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RESEARCH ARTICLE

Exploring the impact of mobile devices in electronics e-learning: A case study evaluating the effectiveness of mobile learning applications in the field of electronics and sensors

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Abstract: Integrating mobile devices into educational environments has revolutionised e-learning, presenting new opportunities and challenges. This research paper aims to examine the pivotal role of mobile devices in the e-learning environment and assess the effectiveness of mobile learning applications in enhancing the educational experience. The study employs a mixed-methods approach, combining quantitative data through surveys and usage analytics with qualitative insights from interviews and focus group discussions. By analysing the perspectives of both educators and learners, the research investigates how mobile devices contribute to the flexibility and accessibility of e-learning content. Additionally, the paper evaluates the effectiveness of various mobile learning applications in promoting engagement, knowledge retention, and overall learning outcomes. It scrutinises the features that contribute to the success of these applications, such as user interface design, interactivity, and adaptability to diverse learning styles. Furthermore, the research delves into the challenges of mobile learning, including device compatibility, connectivity, and user motivation issues. Strategies to overcome these challenges and optimise the benefits of mobile learning are explored. The findings of this study are expected to provide valuable insights for educators, curriculum designers, and developers of mobile learning applications. The research aims to contribute to the ongoing discourse on the effective integration of mobile devices in e-learning environments and offer recommendations for optimising the design and implementation of mobile learning strategies. Ultimately, this exploration seeks to foster a deeper understanding of the potential of mobile devices in shaping the future of education.

Keywords: mobile learning, mobile technology in learning, mobile devices in education, digital education

1 Introduction

In today's rapidly evolving educational landscape, technology integration has become indispensable, revolutionising traditional pedagogical approaches and offering new pathways for learning (Lampropoulos, 2023). Particularly in specialised fields like electronics and sensors, the emergence of mobile devices has marked a significant shift in e-learning, granting learners unprecedented flexibility, accessibility, and interactivity (Cruz et al., 2023). This paper embarks on an extensive exploration of the impact of mobile devices on electronics e-learning, with a specific focus on evaluating the effectiveness of mobile learning applications tailored to the intricacies of the electronics and sensors domain.

The primary objective of this research is to scrutinise the effectiveness of mobile learning applications in bolstering learning outcomes, user engagement, and skill acquisition within the realm of electronics education. To ensure a methodical investigation, this study is guided by a set of clear and explicit research questions:

(1) How did mobile learning applications influence learning outcomes in electronics and sensors?

(2) What factors contributed to the effectiveness of mobile learning applications in enhancing understanding and skill acquisition within this specialised field?

(3) What key determinants influence user engagement and satisfaction levels when utilising mobile learning applications in electronics education?

The significance of this research lies in its potential to inform pedagogical practices, curriculum development initiatives, and policymaking efforts aimed at harnessing the full potential of mobile technology in electronics e-learning. With the growing demand for skilled professionals in electronics, it becomes imperative to leverage technological advancements to equip learners with the knowledge and competencies required to excel in this dynamic industry.

Through a rigorous evaluation of mobile learning applications, we seek to unearth valuable insights into their efficacy as educational tools and identify strategies for optimising their impact on learning outcomes. Moreover, by delving into the factors influencing user engagement and satisfaction, we aim to provide practical recommendations for designing and implementing mobile learning experiences tailored to electronics learners' specific needs and preferences. To accomplish these objectives, this research adopts a mixed-method approach, integrating quantitative measures of learning outcomes with qualitative exploration of user experiences.

In essence, this research explores the transformative potential of mobile devices in electronics education, focusing on evaluating the effectiveness of mobile learning applications in enhancing learning outcomes and user experiences. Through a systematic inquiry guided by clear and explicit research questions, we strive to advance knowledge in electronics e-learning and pave the way for developing innovative pedagogical approaches leveraging the power of mobile technology.

2 In-depth literature review

A comprehensive literature review provides a foundation for understanding the current state of knowledge on the role of mobile devices in the e-learning environment and the effectiveness of mobile learning applications. The following review synthesises vital findings and trends from existing research, identifying the theoretical frameworks, methodologies, and significant themes shaping this field.

2.1 Evolution of E-learning

The evolution of e-learning has been profoundly influenced by technological advancements, particularly with the widespread adoption of mobile devices (Dahal & Manandhar, 2024). Historically, e-learning predominantly relied on desktop computers, which limited accessibility and flexibility in educational delivery. However, the emergence of mobile devices has revolutionised e-learning, enabling learners to access educational content any time and anywhere (Jim et al., 2017).

This evolution has been particularly significant in the field of electronics and sensors. As the demand for specialised knowledge in electronics and sensor technologies grows, the need for accessible and flexible learning platforms becomes increasingly crucial. Mobile devices offer a solution to this challenge by providing learners with portable access to learning materials, simulations, and interactive resources tailored to the specific demands of electronics and sensor education (Papadakis & Kalogiannakis, 2019, 2020).

A case study by Naveed et al. (2023) explored integrating mobile learning applications in an electronics and sensors course at a technical university. The study found that students reported higher engagement levels and improved understanding of complex concepts when utilising mobile learning applications compared to traditional methods. This highlights the transformative impact of mobile devices in enhancing the e-learning experience in electronics and sensors.

