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Integrating theories for insight: an amalgamated model for gamified virtual reality adoption by science teachers

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Abstract
This study examines the factors influencing science teachers' intentions to adopt gamified virtual reality (VR) in educational settings, employing the Theory of Planned Behavior (TPB) and Protection Motivation Theory (PMT) as theoretical frameworks. We investigate how perceived threats, benefits, and motivational and cognitive factors impact these intentions, focusing on science teachers. By integrating TPB and PMT, the study aims to provide a comprehensive model that elucidates the roles of attitude, subjective norm, perceived severity, vulnerability, self-efficacy, response efficacy, and response costs in the decision to adopt gamified VR. The structural analysis conducted on a sample of 1645 science teachers revealed that our amalgamated model demonstrates a robust predictive capacity for their intentions to adopt gamified VR. This model outperformed traditional theories in predicting adoption intentions. The research also demonstrates significant relationships between these factors and the intention to use gamified VR, with differences noted across teacher groups by professional status and gender. This enhanced understanding of adoption barriers and facilitators informs strategies for better integration of VR in science education, potentially enriching teaching practices and improving student engagement and learning outcomes.

Keywords Gamified virtual reality · Science education · Theory of planned behavior · Protection motivation theory · Technology adoption

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1 Introduction

The landscape of science education is in a state of constant evolution, driven by educators and policymakers who are committed to finding innovative methods to enhance both learning and student engagement. Among the forefront of technological advancements is virtual reality (VR), which has emerged as a notably promising tool (Díaz-Pereira et al., 2024; Jiawei & Mokmin, 2023). When enriched with gamification elements, VR transitions into what is known as gamified VR (Yigitbas et al., 2024; Zhao et al., 2023). This integration of VR and gamification not only makes the learning experience more interactive and immersive but also serves as a dynamic platform for deeply engaging students and enhancing their grasp of complex scientific concepts (Lampropoulos & Kinshuk, 2024). However, the adoption of such advanced technologies in educational environments is not without its challenges (Manzano-León et al., 2021; Nadi-Ravandi & Batooli, 2022). It is shaped by a variety of factors, including science teacher attitudes, the perceived utility of the technology, and the level of institutional support, all of which add layers of complexity to its successful integration (Al Darayseh, 2023; Ateş et al., 2023; Yildiz Durak et al., 2023).

Recent research underscores the significant role that psychological and motivational factors play in the adoption of educational technologies by teachers (Al-Mughairin & Bhaskar, 2024; Ayanwale et al., 2024). As pivotal agents of change within educational systems, teachers often encounter several barriers that may hinder their adoption of innovative tools like gamified VR (Huang et al., 2020). These barriers include limited resources, insufficient training, and skepticism about the effectiveness of new technologies (Costan et al., 2021). Such challenges highlight the critical need for a deeper understanding of the psychological drivers that influence teachers' willingness to adopt or reject these emerging technologies. This understanding is essential for developing strategies that effectively address these barriers and support teachers in this transitional process.

This study tackles these complexities by leveraging the robust frameworks of the Theory of Planned Behavior (TPB) and Protection Motivation Theory (PMT), both of which have been extensively applied across various domains to analyze behavioral influences. However, their application to the adoption of gamified VR in educational contexts is relatively novel. The decision to utilize the TPB in this study stems from its capacity to offer a systematic framework for comprehending the multifaceted decision-making process involved in technology adoption among science teachers (Ateş & Gündüzalp, 2023). TPB elucidates how three critical components—attitudinal, normative, and control perceptions— collectively shape the behavioral intentions of individuals, providing researchers with a structured lens through which to examine the complexities of technology adoption within educational contexts. Firstly, TPB delves into attitudinal perceptions, which encompass the subjective evaluations and beliefs held by science teachers regarding gamified VR technology. Secondly, normative perceptions within TPB address the social influences and contextual pressures that impact teachers' intentions regarding technology adoption. This includes considerations of peer opinions, institutional norms, and perceived expectations from colleagues or educational stakeholders regarding the integration of gamified VR in teaching practices. Lastly, TPB explores control perceptions, which pertain to teachers' assessments of their ability to effectively implement gamified VR technology in their teaching routines. Through this systematic approach, TPB enables researchers to identify key determinants of behavioral intentions and provides valuable insights into the factors influencing teachers' readiness to embrace gamified VR in educational settings. Therefore, the incorporation of TPB in this study enriches our understanding by offering a methodical approach to dissecting the intricacies of technology adoption behaviors among science educators. Meanwhile, PMT plays a crucial role in this study due to its ability to unveil the underlying motivational factors driving teachers' inclination towards either embracing or rejecting new technological tools (Arpaci, 2023). PMT delves into the intricate cognitive processes that individuals engage in when assessing perceived threats and their subsequent coping responses (Rogers, 1975). In the context of educational technology adoption, PMT provides valuable insights into how teachers perceive the potential risks and challenges associated with integrating innovative tools like gamified VR into their teaching practices. By exploring these motivational aspects, PMT sheds light on teachers' readiness to either embrace these new technologies or resist their adoption. This deeper understanding of teachers' motivations is essential for developing targeted strategies that effectively address barriers to technology adoption and promote successful integration in educational settings. Therefore, the inclusion of PMT in this study enriches our analysis by uncovering the complex interplay between motivational factors and teachers' technology adoption behaviors. By integrating these theories, the study aims to provide a comprehensive analysis of the factors driving or deterring science educators from embracing gamified VR in their teaching practices.

This research endeavors to synthesize the TPB and PMT into an amalgamated model that elucidates the factors influencing science teachers' intentions to adopt gamified VR. By integrating key constructs such as perceived vulnerability and perceived severity from PMT with attitude, subjective norm, and perceived behavioral control from TPB, this study aims to uncover new insights into the intricate blend of motivational and cognitive factors that shape technology adoption decisions in science education. Through this comprehensive approach, the research seeks to deepen our understanding of the diverse influences that drive or hinder educators in embracing innovative teaching tools, thereby offering valuable perspectives on how to effectively support technology integration in the educational landscape.

