Davis[9] and Venkatesh[38], measuring frequency, dependence, integration, help-seeking, preference, and habitual use in mathematics learning contexts. Mathematics Motivation (8 items): Adapted from Ryan's[39] Intrinsic Motivation Inventory, capturing enjoyment, perceived competence, autonomy, and value/utility dimensions specific to mobile mathematics learning. Mathematics Engagement (8 items): Adapted from Appleton *et al*.[40] and Wang *et al*.[27], measuring behavioral, emotional, and cognitive engagement with mathematics through mobile apps. Perceived Barriers (12 items): Developed based on TAM literature and Pakistan-specific studies, covering four dimensions: technological (device access, connectivity), economic (data costs, affordability), cultural (family restrictions, gender limitations), and pedagogical (teacher support, curriculum alignment) barriers. To ensure cultural appropriateness, all items were reviewed by local education experts to verify linguistic and contextual relevance before translation. Questionnaires were developed bilingually (English/Urdu) using back-translation procedures.[41] Pilot testing with 30 students confirmed clarity and reliability before main data collection.

Data collection and analysis

A total of 390 questionnaires were distributed in the selected schools. Out of these, 350 questionnaires were returned, yielding a response rate of 89.7%. After screening for incomplete responses and data quality issues, 343 questionnaires were deemed suitable for analysis, yielding a usable response rate of 88.0%.

Following the methodological recommendations of Podsakoff et al.[42] and Kock[43], we implemented multiple approaches to assess and mitigate common method bias (CMB). First, we executed Harman's single factor test using SPSS by entering all principal constructs into an unrotated principal component analysis This analysis revealed a solution having six factors that explain 70.09% of total variance, and the first factor explained variance at 32.76%, which is well below the 50% level that is considered problematic for CMB. Second, we conducted Kock's[43] full collinearity assessment using the variance inflation factor (VIF) analysis. VIF values above 3.3 indicate pathological collinearity and potential CMB contamination. Our PLS algorithm analysis revealed VIF values ranging from 1.646 to 3.291 across all measurement items, with all values remaining below the critical threshold of 3.3, indicating no significant CMB issues. Third, examination of the inter-correlation matrix showed no correlations exceeding 0.90, with the highest correlation at 0.751, further confirming the absence of severe multicollinearity. Additionally, procedural remedies were implemented, including psychological separation through varied question formats and anonymous data collection with assurances of confidentiality. These comprehensive assessments provide strong evidence that CMB does not significantly impede the validity of our findings. We conducted descriptive statistics and reliability analysis of the collected data using SPSS version 21.0 and evaluated the demographic profile of the sample and internal consistency of constructs. We then employed PLS-SEM using SmartPLS 4.0 software to analyze our research model. Consistent with the suggested two-stage approach to SEM analysis, the measurement model was tested initially, followed by the testing of the structural model.[36] PLS-SEM was selected for this study because of its efficiency in complex model handling, prediction focus, and non-normal data accommodation suitable when the objective is prediction and theory development rather than theory confirmation in the context of a developing country.

Ethical approval

This study received ethical approval from the District Education Office of Sahiwal, Pakistan (Date: January 14, 2025, Approval No: 218/G). Following approval, the researchers visited participating schools individually, presented the approval letter to school principals, and provided copies for institutional records. Data collection proceeded only after obtaining written permission from school administrators. Written informed consent was obtained from the parents or legal guardians of all participating students, and student assent was secured after explaining the research purpose, the voluntary nature of participation, confidentiality measures, and the right to withdraw without penalty. All data were anonymized and stored securely in compliance with data protection standards.

Results

Measurement model

At first, the measurement model was assessed for convergent validity (see Appendix A). This was calculated using factor loadings, Variance Inflation Factor (VIF) values, Composite Reliability (CR), Cronbach's alpha, and Average Variance Extracted (AVE). Table 2 indicates that all the loadings of the items exceeded the recommended measurement cut-off of 0.6 suggested by Chin.[44] In addition, the range of the estimates of composite reliability, which is actually the extent to which the indicator variables reflect the latent construct, exceeded the recommended level (0.70). Cronbach alpha value also meets the standard criteria of 0.70, while mean variance extracted (0.60) was higher than the suggested amount of 0.5, and as such, the indicators accounted for a significant proportion of the variance of the latent construct.[36]