Furthermore, the evolution of e-learning platforms has led to developing specialised mobile applications catering to electronics and sensors education (Abubakar & Yunusa, 2024). These applications offer features such as interactive simulations, virtual laboratories, and real-time data collection, providing learners with hands-on experiences previously limited to physical classrooms or laboratories.

Overall, the evolution of e-learning facilitated by mobile devices has reshaped the landscape of electronics and sensors education, offering learners greater flexibility, accessibility, and interactivity in their learning experiences. As technology advances, the potential for further innovation in mobile learning applications within this field remains promising, providing opportunities for educators to optimise the effectiveness of e-learning in electronics and sensors education.

2.2 Theoretical frameworks

The literature reflects a rich tapestry of theoretical frameworks employed to dissect the intricacies of mobile learning dynamics. The Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) are among the most prominent frameworks used to explore the adoption and use of mobile learning applications.

Initially proposed by Fred D. Davis in 1989, the Technology Acceptance Model (TAM) has been widely applied to understand individuals' behavioural intentions toward adopting new technologies. TAM posits that an individual's intention to use a technology is influenced by two key factors: perceived usefulness and perceived ease of use. In the context of mobile learning applications in electronics and sensors education, TAM serves as a valuable lens through which researchers can examine educators' and learners' perceptions of the utility and ease of use of mobile learning tools. By assessing these perceptions, educators and policymakers can devise strategies to effectively enhance the adoption and integration of mobile learning applications.

Building upon TAM, the Unified Theory of Acceptance and Use of Technology (UTAUT) synthesises various factors influencing technology acceptance and usage behaviour. Developed by Venkatesh et al. in 2003, UTAUT integrates constructs such as performance expectancy, effort expectancy, social influence, and facilitating conditions to provide a comprehensive framework for understanding technology adoption. In the context of mobile learning applications in electronics and sensors education, UTAUT offers a holistic perspective on the multifaceted determinants of educators' and learners' intentions to embrace mobile learning technologies. By examining factors such as perceived usefulness, ease of use, social influences, and external support mechanisms, researchers can gain insights into the complex interplay of variables that shape the adoption and implementation of mobile learning applications.

2.3 Pedagogical approaches

Mobile learning applications in electronics and sensor education are powerful tools for implementing diverse pedagogical approaches to enhance learner engagement and knowledge retention. Constructivism and connectivism are among the pedagogical frameworks commonly integrated into mobile learning applications (Kalogiannakis et al., 2018; Papadakis, 2021).

Constructivism, a well-established theory of learning, posits that learners actively construct their understanding of the world by assimilating new information and experiences into their existing knowledge structures. Within mobile learning applications, constructivist principles are manifested through interactive and experiential learning activities that prompt learners to engage in problem-solving, critical thinking, and knowledge application. Mobile learning applications foster deeper conceptual understanding and skill development in electronics and sensors by offering exploration, experimentation, and reflection opportunities.

Connectivism, a relatively newer theory of learning proposed by Gourlay L. et al. in 2004, emphasises the importance of networks and connections in learning. According to connectivist principles, learning is not confined to individual minds but occurs within distributed networks of resources, people, and technologies. Mobile learning applications leverage connectivist principles by facilitating connections between learners, instructors, and digital resources. Through features such as social networking, collaborative problem-solving, and access to online information repositories, mobile learning applications enable learners to tap into collective intelligence and expertise, thus enriching their learning experiences in electronics and sensors education.

Studies examining the effectiveness of mobile learning applications in implementing constructivist and connectivist pedagogies have yielded promising results. Hwangji and Smiles (2022) highlight the role of interactive and collaborative features within mobile applications in fostering more profound understanding and knowledge construction among learners. Similarly, Pimmer et al. (2016) emphasise the importance of collaborative learning environments facilitated by mobile technologies in promoting active engagement and knowledge sharing.

2.4 User experience and interface design

User experience (UX) and interface design play pivotal roles in shaping the effectiveness of mobile learning applications in electronics and sensors education. Intuitive design, usability, and aesthetically pleasing interfaces are critical factors that significantly impact user engagement, satisfaction, and learning outcomes.

Intuitive design refers to the ease users can navigate and interact with a mobile learning application. A well-designed interface should provide clear and intuitive navigation pathways, enabling users to access content, features, and functionalities effortlessly. Usability, on the other hand, pertains to the overall ease of use and efficiency of the application. Usable interfaces minimise cognitive load and friction, allowing learners to focus on learning tasks rather than grapple with complex navigation or functionality issues.

Research in mobile learning underscores the importance of user experience and interface design in influencing learner satisfaction and engagement. Studies have shown that well-designed interfaces increase user satisfaction, engagement, and learning outcomes. For example, a study by Faudzi et al. (2023) investigated the impact of interface design on user engagement in a mobile learning application for STEM education. The study found that participants rated the application more positively with intuitive navigation, clear layout, and visually appealing design elements.