This study distinguishes itself by uniquely integrating the TPB and PMT to specifically investigate the adoption of gamified VR technologies in science education. It seeks to deliver a comprehensive understanding of the myriad factors at play—ranging from perceived threats and benefits to normative pressures and behavioral controls—and how these collectively shape science teachers' intentions to use gamified VR. By delving into these complex interrelations, the study aims to inform the development of more nuanced and effective strategies that could significantly enhance the integration of VR technologies across science classrooms. This holistic approach not only addresses the immediate factors influencing adoption but also provides actionable insights that could support sustained technology integration in educational practices.

Objectives of the Study:

1. To construct an amalgamated model that integrates elements of the TPB and PMT, enhancing our understanding of the factors that influence science teachers' intentions to use gamified VR in education.
2. To assess and compare the predictive efficacy of the combined TPB and PMT model relative to each theory applied individually, aiming to verify the superiority of the amalgamated model in explaining science teachers' intentions to adopt gamified VR.
3. To investigate the moderating effects of professional status—distinguishing between pre-service and in-service science teachers—and gender on the relationships within the proposed theoretical framework.
4. To delineate and rank the relative significance of various constructs within the amalgamated model in predicting teachers' intentions to adopt gamified VR, thus identifying key drivers and barriers in this technological adoption.

This paper is organized into several sections, beginning with a literature review that sets the theoretical groundwork for the study. This is followed by a detailed description of the research methodology and data collection process. Subsequent sections present the analysis of the findings and discuss their implications for the adoption of gamified VR in science education. The paper concludes with a summary of the results and suggestions for future research, aiming to contribute to the enhancement of teacher training programs and the effective integration of new technologies in educational settings.

2 Literature review

2.1 Virtual reality in education

Virtual Reality (VR) has rapidly emerged as a transformative tool in the educational sector, revolutionizing the way educational content is delivered and experienced (Lege & Bonner, 2020). Its application spans various disciplines, but its impact is particularly notable in the field of education, where it offers unique immersive learning experiences that traditional teaching methods cannot (Fu et al., 2024).

In general educational contexts, VR has been lauded for its ability to provide interactive environments that simulate real-world scenarios, thereby enhancing students' engagement and facilitating deeper understanding of complex subjects (Chen et al., 2024). Studies have consistently shown that VR can increase student motivation and engagement levels significantly compared to conventional learning methods (AlGerafi et al., 2023; Zhao et al., 2023). For instance, the immersion and interactivity afforded by VR can lead to higher retention rates of information by providing learners with hands-on experience and the ability to practice skills in a controlled, repeatable environment (Freina & Ott, 2015).

Specifically, in science education, VR has been instrumental in demystifying abstract scientific concepts through visualization and manipulation (Liu et al., 2020). By allowing students to visualize atomic structures in three dimensions or explore ecosystems in a lifelike virtual setting, VR not only enhances comprehension but also fosters a more intuitive understanding of scientific laws and phenomena. Research by Makransky et al. (2020) demonstrated that VR could improve learning outcomes in science by providing students with experiential learning scenarios that are otherwise not feasible in a traditional classroom.

Moreover, the use of VR in science education has been shown to bridge the gap between theoretical knowledge and practical application (Matovu et al., 2023). For example, a study by Johnson-Glenberg et al. (2016) found that students who used VR for learning complex biological processes were able to translate their knowledge into practice more effectively than those who used traditional learning tools. This capability is particularly beneficial in science education, where practical application and experimentation are crucial for understanding.

However, while the benefits of VR in education are vast, its integration into mainstream educational practices faces several challenges. These include the high cost of VR equipment, the need for substantial technical support, and the potential for cognitive overload due to overly complex virtual environments (Radianti et al., 2020). Additionally, there is a need for well-designed educational content that aligns with curricular goals to fully exploit the potential of VR in education.

2.2 Gamification and learning

Gamification, which involves the application of game-design elements in non-game contexts, has gained significant recognition as a powerful educational tool (Zeng et al., 2024). By integrating elements such as points, levels, badges, and other game mechanics, gamification aims to boost motivation, enhance engagement, and improve educational outcomes (Zhao et al., 2023). The combination of gamification with VR represents a notable advancement in educational technology, offering highly engaging and immersive learning experiences (Fernández-Vázquez et al., 2024). This integration utilizes the interactive and immersive capabilities of VR to deliver gamified learning experiences that are contextually rich and highly interactive, making learning both enjoyable and informative (Yigitbas et al., 2024).

The fusion of VR and gamification benefits both intrinsic and extrinsic motivation factors. Intrinsic motivation is enhanced as students find enjoyment and satisfaction in the learning process itself, while extrinsic motivators such as rewards and recognition further encourage sustained engagement and effort (Anderson et al., 2024). For example, VR simulations that incorporate scoring and competitive elements can motivate students to engage more deeply and persist longer in learning activities. This is supported by research suggesting that gamified VR environments can lead to increased motivation by providing instant feedback and rewards that are visually and contextually integrated into the learning process (Lampropoulos & Kinshuk, 2024).

Different gamification elements contribute various benefits to the educational process. Points provide a quantifiable measure of progress, badges and achievements recognize and celebrate students' accomplishments, and leaderboards introduce a competitive element (Deterding et al., 2011; Hamari et al., 2014). Additionally, storytelling elements, which can be effectively implemented in VR, help to contextualize learning activities, making them more relatable and memorable (Chen, 2024). Challenges and quests within VR simulate complex problem-solving scenarios relevant to real-world applications, enhancing problem-solving skills (Moulaei et al., 2024).

Research has demonstrated that gamified learning environments can improve both knowledge acquisition and skill development (Busarello et al., 2016; Khasawneh, 2024). Studies indicate that gamification increases both cognitive and motivational outcomes, with students not only learning more effectively but also feeling more emotionally connected to the content (Abu-Dawood, 2016) Moreover, the sensory and cognitive involvement that comes with VR is heightened when combined with gamification, leading to deeper learning and retention (Lampropoulos & Kinshuk, 2024). As gamified VR applications continue to evolve, their impact on educational outcomes is likely to expand, offering rich opportunities for further research and application across various educational settings.

2.3 The research model and hypotheses

The theoretical model for this study integrates key constructs from the TPB and the PMT, aiming to explore the factors influencing science teachers' intentions to adopt gamified VR in their teaching practices. The model posits that these intentions are influenced by a variety of psychological and behavioral factors which are conceptualized within these two well-established theories.