These results confirm that the measurement model is both reliable and valid, indicating that the constructs consistently capture students' mathematics motivation, engagement, and barriers. In practical terms, this means the instruments used provide dependable insights into students' learning experiences. This was followed by an assessment of discriminant validity, which describes how dissimilar constructs are measured. Table 3 indicates that the diagonal values representing the square root of AVE (of each construct) have higher values compared to their corresponding correlation coefficients thus satisfying discriminant validity criteria.[45]

To address recent criticism of traditional discriminant validity assessment, we conducted heterotrait-monotrait (HTMT) ratio analysis following Henseler et al.[46] recommendations. This approach offers improved detection of discriminant validity issues compared to the conventional Fornell-Larcker criterion. Using the conservative 0.85 threshold,[47] all HTMT values in our study fell below this criterion (see Table 4), indicating satisfactory discriminant validity between constructs.

Structural model

To assess the structural model, Hair et al.[36] recommended considering the R^2, beta, and their t-values through the bootstrapping process at a resample of 5000 (see Appendix B). First, we assessed the direct relationship between the targeted variables. As given in Table 5, mobile learning app usage positively influences students' mathematics motivation ($\beta = 0.557$; $t = 15.696$; $p < 0.001$) and students' mathematics engagement ($\beta = 0.283$; $t = 6.559$; $p < 0.001$). In addition, students' mathematics motivation also positively influenced students' mathematics engagement ($\beta = 0.525$; t =

Table 2: Validity and reliability for constructs

Constructs	Items	Loadings	VIF	Cronbach's α	AVE	CR
Mobile Learning App Usage	MA1	0.816	2.118	**0.885**	**0.636**	**0.913**
	MA2	0.803	2.046			
	MA3	0.796	1.940			
	MA4	0.791	1.926			
	MA5	0.797	1.921			
	MA6	0.781	1.895			
Students' Mathematics Motivation	SM1	0.714	1.665	**0.888**	**0.560**	**0.910**
	SM2	0.763	1.863			
	SM3	0.712	1.646			
	SM4	0.760	1.848			
	SM5	0.748	1.787			
	SM6	0.772	1.869			
	SM7	0.766	1.894			
	SM8	0.748	1.763			
Students' Mathematics Engagement	SE1	0.813	2.348	**0.919**	**0.640**	**0.934**
	SE2	0.782	2.069			
	SE3	0.816	2.371			
	SE4	0.807	2.311			
	SE5	0.794	2.147			
	SE6	0.792	2.147			
	SE7	0.805	2.216			
	SE8	0.787	2.163			
Perceived Barriers	B1	0.896	3.291	**0.972**	**0.611**	**0.974**
	B2	0.751	3.117			
	B3	0.779	3.291			
	B4	0.618	3.287			
	B5	0.752	3.054			
	B6	0.874	3.201			
	B7	0.844	3.156			
	B8	0.798	3.273			
	B9	0.819	3.098			
	B10	0.759	3.248			
	B11	0.755	3.156			
	B12	0.696	3.137			

Table 3: Discriminant validity

Constructs	1	2	3	4
Mobile App Usage	**0.797**	0.646	0.654	-0.192
Students' Mathematics Motivation	0.646	**0.748**	0.746	-0.124
Students' Mathematics Engagement	0.654	0.746	**0.800**	0.099
Perceived Barriers	-0.192	-0.124	-0.099	**0.782**

Table 4: Heterotrait-monotrait (HTMT)

Constructs	1	2	3	4
Mobile App Usage	1.000	0.726	0.723	0.135
Students' Mathematics Motivation	0.726	1.000	0.824	0.056
Students' Mathematics Engagement	0.723	0.824	1.000	0.047
Perceived Barriers	0.135	0.056	0.047	1.000

Note: An empty box is used as a standard reporting method of the HTMT procedure

Table 5: Structural estimates (hypothesis testing)

Hypotheses	Path	Beta	SD	T Value	2.5%	97.5%	P Value	Decision
Direct Effects								
H1	MA → SM	0.557	0.035	15.696	0.484	0.624	0.000	Supported
H2	MA → SE	0.283	0.043	6.559	0.204	0.372	0.000	Supported
H3	SM → SE	0.525	0.040	13.202	0.442	0.596	0.000	Supported
Moderation Effects								
H4	B × MA → SM	-0.125	0.040	3.164	-0.229	-0.079	0.002	Supported
H5	B × MA → SE	-0.052	0.026	1.995	-0.097	-0.010	0.046	Supported
Mediation Effect								
H6	MA → SM → SE	0.292	0.030	9.727	0.232	0.351	0.000	Supported (Partial mediation analysis)