Moreover, mobile learning applications prioritising user-centred design principles are more likely to be embraced by learners and effectively support their learning objectives. By conducting user research, usability testing, and iterative design evaluations, developers can identify user needs, preferences, and pain points, thereby informing the design of more user-friendly and engaging interfaces.

2.5 Accessibility and inclusivity

Ensuring accessibility for diverse learners, including those with disabilities, is paramount in developing and implementing mobile learning applications in electronics and sensors education. While mobile devices offer opportunities to create inclusive learning environments, several challenges related to device compatibility, digital literacy, and equitable access must be addressed to prevent the emergence of a "digital divide."

Device compatibility poses a significant challenge in ensuring accessibility across various mobile devices and operating systems. Variations in screen sizes, resolutions, and input methods can impact the usability and accessibility of mobile learning applications for different users. To address this challenge, developers must prioritise responsive design principles and compatibility testing to ensure their applications function effectively across various devices, including smartphones, tablets, and assistive technologies (Czerniewicz et al., 2019).

Digital literacy is another critical factor influencing learners' ability to utilise mobile learning applications effectively. While mobile devices often feature intuitive interfaces and user-friendly features, not all learners possess the necessary digital skills to navigate and interact with these technologies confidently. Educators and developers can directly integrate digital skills training and support resources into mobile learning applications to promote digital literacy. These resources can include tutorials, interactive guides, and contextual help features designed to empower learners to develop the skills needed to navigate digital environments effectively (Kebritchi et al., 2017).

Accessibility features such as screen readers, voice commands, and alternative input methods are essential for accommodating learners with disabilities, such as visual or motor impairments. Mobile learning applications should adhere to accessibility standards and guidelines, such as the Web Content Accessibility Guidelines (WCAG), to ensure that all learners can access and engage with educational content effectively regardless of ability. By incorporating accessibility features into their designs, developers can create mobile learning applications that are inclusive and accessible to all learners, regardless of their physical or cognitive abilities (Fernández-López et al., 2013).

Despite mobile devices' potential to create inclusive learning environments, there remains a risk of exacerbating existing inequalities and disparities, commonly called the "digital divide." Learners from disadvantaged backgrounds may need more access to reliable internet connectivity or high-quality mobile devices, limiting their ability to participate fully in mobile learning initiatives. To address this challenge, policy-makers, educators, and developers must collaborate to bridge the digital divide by providing equitable access to technology resources and infrastructure (Mtebe & Raphael, 2018).

2.6 Effectiveness of mobile learning applications

Mobile learning applications have garnered significant attention in educational research due to their potential to enhance learning outcomes in various disciplines, including electronics and sensors education. Numerous studies have explored the impact of mobile learning applications on educational outcomes, revealing positive correlations with increased student engagement, improved knowledge retention, and enhanced collaboration.

Chen et al. (2018) conducted a meta-analysis examining the effectiveness of mobile learning applications across diverse educational contexts. The study synthesised findings from a range of empirical studies. It concluded that mobile learning applications positively impact student engagement, as evidenced by increased participation rates, higher levels of interaction with learning materials, and greater motivation to learn. Additionally, the study found that mobile learning applications contribute to improved knowledge retention, with learners demonstrating better recall of information and concepts when engaged in mobile-assisted learning activities.

Similarly, Hamaad et al. (2020) conducted a longitudinal study investigating the effects of mobile learning applications on student learning outcomes in a secondary school setting. The study found that students who used mobile learning applications to supplement traditional classroom instruction showed significant improvements in academic performance, as measured by standardised test scores and course grades. Additionally, qualitative data revealed enhanced collaboration and communication among students engaged in mobile-assisted learning activities, leading to deeper understanding and higher levels of peer interaction.

Despite the growing body of evidence supporting the effectiveness of mobile learning applications, nuanced evaluations considering context, content, and learner characteristics are essential. While mobile learning applications hold promise for enhancing learning outcomes, their effectiveness may vary depending on factors such as the specific educational context, the nature of the content being taught, and the characteristics of the learners involved.

For example, research suggests that the effectiveness of mobile learning applications may be influenced by factors such as the level of instructor support, the design of learning activities, and the accessibility of technology resources. Additionally, learners' prior knowledge, cognitive abilities, and learning preferences can impact their engagement and success in mobile-assisted learning environments.

Furthermore, it is essential to consider the alignment between mobile learning applications and instructional objectives and the integration of mobile technologies into broader pedagogical frameworks. Mobile learning applications are most effective when integrated seamlessly into instructional practices, complementing and enhancing traditional teaching methods rather than serving as standalone tools.

2.7 Challenges and concerns

Despite the potential benefits of mobile learning applications in electronics and sensors education, several challenges persist that warrant careful consideration by educators, policymakers, and developers. These challenges encompass distraction, data privacy, motivation, and equitable access to technology resources.

Distraction is a significant concern in mobile learning environments, where learners may be susceptible to interruptions from notifications, social media, and other non-educational content. Kearney (2015) highlights the challenge of managing distractions in mobile learning contexts, emphasising the importance of fostering self-regulated learning behaviours and implementing strategies to minimise external distractions. Educators can encourage learners to set boundaries for device usage during learning activities and provide guidance on effective time management techniques to mitigate distractions and maintain focus on educational objectives.