2.3.1 Theory of planned behavior

The TPB provides a robust framework for understanding the psychological underpinnings behind an individual's decision to engage in a particular behavior (Ajzen, 1991). According to TPB, behavior is primarily influenced by behavioral intentions, which are themselves shaped by three critical determinants: attitudes towards the behavior, subjective norms, and perceived behavioral control (Bosnjak et al., 2020). In the realm of educational technology, particularly in the adoption of gamified VR in science education, we suppose that TPB helps elucidate how science teachers' personal beliefs, the influence of their professional community, and their perceived autonomy in using such technologies shape their intentions to incorporate gamified VR into their teaching practices.

Recent empirical evidence has consistently demonstrated the importance of the TPB in science education, particularly within the framework of educational technology. Research such as that conducted by Ateş and Garzón (2023) has demonstrated that the attitudes, subjective norms, and perceived behavioral control of science teachers significantly forecast their intentions to adopt new technological tools. Similarly, Al Breiki et al. (2023) found that these three components of TPB are pivotal in shaping science teachers' intentions to utilize e-learning systems. Another study by Zabasta et al. (2024) reinforced the essential role of subjective norms in influencing these adoption intentions. Additionally, Greisel et al. (2023) highlighted how positive attitudes significantly impact science teachers' readiness to embrace new technologies. Based on this robust body of research, this study posits that favorable social influences and positive perceptions regarding the effectiveness and user-friendliness of gamified VR are likely to bolster teachers' propensity to implement these technologies. The study articulates the following hypotheses to steer the investigation further:

H1 Subjective norms positively influence the intentions of science teachers to adopt gamified VR.

H2 Positive attitudes towards the use of gamified VR significantly influence teachers' intentions to adopt it.

These hypotheses aim to capture the motivational dynamics underpinning the adoption of gamified VR, highlighting how intrinsic beliefs and external influences converge to shape science teachers' intentions. This theoretical approach provides a structured basis for exploring the factors that drive or hinder the adoption of innovative teaching tools in educational settings.

2.3.2 Protection motivation theory

PMT serves as a robust framework for examining the psychological processes driving the adoption of new technologies, particularly in the realm of education (e.g., Al-Emran et al., 2023; Arpaci, 2023). In the current study, we propose that PMT assesses two main components of motivational reasoning—threat appraisal and coping appraisal—each containing constructs that shape teachers' intentions to employ gamified VR in their instructional methods.

In threat appraisal, the constructs of perceived severity and perceived vulnerability are pivotal. Perceived severity refers to the extent to which teachers view the consequences of not using gamified VR as grave, with the assuming that a greater perceived severity about the negative outcomes of not integrating VR into educational practices boosts the intention to adopt it. Supporting evidence from Al-Emran et al. (2023) indicates that perceived severity can significantly impact the readiness to adopt safety measures, analogous to technology adoption in education. Perceived vulnerability concerns teachers' perceptions of their susceptibility to the risks tied to non-adoption of VR. This study posits that an enhanced sense of vulnerability bolsters the motivation to adopt VR technologies. This is supported by findings from Arpaci (2023), which highlight perceived vulnerability as a significant influencer in educational technology adoption. Coping appraisal involves assessing self-efficacy, response efficacy, and response cost. Self-efficacy relates to the teachers' confidence in their ability to effectively use gamified VR, with the hypothesis asserting that higher self-efficacy correlates with stronger intentions to adopt VR technologies. Miraja et al. (2019) supports this, showing that self-efficacy influences engagement in new technology adoption. Response efficacy measures belief in the effectiveness of using gamified VR to achieve educational goals, hypothesizing that confidence in VR's educational benefits will positively influence adoption intentions. This aligns with studies, where response efficacy has motivated protective intentions (Dang-Pham & Pittayachawan, 2015). Lastly, response cost evaluates the perceived burdens associated with adopting VR, such as financial, time, and effort investments. The hypothesis suggests that lower perceived costs lead to higher adoption intentions, a notion rooted in Rosenstock's (1974) foundational PMT work, where response costs were seen as barriers to adopting new technologies. In light of the preceding arguments, the subsequent hypotheses are devised:

H3 Greater self-efficacy in using gamified VR will correlate positively with the intention to adopt VR technologies.

H4 Lower perceived costs associated with adopting VR will lead to higher adoption intentions.

H5 Belief in the effectiveness of using gamified VR to enhance teaching and learning will positively influence adoption intentions.

H6 Increased perceived vulnerability to the risks associated with not adopting VR will enhance the intention to adopt VR technologies.

H7 Higher perceived severity of potential negative outcomes from not integrating VR into educational practices will increase the intention to adopt it.

Together, these hypotheses aim to map out how perceptions about the risks and benefits of gamified VR, coupled with the evaluation of personal capability and resource availability, influence science teachers' intentions to incorporate this technology into their classrooms. The application of PMT in this context not only helps in identifying potential barriers and facilitators of VR adoption but also offers a structured way to approach interventions aimed at enhancing the integration of innovative technologies in education. The Amalgamated model illustrating the connections among the studied constructs is depicted in Fig. 1.

3 Methods

3.1 Data collection process

In the study, we began by providing a detailed overview of gamified VR technology, explaining its purpose, capabilities, and the educational benefits it offers, especially in enhancing science education. This preliminary information helped set the context for stakeholders, clearly outlining the importance of the technology and its alignment with educational objectives. Following the overview, we included comprehensive technical descriptions of the gamified VR system, detailing system requirements, hardware and software needs, and educational content options. This thorough specification aimed to equip users—science educators in this case—with all necessary information for effective implementation. To facilitate the use of this technology, comprehensive user instructions were developed. These guidelines detailed step-by-step procedures for setup and operation, supplemented by visual aids such as diagrams