*Notes: *MA = Mobile App Usage; SM = Student Mathematics Motivation; SE = Student Mathematics Engagement; B = Perceived Barriers*

Table 6: Structural model results

Constructs	R^2	Q^2	SRMR	NFI
Mobile Learning App Usage	–	–	–	–
Students' Mathematics Motivation	0.460	0.226	–	–
Students' Mathematics Engagement	0.616	0.315	0.071	0.915
Perceived Barriers	–	–	–	–

13.202; $p < 0.001$). Therefore, H1, H2, and H3 were supported (See Table 5). Moreover, barriers moderated the relationships between mobile learning app usage and students' mathematics motivation ($\beta = -0.125$; $t = 3.164$; $p < 0.01$) as well as between mobile learning app usage and students' mathematics engagement ($\beta = -0.052$; $t = 1.995$; $p < 0.05$). Therefore, H4 and H5 were also supported. We then assessed the coefficient of determination (R^2). The R^2 values of 0.460 for students' mathematics motivation and 0.616 for students' mathematics engagement indicate that the model demonstrates substantial explanatory power. These values exceed Cohen's[48] guidelines for substantial effect sizes in behavioral research. Model fit was assessed using the standardized root mean square residual (SRMR) and normed fit index (NFI). The SRMR value of 0.071 is below the threshold of 0.08, and the NFI value of 0.915 exceeds 0.90, indicating good model fit.[49] (see Table 6).

Beyond statistical significance, these coefficients suggest meaningful improvements in practice. For example, the strong path coefficient between mobile app usage and mathematics motivation ($\beta = 0.557$) indicates that students who use mobile learning apps are substantially more motivated, which may also translate into greater confidence and persistence in mathematics tasks. Similarly, the positive effect of motivation on engagement ($\beta = 0.525$) highlights that motivated students are not only more likely to participate but also to sustain their effort and enjoyment, reflecting real-world educational benefits. These coefficients, while statistically significant, also carry practical meaning: stronger mobile app usage corresponds to noticeable gains in students' confidence and persistence in mathematics tasks, which reflects both improved engagement and wellbeing.

Mediation analysis

Following Zhao et al.[50], we examined the mediation effect of students' mathematics motivation on the relationship between mobile learning app usage and students' mathematics engagement. The indirect effect was significant ($\beta = 0.292$, $t = 9.727$, $p < 0.001$), with a 95% confidence interval [0.232, 0.351] that does not cross zero, as shown in Table 5. The direct effect remained significant in the presence of the mediator, indicating partial mediation. The variance accounted for (VAF) was calculated as 50.8%, confirming partial mediation and supporting H6.

Discussion

The findings of this study offer compelling evidence that mobile learning apps have the potential to serve as powerful tools for enhancing students' mathematics motivation and engagement among secondary school students in underprivileged regions of Pakistan, provided that implementation barriers are systematically addressed. By integrating the TAM and SDT, we have developed a comprehensive framework that explains not only the adoption of mobile learning technologies but also their psychological influence on students in resource-constrained environments. The significant positive relationships between mobile app usage and both students' mathematics motivation ($\beta = 0.557$) and engagement ($\beta = 0.283$) validate our theoretical proposition that well-designed digital tools can satisfy fundamental psychological needs while overcoming traditional barriers to mathematics learning.[21,23,51] These improvements in motivation and engagement are not only academic in nature but also psychological, as they are associated with reduced mathematics anxiety and enhanced competence, both important aspects of students' wellbeing.

Our analysis identifies that the effectiveness of mobile learning apps works through multiple mechanisms. At the most fundamental level, these tools provide accessible, interactive content that aligns with TAM's core constructs of perceived usefulness and ease of use. However, the stronger relationship with motivation suggests that their actual value lies in their ability to foster intrinsic motivation by supporting autonomy (through self-paced learning), competence (through adaptive challenges), and relatedness (through collaborative features). This finding extends SDT's application to digital learning environments in developing countries, demonstrating that even in contexts with significant infrastructural challenges, technology can still fulfill basic psychological needs when properly implemented.[24,52]

The moderating role of perceived barriers provides critical insights for both theory and practice. Rather than mobile learning simply overcoming traditional educational barriers, our results demonstrate that barriers significantly disrupt the psychological mechanisms through which mobile learning influences outcomes. The stronger adverse moderation effect on motivation ($\beta = -0.125$) compared to engagement ($\beta = -0.052$) suggests that barriers particularly undermine the need-satisfying qualities of technology that are essential for sustained motivation.[32] This finding indicates that the mere provision of mobile learning technology is insufficient; effectiveness requires systematic attention to removing technological, economic, cultural, and pedagogical constraints that may prevent students from fully benefiting from these tools.[53]