Data privacy is another pressing concern associated with mobile learning applications. The collection, storage, and sharing of learner data raise ethical and legal considerations regarding privacy rights and data security. Frank et al. (2018) discuss the importance of safeguarding learner privacy and ensuring compliance with relevant regulations, such as the Family Educational Rights and Privacy Act (FERPA) in the United States. Developers must implement robust data protection measures, such as encryption, anonymisation, and secure authentication protocols, to safeguard learner data from unauthorised access or misuse.

Motivating learners to engage actively with mobile learning applications presents a significant challenge for educators. While mobile technologies offer opportunities for interactive and personalised learning experiences, maintaining learner motivation over time can be challenging. Strategies to enhance learner motivation include gamification, rewards and incentives, peer collaboration, and real-world application of learning outcomes. Educators can foster intrinsic motivation and promote sustained engagement in electronics and sensors education by aligning mobile learning activities with learners' interests, goals, and aspirations.

Moreover, disparities in access to quality mobile devices and reliable internet connectivity pose significant challenges to the equitable implementation of mobile learning initiatives.

Learners from disadvantaged backgrounds may need access to the latest mobile technologies or reliable internet infrastructure, limiting their ability to participate fully in mobile-assisted learning activities. Addressing these disparities requires coordinated efforts to provide equitable access to technology resources, including subsidised devices, internet connectivity subsidies, and community-based digital literacy programs.

2.8 Future directions

The literature highlights emerging trends toward integrating advanced technologies like augmented reality (A.R.) and virtual reality (V.R.) into mobile learning applications. These technologies offer immersive and interactive learning experiences, presenting exciting new avenues for research and development in electronics and sensors education.

Augmented reality (A.R.) overlays digital content in the real-world environment, enhancing learners' perception and interaction with their surroundings. A.R. technologies enable learners to visualise abstract concepts, manipulate virtual objects, and engage in hands-on activities that bridge the gap between theoretical knowledge and real-world application. For example, A.R. applications can simulate circuit assembly processes, allowing learners to interact with virtual components and observe their behaviour in real-time.

Similarly, virtual reality (V.R.) technologies create fully immersive virtual environments where learners can explore and interact using specialised headsets or devices. V.R. simulations offer opportunities for experiential learning, enabling learners to engage in realistic scenarios, conduct virtual experiments, and practice complex tasks in a safe and controlled environment. For instance, V.R. simulations can replicate laboratory experiments, enabling learners to conduct experiments and observe phenomena that would be impractical or hazardous in a traditional laboratory setting.

Integrating A.R. and V.R. technologies into mobile learning applications opens new possibilities for enhancing electronics and sensor education. By leveraging the capabilities of mobile devices, such as smartphones and tablets, learners can access immersive learning experiences anytime and anywhere without needing specialised hardware or infrastructure.

Furthermore, AR and V.R. technologies offer personalised and adaptive learning experiences tailored to individual learners' needs and preferences. By analysing learners' interactions and performance within virtual environments, mobile learning applications can dynamically adjust the difficulty level, pacing, and content delivery to optimise learning outcomes.

Hsiu-Mei and Shu-Sheng (2018) discuss the potential of A.R. and V.R. technologies to revolutionise mobile learning by providing learners with highly engaging and interactive learning experiences. These technologies enable learners to explore complex concepts in electronics and sensors education dynamically and interactively, fostering a more profound understanding and retention of key concepts.

In summary, the literature reviewed underscores mobile devices' transformative potential in the e-learning landscape. Theoretical frameworks, pedagogical considerations, user experience, and implementation challenges collectively inform the ongoing discourse, offering educators, researchers, and policymakers valuable insights to optimise mobile learning applications' integration in diverse educational contexts.

3 Materials and methods

3.1 Research design

This study employed a mixed-methods approach to examine the influence of mobile devices on e-learning comprehensively and to evaluate the effectiveness of mobile learning applications, specifically within the context of electronics and sensors education. Mixed-methods research integrates qualitative and quantitative methodologies, enabling a holistic exploration of research questions and a deeper understanding of complex phenomena (Creswell & Creswell, 2017).

Qualitative methods, such as interviews and focus groups, were utilised to capture educators' and learners' nuanced perspectives and experiences regarding the use of mobile devices in electronics and sensors education. These methods facilitated an exploration of attitudes, preferences, and challenges associated with mobile learning applications.

In parallel, quantitative measures, including surveys and standardised assessments, were employed to quantitatively assess the impact of mobile learning applications on learner engagement, knowledge acquisition, and academic performance. Surveys gathered data on usage patterns, satisfaction levels, and perceived effectiveness, while standardised assessments provided objective measures of learning outcomes.

Integrating qualitative and quantitative data allowed for a comprehensive analysis, providing insights into the qualitative nuances and quantitative trends surrounding mobile learning in electronics and sensors.

3.2 Population and sample selection

This study's population consisted of educators and learners involved in electronics and sensors education across various educational institutions. A mixed-methods approach was utilised to gather insights from both groups, providing a comprehensive understanding of mobile learning in this field.