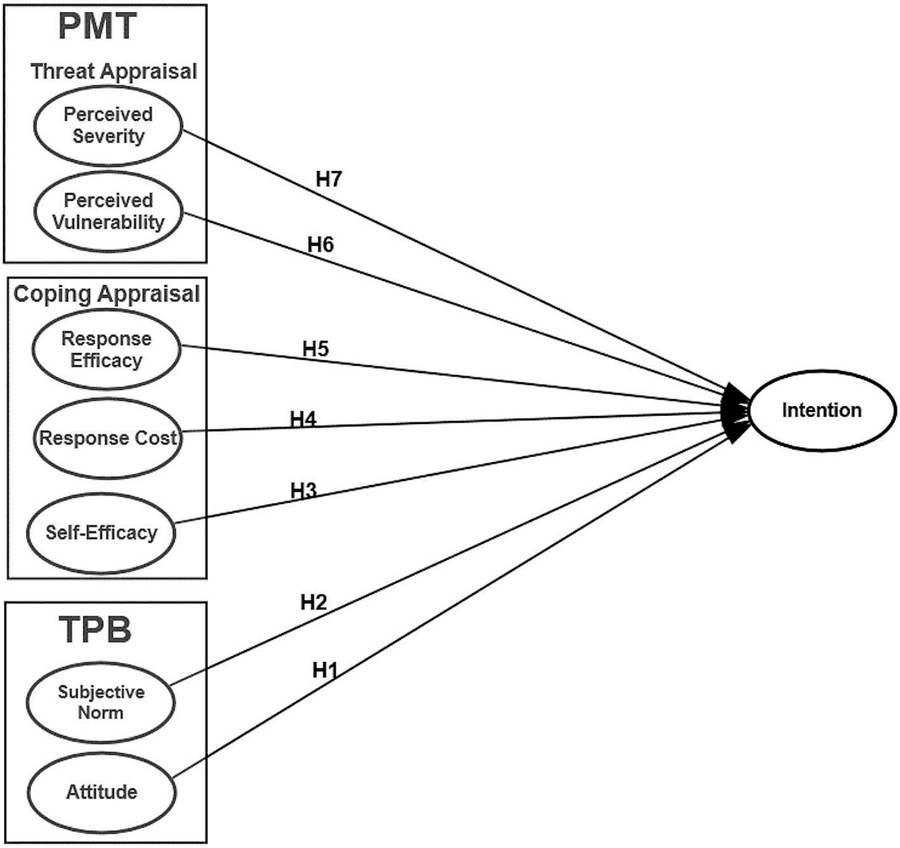

Fig. 1 Research model and hypotheses

and video tutorials to enhance understanding and user-friendliness. Recognizing the importance of hands-on training, we conducted several workshops and training sessions. These sessions were designed to familiarize science teachers with the gamified VR technology, covering everything from basic operations to advanced features and troubleshooting. Understanding the significance of ongoing support, we established a robust support system. This included a dedicated help desk and online forums where teachers could seek assistance and share insights. Regular Q&A sessions were also scheduled to address any arising issues in real time. To continuously improve the implementation process and the technology itself, we set up a structured feedback mechanism. This involved collecting data through surveys and informal feedback during training sessions, which was invaluable for gauging user satisfaction and identifying areas for improvement. Regular updates about advancements and changes in the gamified VR technology were communicated to all users. These updates were crucial for keeping the educational tool relevant and effective, ensuring that both the documentation and training materials were regularly revised to reflect the latest developments. Moreover, we included case studies and success stories within the study to illustrate practical examples of how gamified VR has been successfully integrated into science education. These narratives provided powerful testimonials on the technology's effectiveness, serving as a motivational tool for other educators considering its adoption. By providing thorough information and comprehensive support from the outset, the study not only facilitated smoother transitions into the use of innovative technology but also enhanced engagement and successful outcomes in the integration of gamified VR into science education.

3.2 Participants

Data collection for this study was conducted through a self-administered questionnaire distributed at the onset of the fall semester, spanning from January to May 2024. The participants, chosen through convenience sampling, comprised both in-service and pre-service science teachers from several major cities in Turkey, each with populations exceeding one million. Notably, the pre-service teachers were typically enrolled in science education programs. Prior to the commencement of data collection, all participants were provided with informed consent forms. These forms detailed the study's objectives, the importance of their participation, and reiterated the voluntary nature of their involvement, ensuring compliance with ethical standards. The study achieved a high level of engagement, with 1896 questionnaires distributed, of which 1744 were returned, resulting in a commendable response rate of approximately 92%. Of these, 1645 responses were validated and included in the final analysis, consisting of 660 from in-service teachers and 985 from pre-service science teachers. The participant pool was diverse, including 994 females and 651 males, providing a comprehensive representation of the demographic spectrum involved in the study. According to Kline (2011), a minimum of 10 cases per item is needed to ensure statistical reliability, hence with 30 items in our survey, a minimum of 300 participants was required. Our sample size of 1645 far exceeded this threshold, thereby providing a robust basis for analysis. Demographic details revealed in the survey showed a diverse range of backgrounds. The majority of in-service teachers were married (72%) and fell within the 35–40 age group (68%). A small portion (25%) held postgraduate degrees and actively used VR in their teaching practices (10%). Conversely, the pre-service teachers were predominantly third-year university students, with 18% being male and 65% expressing a proactive interest in using VR for teaching science, highlighting a forward-thinking stance towards educational technology. This comprehensive approach to data collection not only underpins the validity of the study but also enriches the analysis by offering a clear view of the participant profile and their engagement with the subject matter.

3.3 Measures

The data collection tools for this study were developed through a meticulously structured process that began with a detailed review of the literature on the TPB and PMT. Initial scale items were crafted based on these theories and integrated into the proposed model. To ensure the robustness and relevance of these items, four experts in science education, technology education, and psychology evaluated their face and content validity, ensuring alignment with the constructs of our theoretical model as guided by Gravetter and Forzano (2012).