Our mediation analysis provides additional nuance, showing that students' mathematics motivation explains approximately half of the impact of mobile learning on engagement (VAF = 50.8%). This partial mediation indicates that although apps directly facilitate certain engagement behaviors (e.g., time spent practicing problems), their most powerful effects emerge through the motivational pathways described by SDT. This has important implications for app design, suggesting that features supporting psychological needs may be as crucial as content delivery mechanisms for achieving meaningful learning outcomes.[54]

The study makes several theoretical contributions. First, it bridges the gap between adoption-focused models like TAM and learning-focused theories like SDT, providing a more comprehensive framework for understanding educational technology effectiveness. Second, it extends moderation theory to educational technology contexts, demonstrating how barriers fundamentally alter the relationships between technology use and learning outcomes. Third, it contributes to mathematics education research by identifying specific mechanisms through which technology can address the motivational challenges that often hinder mathematics learning in developing countries.

Implications for policy and practice

The findings have important implications for educational stakeholders in resource-constrained environments. Policymakers should recognize that mobile learning interventions require comprehensive support systems beyond providing devices or apps, as our barrier moderation findings demonstrate that benefits are conditional rather than automatic. Technological solutions must account for limited connectivity through offline capabilities, while economic interventions might include subsidized data plans or low-cost devices. Cultural barriers require engagement with families and communities, particularly for female students.[55,56] Pedagogical integration demands teacher training and curriculum alignment to ensure apps complement rather than compete with classroom instruction.[57] For app developers, designing for psychological need satisfaction may be as crucial as technical features. We recommend collaborative efforts among policymakers, educators, and developers to create interventions that are not merely accessible but actually effective in improving students' mathematics motivation and engagement.

Strengths and limitations

This study has several notable strengths, including the integration of TAM and SDT within a barrier-moderated framework, valuable evidence from Pakistan, where mobile learning research has been limited, the PLS-SEM methodology allowing for the simultaneous testing of relationships, and an adequate sample size (n = 343). However, limitations should be acknowledged. The cross-sectional design prevents the establishment of causality, as pre-existing motivated students may be more likely to engage with apps. Convenience sampling from the Sahiwal District limits generalizability. Self-report measures may introduce bias, though CMB assessments indicated minimal concern. The study did not examine specific app features. Future research should employ experimental designs, longitudinal approaches, and cross-contextual examinations to establish causality and generalizability

Conclusion

This study provides comprehensive evidence for the effectiveness of mobile learning apps in enhancing students' mathematics motivation and engagement among secondary students in Pakistan. The integration of TAM and SDT offers a comprehensive theoretical framework for understanding both technology adoption and learning effectiveness in developing educational contexts, particularly for mathematics education, where motivational challenges are prevalent. The significant positive effects of mobile learning app usage on student outcomes, combined with the essential moderating role of perceived barriers, highlight both the potential and challenges of mobile learning implementation. In particular, the moderating role of barriers requires continuous attention, as it fundamentally shapes how mobile learning influences student motivation and engagement in developing contexts. The findings suggest that while mobile learning can significantly improve mathematics education, realizing its full potential requires systematic attention to contextual constraints that may undermine effectiveness. As educational systems worldwide increasingly embrace digital transformation, understanding these relationships becomes essential for ensuring equitable and effective learning opportunities. Although the study primarily focused on motivation and engagement, the findings indirectly support students' wellbeing by showing how mobile learning can help reduce anxiety, foster confidence, and build a stronger sense of competence in mathematics. Our findings offer both theoretical insights and practical guidance for stakeholders seeking to leverage mobile technology for improving mathematics education in resource-constrained environments. The study's contribution extends beyond the Pakistani context, offering insights applicable to similar developing educational settings worldwide. As the global community works toward achieving Sustainable Development Goal 4 (Quality Education), evidence-based understanding of mobile learning effectiveness becomes increasingly critical for educational policy and practice.

Contribution of authors

MSR and KN conceived the study and designed the research methodology. MSR collected the data. MSR, KN, DW, and FA conducted the data analysis and interpreted the findings. MSR and KN drafted the original manuscript, and MSR, KN, DW, and FA critically reviewed and revised it. All authors approved the final version.