Educators: A diverse sample of 25 educators was recruited using purposive sampling techniques. Purposive sampling enabled the selection of participants based on their expertise and experience in electronics and sensors education, ensuring that a wide range of perspectives were represented. Educators included instructors, curriculum developers, and educational technology specialists from different educational institutions, offering insights into various teaching methodologies and approaches to integrating mobile learning applications.

Learners: The participant pool comprised 738 students from different educational levels, selected through stratified random sampling. Stratified random sampling ensured participants were drawn from diverse demographic backgrounds and educational contexts, including undergraduate and graduate students and vocational learners. This approach facilitated a representative sample that captured the experiences and perceptions of a broad spectrum of learners engaged in electronics and sensors education.

By including educators and learners in the study, the research aimed to gather comprehensive insights into the impact and effectiveness of mobile learning applications in the electronics and sensors field, informing the development of evidence-based recommendations and best practices.

3.3 Ethical considerations

Ethical considerations are paramount in research involving human participants. This study obtained ethical approval from the Research Ethics Committee, ensuring the research adhered to established ethical principles and guidelines (World Medical Association, 2013). The ethical review process involved a comprehensive evaluation of the research protocol to assess the potential risks and benefits to participants and ensure that appropriate safeguards were in place to protect their rights and welfare.

Informed consent was obtained from all participants before their involvement in the study. Participants were provided with detailed information about the purpose of the study, the procedures involved, and their rights as research subjects. Particular emphasis was placed on confidentiality, assuring participants that their personal information would be kept confidential and used solely for research purposes. Additionally, participants were informed of their right to withdraw from the study at any time without penalty or consequence.

Voluntary participation was emphasised throughout the research process, ensuring that participants were not coerced or unduly influenced to participate. Participants were free to decline participation or withdraw from the study at any stage without facing any repercussions. This approach upheld the principles of autonomy and respect for participants' rights, fostering a trusting and ethical research environment.

By adhering to rigorous ethical standards, the study aimed to uphold the integrity and credibility of the research findings while prioritising the well-being and rights of the participants involved.

3.4 Data collection instruments

Surveys: A structured questionnaire was designed to gather quantitative data on participants' perceptions, attitudes, and experiences with mobile devices in e-learning. The survey included 22 items structured to comprehensively cover various aspects of mobile learning in electronics and sensors education. The questionnaire utilised Likert scales (1 to 5, with one representing 'Strongly Disagree' and 5 representing 'Strongly Agree') and multiple-choice questions to elicit detailed and quantifiable responses. To ensure the reliability of the survey instrument, a pilot test was conducted with a small sample of participants (n = 30) prior to the main study. Cronbach's alpha was calculated to assess the internal consistency of the items, yielding a value of 0.87, indicating high reliability. The feedback from the pilot test was used to make minor adjustments to the wording and format of the questions, ensuring clarity and relevance.

Interviews: In-depth semi-structured interviews were conducted with a subset of educators and students to explore their insights and opinions on the impact of mobile devices. Interviews were audio-recorded and transcribed for qualitative analysis.

Observation: Classroom observations were carried out to assess the actual integration of mobile devices into the e-learning environment and to note any observable patterns or challenges.

Application Analysis: Five mobile learning applications were evaluated based on usability, features, and educational effectiveness.

3.5 Mobile learning applications integration

Integrating mobile learning applications into the language and I.T. subjects curriculum was carefully planned and executed to maximise their effectiveness and relevance to the study participants. A systematic approach was employed to select mobile learning applications aligned with the learning objectives and content of the language and I.T. courses.

Firstly, a thorough review of existing mobile learning applications relevant to language learning and I.T. skills development was conducted. This review considered educational content, user interface design, interactivity, and compatibility with mobile devices.

Following the review, a shortlist of mobile learning applications was compiled based on suitability and alignment with the curriculum objectives. The selected applications were then piloted with a small group of students to assess their usability, effectiveness, and learner engagement.

After finalising the selection, the chosen mobile learning applications were integrated into the language and I.T. subjects' curricula. During the study, participants accessed these applications through institutional learning management systems or direct download/installation on their mobile devices.

3.6 Data analysis

Quantitative Analysis: Survey data collected from participants were thoroughly analysed using SPSS (Statistical Package for the Social Sciences). Descriptive statistics such as frequencies, means, and standard deviations were computed to summarise the survey responses, providing insights into participants' perceptions, behaviours, and experiences with mobile learning applications. Inferential analysis techniques, including correlation and regression analyses, were also employed to examine relationships between variables and identify significant trends or associations within the data.

Qualitative Analysis: The qualitative data from interview transcripts underwent thematic analysis to uncover underlying themes, patterns, and insights embedded within participants' qualitative responses. Through a systematic coding and categorisation process, recurring themes and patterns were identified, allowing for a rich and nuanced understanding of participants' perspectives, experiences, and attitudes towards mobile learning in the context of electronics and sensors education.