Following the initial validation, a pilot study was conducted with 148 in-service and 312 pre-service science teachers to test the model's reliability and validity. This phase allowed for the identification and correction of any issues related to the measurement scales. Considering the geographical context of the study in Turkey, the scale was translated from English to Turkish using a blind translation-back-translation method, as recommended by Esfandiar et al. (2020), to ensure accuracy and cultural appropriateness. The final instrument combined TPB and PMT to create a new model specifically designed to assess the acceptance of gamified VR in science education. Within this framework, PMT was divided into threat appraisal, with constructs of perceived severity and perceived vulnerability, and coping appraisal, with constructs of response efficacy, self-efficacy, and response cost. TPB was represented through attitudes, subjective norms, and perceived behavioral control. However, due to overlapping concepts between self-efficacy (PMT) and perceived behavioral control (TPB), the study prioritized self-efficacy. Each construct was analyzed independently to examine their interactions and to validate the model comprehensively. This approach not only facilitated a deep exploration of the theoretical underpinnings but also enriched the analysis by integrating intention and behavior scales for a thorough investigation into the factors that influence the adoption of gamified VR by science teachers.

The construction of TPB constructs for this study followed the guidelines set by Ajzen (2006), incorporating insights from previous research (Davis, 1989; Lu et al., 2009; Nikou & Economides, 2017; Taylor & Todd, 2005). The attitude component of the scale was captured through three items, an example of which is "Using gamified VR for science teaching is a good idea." The subjective norm component comprises two items, including "People who are important to me think that I should use gamified VR in science classes." For the PMT constructs, perceived severity was assessed through three items adapted from Yazdanpanah et al. (2015), one of which states, "I believe that gamified VR has adequate features in place to enhance educational engagement and protect student data." Perceived vulnerability was evaluated through three items, with sources including Wang et al. (2019), an example being "I am aware of the best practices for using gamified VR in science education and feel confident in my ability to implement them effectively." Response efficacy was gauged using three items derived from studies by Kim et al. (2013) and Wang et al. (2019), with one such item being "I am confident that gamified VR's interactive and immersive features are effective in preventing disengagement and enhancing science learning." Self-efficacy was measured by three items from past research like Abrahamse and Steg (2009), with a representative item being "I am confident in my ability to use gamified VR effectively and safely in my science classes." Three items pertaining to response cost, sourced from Shafiei and Maleksaeidi (2020), included "The cost of using gamified VR in science education is reasonable and justifiable given the educational benefits." Lastly, to assess energy-saving behavioral intention, three items were developed from the work of Kim et al. (2013), such as "I predict I would use gamified VR for science teaching in the future." In total, 30 items were included in the study, with responses recorded on 7-point scales ranging from "strongly disagree" to “strongly agree,” covering both TPB and PMT constructs. Further details about these items and their organization can be found in Table 1.

3.4 Data analysis

The data analysis for this study was performed using SPSS version 21 for descriptive statistics and reliability analysis and AMOS version 20 for structural equation modeling, ensuring a robust statistical foundation for the evaluation of our theoretical model. Initially, we conducted a thorough examination of descriptive statistics, focusing on the means and standard deviations of the survey responses to gauge general trends.

Subsequently, confirmatory factor analysis (CFA) was conducted using AMOS to assess the measurement structure of the proposed model, emphasizing the validation of reliability and validity. This step included an evaluation of internal consistency, where Cronbach’s alpha was calculated for each construct, achieving satisfactory values above the acceptable threshold of 0.70. The validation process was further supported by examining convergent validity, where composite reliability (CR) values and factor loadings (FL) exceeded the minimum criterion of 0.60, and the average variance extracted (AVE) surpassed 0.50, indicating a good level of explained variance. Discriminant validity was also assessed by ensuring that the square roots of the AVE for each construct were greater than the inter-construct correlations, adhering to the criteria set by Fornell and Larcker (1981). This step confirms that the constructs are distinct and not excessively overlapping. The structural model’s fit was rigorously tested through several fit indices, providing a comprehensive view of how well the theoretical model represented the data. Fit indices for both middle school teachers and students indicated a good model fit, with values including the Chi-square to degrees of freedom ratio ($\chi 2/df$), Goodness of Fit Index (GFI), Incremental Fit Index (IFI), Tucker-Lewis Index (TLI), Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR) all within acceptable ranges. Results from these analyses, providing detailed statistical outcomes for teachers, are presented systematically in Tables 2 and 3.

4 Findings

4.1 Comparative goodness of fit analysis for models

Hypothesis testing within this study was conducted using Structural Equation Modeling (SEM) with the maximum likelihood estimation method. The analysis of goodness of fit statistics indicated that the PMT, TPB, and the amalgamated model each provided a satisfactory fit to the data for both samples—pre-service science teachers and in-service science teachers. The evaluation revealed that the amalgamated model demonstrated superior fit compared to the individual TPB and PMT models for both groups. Specifically, the combined model exhibited enhanced predictive power for intentions, with the squared multiple correlations (R^2) for pre-service science teachers at 0.51 and for in-service teachers at 0.55. In comparison, the TPB model yielded

Table 1 Constructs, statements, and reliability and validity metrics

Construct	Item	Statements	FL	α	AVE	CR
Perceived Severity	PS 1	I believe that gamified VR has adequate features in place to enhance educational engagement and protect student data.	0.89	0.89	0.71	0.88
	PS 2	I am concerned about the potential impact of poorly implemented VR on students' learning outcomes.	0.85			
	PS 3	I believe that the efficiency and productivity of my teaching are affected by the quality and reliability of VR technology.	0.78			
Perceived Vulnerability	PV 1	I am aware of the best practices for using gamified VR in science education and feel confident in my ability to implement them effectively	0.88	0.90	0.79	0.94
	PV 2	I believe that educational outcomes are vulnerable to ineffective VR applications, and my adherence to educational guidelines is critical.	0.92			
	PV 3	I feel secure in the knowledge that well-implemented gamified VR protects and enhances educational quality.	0.89			
	PV 4	I am concerned about the potential risks of misusing VR in educational settings, including privacy and data security risks.	0.86			
Self-Efficacy	SE 1	I am confident in my ability to use gamified VR effectively and safely in my science classes.	0.86	0.88	0.76	0.90
	SE 2	I am comfortable using gamified VR without assistance from others.	0.88			
	SE 3	I am confident in my ability to seek help and guidance when necessary while using gamified VR in education.	0.87			
Response Efficacy	RE 1	I am confident that gamified VR's interactive and immersive features are effective in preventing disengagement and enhancing science learning	0.86	0.90	0.76	0.91
	RE 2	I am aware of the solutions provided by gamified VR in enhancing engagement and learning outcomes in science education.	0.91			
	RE 3	I believe that my effective use of gamified VR is crucial in improving students' scientific understanding and engagement.	0.85			
Response Costs	RC 1	The cost of using gamified VR in science education is reasonable and justifiable given the educational benefits.	0.81	0.84	0.71	0.91
	RC 2	The equipment and software required to use gamified VR in science education are readily available and affordable.	0.82			
	RC 3	I believe that technical issues with VR do not significantly affect the overall teaching effectiveness.	0.89			
	RC 4	I am willing to invest the necessary effort to ensure effective use of gamified VR in my teaching practices.	0.84			