Conflict of interests

The authors declare no conflicts of interest related to the research, authorship, or publication of this article. This research received no funding from public, commercial, or not-for-profit sectors.

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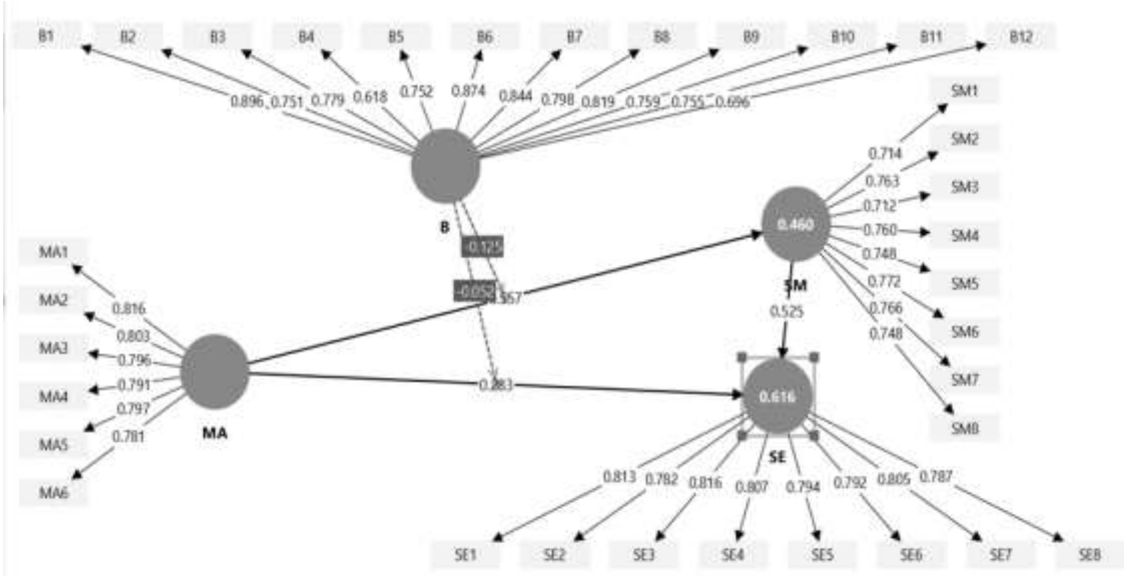
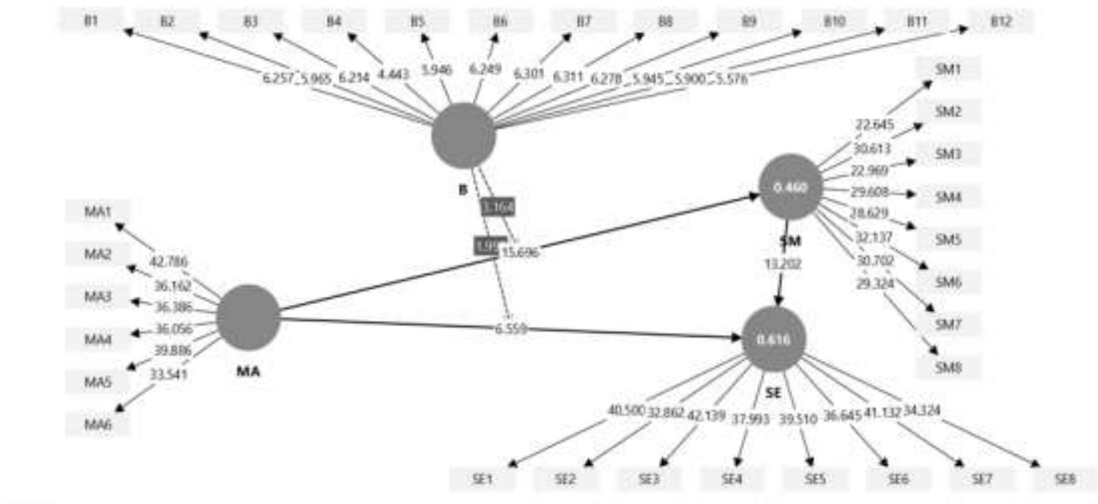
Appendix



Appendix A: Measurement model: Factor loadings, VIF values, composite reliability (CR), Cronbach's α, and average variance extracted (AVE) for all constructs



Appendix B: Standardized path coefficients (β) and t-values from the bootstrapping procedure (5,000 resamples) illustrating direct, moderation, and mediation effects