Content Analysis: The content and features of selected mobile learning applications were rigorously examined through content analysis techniques. This analysis evaluated mobile learning applications' usability, interactivity, and alignment with educational objectives. By systematically coding and categorising the content and features of mobile learning applications, researchers were able to assess their effectiveness in facilitating learning outcomes and meeting the needs of learners in the electronics and sensors field.

The research aimed to triangulate data from multiple sources by employing a combination of quantitative, qualitative, and content analysis methods, providing a comprehensive and robust analysis of the impact and effectiveness of mobile learning applications in electronics and sensor education.

3.7 Validity and reliability

Pilot testing of survey instruments and interviews was conducted to enhance validity, and adjustments were made based on feedback. Reliability was ensured through inter-rater reliability checks in trustworthiness analysis and consistency in data collection procedures.

3.8 Limitations

Several factors were considered to ensure the integrity of the study in recognising potential limitations. Firstly, the sample size was acknowledged as a possible constraint. Despite efforts to recruit a diverse pool of participants, the sample size may have limited the extent to which findings could be generalised to broader populations. Additionally, the generalizability of findings was recognised as a limitation due to the study's specific context, which focused on electronics and sensors education. While efforts were made to select mobile learning applications relevant to this field, the applicability of findings to other disciplines may be limited.

Furthermore, the dynamic nature of technology in the e-learning landscape challenged the study's sustainability over time. Given the rapid advancements in mobile technology and the continuous evolution of e-learning platforms, findings from the study may need to be updated quickly. This limitation highlights the importance of ongoing research and adaptation to keep pace with technological advancements and changes in educational practices. Despite these limitations, the study aimed to provide valuable insights into the impact of mobile devices on e-learning in the context of electronics and sensors education, offering a foundation for future research and practice in the field.

3.9 Statistical tests

In conducting statistical analyses, the study utilised descriptive statistics and inferential tests to understand the quantitative data collected comprehensively. Descriptive statistics were employed to summarise and present essential characteristics of the data, including measures of central tendency (such as mean, median, and mode) and variability (such as standard deviation and range). These statistics provided a clear overview of the distribution and patterns within the dataset, offering insights into the central tendencies and variability of the variables under investigation.

Furthermore, inferential tests, such as chi-square or regression analyses, were employed to explore relationships and determine statistical significance between variables of interest. Chi-square tests were utilised to examine associations between categorical variables, providing insights into significant relationships or differences within the data. Regression analyses, on the other hand, allowed for the investigation of the relationship between one or more predictor variables and an outcome variable, providing insights into the strength and direction of these relationships.

By employing a combination of descriptive statistics and inferential tests, the study aimed to uncover meaningful patterns, associations, and relationships within the quantitative data, thereby enhancing the depth and rigour of the research findings. These statistical analyses provided valuable insights into the impact of mobile devices on e-learning in the context of electronics and sensors education, contributing to a more robust understanding of the phenomena under investigation.

3.10 Data integration

This study used a systematic approach to integrate data from multiple sources, including surveys, interviews, observations, and application analysis, to understand the research questions comprehensively. Triangulation of findings from diverse data sources allowed for the validation and cross-verification of results, enhancing the reliability and credibility of the study's outcomes. Surveys provided quantitative insights into participants' perceptions and behaviours regarding mobile learning applications, while interviews offered deeper qualitative insights into their experiences, attitudes, and perspectives. Observations complemented these data by providing real-time insights into participants' interactions with mobile devices and applications in educational settings. Additionally, application analysis systematically evaluated mobile learning applications' content, features, and usability, highlighting their effectiveness in facilitating learning outcomes.

4 Results

The study encompassed a comprehensive examination involving 738 students and 25 educators from institutions specialising in electronics and sensors courses. Through meticulously designed surveys and assessments, key variables were scrutinised, including educators' perceptions, student engagement levels, the efficacy of mobile learning applications, and academic performance metrics.

4.1 Descriptive statistics

Before delving into the hierarchical regression analysis, it is essential to present the descriptive statistics for each variable: (see in Table 1)

Table 1 Descriptive statistics

Variable	Mean	Standard Deviation	Rang
Student Engagement (score 0-100)	75.2	12.5	40-100
Educator Training and Support (score 0-100)	68.4	14.1	30-95
Mobile Learning Application Effectiveness (score 0-100)	82.7	10.3	50-100
Academic Performance (GPA 0-4)	3.2	0.5	2.0-4.0

4.2 Measurement of variables

(1) Student Engagement: Measured using a validated survey with a scale ranging from 0 to 100, where higher scores indicate higher levels of student engagement.

(2) Educator Training and Support: Assessed through a survey evaluating the quality and extent of training and support provided to educators, scored from 0 to 100.

(3) Mobile Learning Application Effectiveness: Evaluated using a specific questionnaire focusing on various aspects of mobile learning applications, scored from 0 to 100.

(4) Academic Performance: Measured by students' Grade Point Average (GPA) on a scale from 0 to 4.

4.3 Hierarchical regression analysis

Seeking to delve into the nuanced relationship between mobile learning applications and academic achievement, the research employed hierarchical regression analysis. This statistical technique allowed for a meticulous dissection of the influence of mobile learning applications on academic performance while simultaneously considering the potential impact of student engagement, educator training, and support mechanisms.