Table 1 (continued)

Construct	Item	Statements	FL	α	AVE	CR
Attitude	ATT 1	Using gamified VR for science teaching is a good idea.	0.86	0.87	0.69	0.87
	ATT 2	I like using gamified VR for science teaching.	0.82			
	ATT 3	Using gamified VR for science teaching would be pleasant.	0.81			
Subjective Norm	SN 1	People who are important to me think that I should use gamified VR in science classes	0.84	0.84	0.75	0.86
	SN 2	People who influence my behavior would think that I should use gamified VR for science teaching.	0.89			
Intention	INT 1	I predict I would use gamified VR for science teaching in the future.	0.86	0.87	0.74	0.89
	INT 2	I plan to use gamified VR for science teaching in the future.	0.87			
	INT 3	I will try to use gamified VR for science teaching in the future.	0.85			

Note FL represents Factor Loading, α stands for Cronbach's Alpha, AVE denotes Average Variance Extracted, and CR refers to Composite Reliability

Table 2 Descriptive statistics and discriminant validity for pre-service science teachers

Constructs	1	2	3	4	5	6	7	8	9
1. PS	**0.83**								
2. PV	0.58	**0.88**							
3. SE	0.45	0.44	**0.86**						
4. RE	0.49	0.46	0.44	**0.86**					
5. RC	0.36	0.52	0.45	0.52	**0.83**				
6. ATT	0.42	0.46	0.48	0.49	0.55	**0.82**			
7. SN	0.55	0.48	0.51	0.59	0.49	0.47	**0.86**		
8. INT	0.55	0.45	0.52	0.41	0.44	0.51	0.54	**0.85**	
M	4.89	5.00	4.62	4.25	4.77	4.82	4.79	4.88	4.78
SD	1.14	1.23	1.15	1.22	1.32	1.31	1.21	1.23	1.25

Note The bold values indicate $\sqrt{AVE}$ ($p<0.01$)

Table 3 Descriptive statistics and discriminant validity for in-service science teachers

Constructs	1	2	3	4	5	6	7	8	9
1. PS	**0.85**								
2. PV	0.60	**0.89**							
3. SE	0.51	0.42	**0.87**						
4. RE	0.49	0.56	0.45	**0.87**					
5. RC	0.47	0.56	0.50	0.49	**0.84**				
6. ATT	0.44	0.55	0.58	0.54	0.45	**0.83**			
7. SN	0.48	0.48	0.51	0.51	0.46	0.49	**0.87**		
8. INT	0.58	0.54	0.58	0.47	0.46	0.50	0.49	**0.86**	
M	5.22	4.98	4.58	4.89	4.47	4.88	4.99	4.56	4.98
SD	1.12	0.99	1.20	1.12	1.2	1.25	1.14	1.12	0.98

Note The bold values indicate $\sqrt{AVE}$ ($p<0.01$)

an R^2 of 0.46 for pre-service science teachers and 0.49 for in-service teachers, while the PMT model showed an R^2 of 0.41 for pre-service science teachers and 0.45 for in-service teachers. For a detailed exposition of these fit statistics and model comparisons, refer to Table 4, where specific indices are comprehensively presented.

4.2 Path analysis and hypothesis testing in gamified vr adoption

4.2.1 Results of TPB model

The results of the path analysis, tailored to the specific context of gamified VR in science education, revealed significant effects among the constructs of the TPB. Particularly noteworthy were the strong direct impacts of attitudes toward using gamified VR for teaching (βPST=0.39, $p<0.01$; βIST=0.42, $p<0.01$), subjective norm (βPST=0.21, $p>0.05$; βIST=0.25, $p>0.05$), and Perceived Behavioral Control (βPST=0.32, $p<0.01$; βIST=0.35, $p<0.01$) on the intention to integrate VR technologies. These findings imply that fostering positive attitudes towards gamified VR, enhancing perceived social approval and support, and providing teachers with a sense of control over technology usage are crucial for fostering intentions to incorporate VR into science education practices. The detailed path coefficients elucidating these relationships within the TPB framework are visually depicted in Figs. 2 and 3.

4.2.2 Results of PMT model

The PMT analysis, tailored to the adoption of gamified VR in science education and depicted in Figs. 4 and 5, yielded insightful results regarding the relationship between threat appraisal components and teachers' intentions to integrate VR into their teaching practices. Notably, perceived severity (βPST=0.22, $p<0.01$; βIST=0.31, $p<0.01$) and perceived vulnerability (βPST=0.28, $p<0.01$; βIST=0.36, $p<0.01$) demonstrated significant positive associations with intention. Furthermore, within coping appraisal, response efficacy (βPST=0.20, $p<0.01$; βIST=0.25, $p<0.01$), self-efficacy (βPST=0.30, $p<0.01$; βIST=0.35, $p<0.01$), and response cost (βPST=0.31, $p<0.01$; βIST=0.40, $p<0.01$) each exerted a significant direct impact on the intention to use gamified VR. These findings not only highlight the critical role of both threat and coping appraisals but also imply that educators' perceptions of the severity and vulnerability of adopting VR, alongside their beliefs in the effectiveness of coping strategies and the associated costs, significantly influence their intentions to incorporate gamified VR into educational settings.

Table 4 Results of goodness of fit and R^2

Sample	Models	χ^2	df	χ^2/df	NFI	IFI	TLI	CFI	RMSEA	R^2
Pre-Service Science Teachers	Amalgamated model	401.65	174	2.31	0.94	0.93	0.94	0.95	0.05	0.51
	PMT	476.85	165	2.89	0.90	0.91	0.91	0.92	0.07	0.41
	TPB	369.75	145	2.55	0.92	0.93	0.95	0.94	0.06	0.46
In-Service Teachers	Amalgamated model	382.72	184	2.08	0.95	0.95	0.96	0.96	0.04	0.55
	PMT	421.35	159	2.65	0.93	0.92	0.92	0.93	0.05	0.45
	TPB	310.2	132	2.35	0.94	0.94	0.93	0.93	0.06	0.49

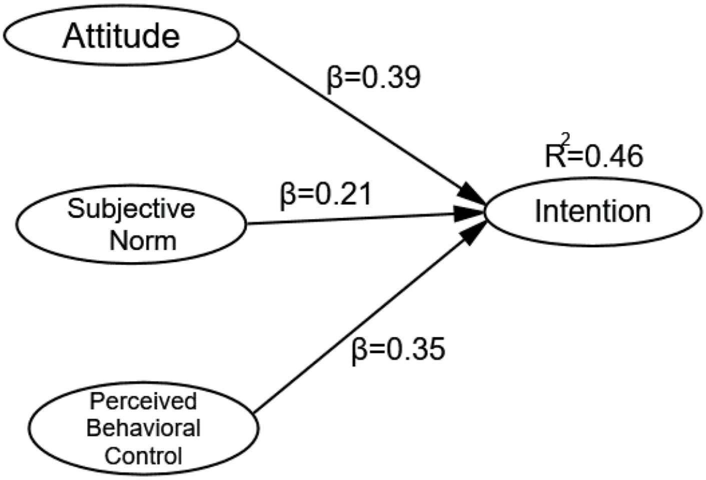

Fig. 2 Structural equating modeling results toward TPB for pre-service science teachers

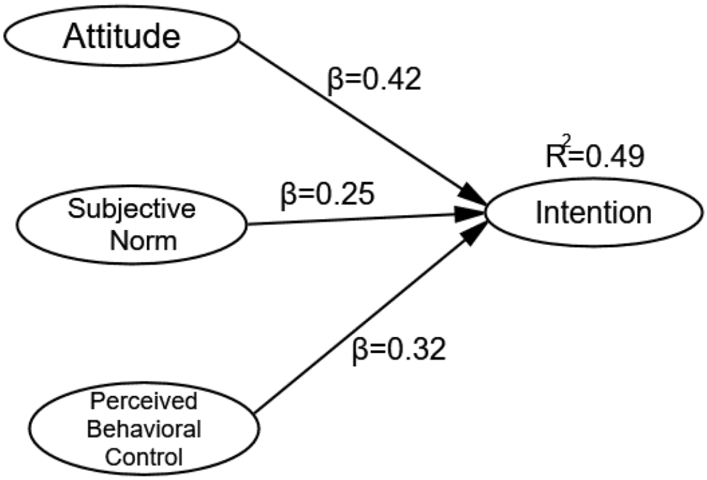

Fig. 3 Structural equating modeling results toward TPB for in-service science teachers

4.2.3 Results of amalgamated model

The rigorous examination of the relationships depicted in Figs. 6 and 7 within the amalgamated model confirmed all hypotheses from H1 to H7. Analyzing the structured model revealed significant influences on intentions for both pre-service and in-service science teachers. For pre-service teachers, the effects on intentions were statistically significant across various constructs: attitude towards using gamified VR (βATT = 0.45, $p < 0.01$), subjective norm (βSN = 0.24, $p < 0.01$), perceived severity of not using VR (βPS = 0.23, $p < 0.01$), perceived vulnerability (βPV = 0.34, $p < 0.01$),

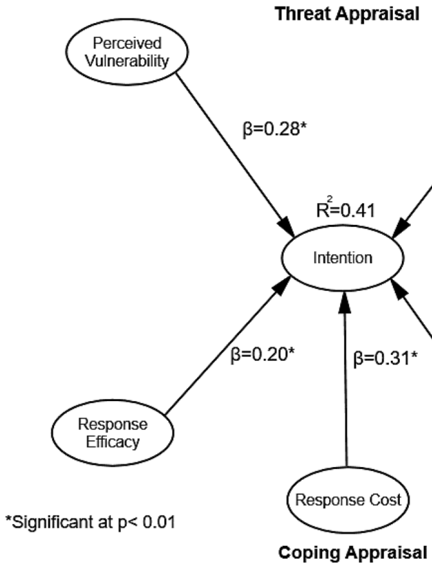

Fig. 4 Path analysis of PMT for pre-service science teachers

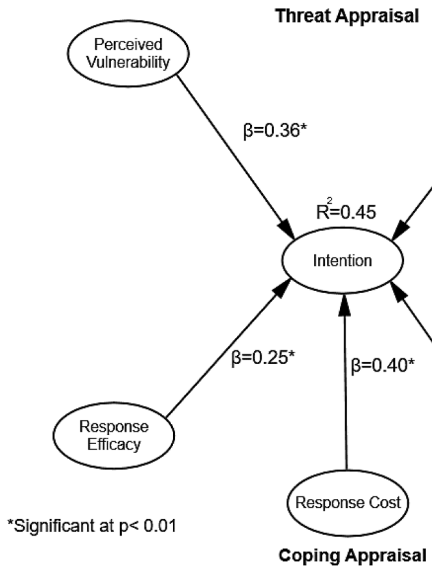

Fig. 5 Path analysis of PMT for in-service science teachers

response efficacy (βRE = 0.22, $p < 0.01$), self-efficacy (βSE = 0.33, $p < 0.01$), and response cost (βRC = 0.36, $p < 0.01$). Similarly, for in-service teachers, the results showed significant effects from attitude towards VR (βATT = 0.50, $p < 0.01$), subjective norm (βSN = 0.26, $p < 0.01$), perceived severity (βPS = 0.26, $p < 0.01$), perceived