4.4 Model assumptions

Before performing the hierarchical regression analysis, we assessed and addressed several key model assumptions to ensure the validity and reliability of our findings. These assumptions include normality of residuals, homoscedasticity, and multicollinearity.

4.4.1 Normality of residuals

The normality of residuals was evaluated to ensure that the residuals (differences between observed and predicted values) follow a normal distribution, a crucial assumption for valid hypothesis testing in regression analysis.

(1) Q-Q Plots: Quantile-Quantile (Q-Q) plots were used to inspect the distribution of residuals visually. In these plots, the residuals were plotted against a theoretical normal distribution. The points closely followed the 45-degree reference line, indicating that the residuals were approximately normally distributed.

(2) Shapiro-Wilk Test: The Shapiro-Wilk test assessed the statistical normality of residuals. The test yielded a p-value greater than 0.05, suggesting no significant departure from normality.

4.4.2 Homoscedasticity

Homoscedasticity refers to the assumption that the variance of residuals is constant across all levels of the independent variables. Violations of this assumption can lead to inefficient estimates and affect the validity of hypothesis tests.

(1) Residuals *vs.* Fitted Values Plot: A plot of residuals versus fitted values was generated to check for homoscedasticity. The plot did not exhibit any discernible pattern or funnel shape, indicating that the residuals had constant variance across all levels of the predicted values.

(2) Breusch-Pagan Test: The Breusch-Pagan test was performed to test for statistical heteroscedasticity. The test yielded a p-value greater than 0.05, confirming the assumption of homoscedasticity.

4.4.3 Multicollinearity

Multicollinearity occurs when the independent variables in a regression model are highly correlated. This can inflate the variance of the coefficient estimates and make the model unstable.

Variance Inflation Factors (VIF): To assess multicollinearity, Variance Inflation Factors (VIF) were calculated for each independent variable. All VIF values were below the threshold of 5, with most below 2, indicating that multicollinearity was not a concern in this study. (see in Table 2)

Table 2 Variance inflation factors (VIF)

Variable	VIF
Student Engagement	1.25
Educator Training and Support	1.30
Mobile Learning Application Effectiveness	1.45

4.4.4 Linearity

The assumption of linearity requires that the relationship between the independent and dependent variables is linear.

Component Plus Residual (Partial Residual) Plots: These plots were examined to check the linearity assumption. The relationships between each predictor and the dependent variable appeared linear, suggesting that this assumption was met.

4.4.5 Independence of residuals

The independence of residuals assumes that the residuals are independent of each other, which is particularly important for time-series data but also relevant in cross-sectional studies.

Durbin-Watson Test: The Durbin-Watson statistic was calculated to check for autocorrelation in the residuals. The value was approximately 2, indicating no significant autocorrelation.

By rigorously testing and confirming these assumptions, we ensured the robustness of our hierarchical regression analysis, allowing for more reliable and valid interpretations of the relationships between mobile learning applications, student engagement, educator training, and academic performance.

4.5 Model 1: Control variables

The first step of the analysis included control variables:

(1) Student Engagement;

(2) Educator Training and Support.

These variables were entered into the regression model to account for their potential influence on academic performance. (see in Table 3)

Table 3 Results control variables

Variable	Coefficient (β)	95% CI	t-value	p-value	ΔR^2
Student Engagement.	0.20	[0.09, 0.31]	3.45	<0.001	0.10
Educator Training and Support	0.15	[0.04, 0.26]	2.78	0.005	0.06
Total R^2					0.16
Adjusted R^2					0.14

These variables were entered into the regression model to account for their potential influence on academic performance.

Table 4 Results mobile learning applications effectiveness

Variable	Coefficient (β)	95% CI	t-value	p-value	ΔR^2
Student Engagement	0.18	[0.08, 0.28]	3.26	0.001	0.08
Educator Training and Support	0.13	[0.03, 0.23]	2.54	0.011	0.05
M-Learning Applications Effectiveness	0.35	[0.25, 0.45]	6.92	<0.001	0.25
Total R^2					0.41
Adjusted R^2					0.39

4.6 Model 2: Mobile learning applications effectiveness

In the second step, the effectiveness of mobile learning applications was added to the model to examine its unique contribution to academic performance beyond the control variables. (see in Table 4)

4.7 Model comparison

Comparing the two models provides insights into the incremental contribution of mobile learning applications' effectiveness to academic performance.

(1) ΔR^2 (Change in R^2) between Model 1 and Model 2: 0.25;

(2) This indicates that adding mobile learning applications effectiveness significantly improved the model's ability to explain variance in academic performance ($\Delta R^2 = 0.25$, $p < 0.001$).

The hierarchical regression analysis revealed that after accounting for student engagement, educator training, and support, the effectiveness of mobile learning applications remained a significant predictor of academic performance. This suggests that mobile learning applications play a crucial role in enhancing academic outcomes beyond the influence of traditional factors.

5 Discussion

5.1 Quantitative analysis

The findings of this study underscore the significant impact of mobile learning applications on academic performance within the context of electronics and sensors courses. Our quantitative analysis, employing hierarchical regression, revealed that the effectiveness of mobile learning applications made a substantial and unique contribution to students' academic achievements, even after controlling for other influential factors such as student engagement and educator training and support.

The results from Model 2 demonstrated a statistically significant increase in the variance explained in academic performance ($\Delta R^2 = 0.25$, $p < 0.001$) when mobile learning application effectiveness was included in the analysis. This indicates that mobile learning applications play a pivotal role in enhancing academic outcomes beyond the influence of traditional educational factors. The coefficient for mobile learning application effectiveness ($\beta = 0.35$) suggests that for every unit increase in the effectiveness of mobile learning applications, there was a corresponding increase in academic performance.

Moreover, the observed increase in adjusted R^2 from Model 1 to Model 2 (0.14 to 0.39) further confirms the substantial contribution of mobile learning applications to explaining variance in academic performance. This improvement in model fit highlights the importance of integrating mobile learning technologies into educational practices to optimise student learning outcomes.

These findings align with existing literature that emphasises the benefits of mobile learning technologies in enhancing student learning and engagement. For instance, studies by **?** and Khaddage et al. (2016) have demonstrated that mobile learning applications improve accessibility to educational resources and foster more interactive and engaging learning environments. Accessing learning materials any time and anywhere supports self-directed learning and increases opportunities for practice and review, which are crucial for mastering complex subjects like electronics and sensors.

5.2 Qualitative analysis

Beyond the quantitative findings, qualitative insights gleaned from participant responses offer valuable perspectives on the impact of mobile learning applications on academic performance. Educators and students alike reported enhanced accessibility to course materials, increased flexibility in learning, and greater engagement with course content using mobile learning applications.

Educators noted that mobile learning applications facilitated personalised learning experiences, allowing them to effectively tailor instructional materials to meet individual student needs. This finding is consistent with research by Hwang and Tsai (2011), who found that mobile learning supports differentiated instruction and helps educators address diverse learning styles and needs. Furthermore, the interactive nature of these applications encouraged collaborative learning and knowledge sharing among students, fostering a more dynamic and engaging learning environment.

Students expressed appreciation for the convenience and portability of mobile learning applications, enabling them to access learning resources anytime, anywhere. Many reported feeling more motivated and empowered to take control of their learning journey, leading to improved retention of course concepts and better academic performance. This aligns with findings from Song and Kong (2017), who highlighted that mobile learning applications enhance student autonomy and motivation.

However, it is essential to acknowledge potential challenges associated with integrating mobile learning applications, such as technological barriers, digital distractions, and data privacy and security concerns. Addressing these challenges requires proactive measures, including adequate technical support, digital literacy training, and robust data protection protocols. As suggested by Crompton (2013), overcoming these barriers is crucial for maximising the educational potential of mobile technologies.

In conclusion, this study's findings underscore the transformative potential of mobile learning applications to enhance academic performance in electronics and sensors education. By leveraging mobile technology's affordances, educators can create more engaging and personalised learning experiences, ultimately empowering students to achieve their full academic potential.

6 Conclusion

In the dynamic landscape of modern education, this research has delved into the transformative impact of mobile devices on e-learning, explicitly focusing on the effectiveness of mobile learning applications. The exploration has revealed a nuanced understanding of the opportunities, challenges, and considerations of integrating mobile technology into educational practices.

The overwhelmingly positive perceptions from educators and the reported increase in student engagement underscore the potential of mobile devices to revolutionise traditional learning paradigms. Mobile learning applications, with their interactive features and accessibility, contribute to creating dynamic and engaging learning environments, aligning with the evolving needs of digitally connected learners. Earlier studies corroborate this, such as those by Ally (2009) and Kukulska-Hulme (2012), which found that mobile technologies enhance learning by providing flexible and personalised educational experiences.

The positive feedback regarding the effectiveness of mobile learning applications emphasises their role as valuable educational tools. The user-friendly interfaces, interactive features, and alignment with diverse learning styles contribute to their efficacy. This highlights the importance of continual advancements in application design and functionality to meet the evolving demands of education. Research by Cheon et al. (2012) also supports this view, indicating that the usability and design of mobile applications are critical factors in their adoption and effectiveness.

However, the study has also illuminated challenges that warrant attention. Technical issues, concerns about distraction, and the digital divide underscore the need for a holistic approach to overcome barriers hindering the seamless integration of mobile devices. Acknowledging these challenges sets the stage for further exploration and refinement of strategies to ensure equitable access and a distraction-free learning environment.

In essence, this research underscores the transformative potential of mobile devices in e-learning. The positive outcomes celebrated here, combined with the acknowledgement of challenges, create a roadmap for educators and policymakers to navigate the integration of mobile technology thoughtfully. By embracing opportunities, addressing challenges, and fostering a culture of continuous improvement, we can pave the way for a future where mobile devices seamlessly enhance the educational journey, making learning more accessible, engaging, and inclusive for all.

Conflicts of interest

The authors declare that they have no conflict of interest.

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