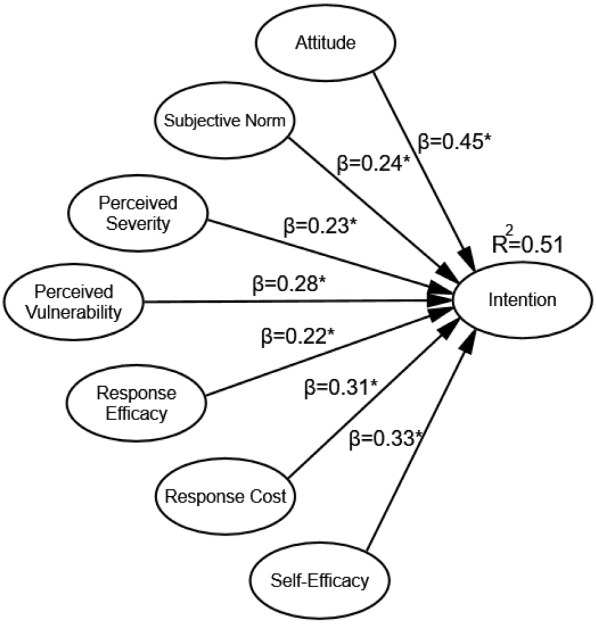

Fig. 6 Structural equating modeling results toward combined model for pre-service teachers

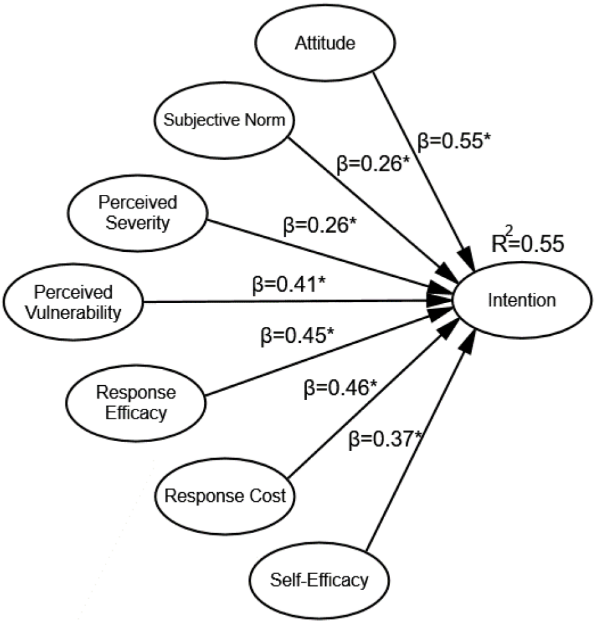

Fig. 7 Structural equating modeling results toward combined model for in-service teachers

vulnerability (βPV = 0.37, $p < 0.01$), response efficacy (βRE = 0.25, $p < 0.01$), self-efficacy (βSE = 0.40, $p < 0.01$), and response cost (βRC = 0.42, $p < 0.01$).

These findings highlight the strong influence of gamified VR-related constructs on the intentions of both pre-service and in-service teachers to incorporate VR into their teaching, underscoring the relevance and effectiveness of the combined model in predicting behavioral intentions in the educational context. The significant effects observed across various constructs, including attitudes towards using gamified VR, subjective norms, perceived severity and vulnerability, response efficacy, self-efficacy, and response cost, underscore the importance of considering multiple psychological and motivational factors when examining teachers' readiness to adopt new technologies like gamified VR.

4.3 Moderating effects of gender and professional status on gamified VR adoption

The study explored the moderating impact of gender and professional status (pre-service and in-service teachers) on the adoption of gamified VR in science education. The sample included 994 females and 651 males, comprising 985 pre-service teachers and 660 in-service teachers. Invariance testing was conducted using measurement and structural models to assess potential differences across these groups.

Initially, a non-restricted model was established, showing acceptable fit indices for both professional status ($\chi2$ = 1950.25, df = 750, $p < 0.001$, $\chi2$/df = 2.60, RMSEA = 0.043, CFI = 0.93, IFI = 0.93, TLI = 0.91) and gender ($\chi2$ = 2002.18, df = 750, $p < 0.001$, $\chi2$/df = 2.67, RMSEA = 0.044, CFI = 0.91, IFI = 0.91, TLI = 0.90). Subsequent analysis involved a full-metric invariance model, which also demonstrated a good fit for professional status ($\chi2$ = 2051.40, df = 785, $p < 0.001$, $\chi2$/df = 2.61, RMSEA = 0.043, CFI = 0.92, IFI = 0.91, TLI = 0.91) and gender ($\chi2$ = 2087.59, df = 785, $p < 0.001$, $\chi2$/df = 2.66, RMSEA = 0.042, CFI = 0.92, IFI = 0.92, TLI = 0.92). The chi-square difference tests comparing the non-restricted and full-metric invariance models revealed no significant differences for professional status ($\Delta\chi2(35)$ = 101.15, $p > 0.01$) and gender ($\Delta\chi2(35)$ = 36.41, $p > 0.01$), supporting full-metric invariance. Consequently, the baseline model was established, and proposed relationships were integrated into the full-metric invariance model. The baseline model fit indices were acceptable for both professional status ($\chi2$ = 2250.47, df = 800, $p < 0.001$, RMSEA = 0.049, CFI = 0.91, IFI = 0.91, TLI = 0.91) and gender ($\chi2$ = 2310.62, df = 800, $p < 0.001$, RMSEA = 0.047, CFI = 0.94, IFI = 0.93, TLI = 0.93). Further, the nested model comparison showed significant differences between attitudes and intentions for professional status ($\Delta\chi2(1)$ = 5.46, $p < 0.05$) and gender ($\Delta\chi2(1)$ = 6.00, $p < 0.05$). Additionally, perceived vulnerability and intention ($\Delta\chi2(1)$ = 5.75, $p < 0.05$), response efficacy and intention ($\Delta\chi2(1)$ = 5.90, $p < 0.05$), and response cost and intention ($\Delta\chi2(1)$ = 6.00, $p < 0.05$) also displayed significant differences for professional status. Similar significant differences were observed in the paths between response efficacy and intention for gender ($\Delta\chi2(1)$ = 6.15, $p < 0.05$). The implications suggest the necessity for tailored strategies in promoting gamified VR adoption in science education, acknowledging demographic differences in attitudes and intentions. While confirming measurement model comparability across professional status and gender, the findings underscore the importance of considering diverse educator backgrounds for effective technology integration initiatives. Results of these invariance tests for the measurement and structural models regarding professional status and gender are detailed in Tables 5 and 6.

5 Discussion

5.1 Summary of results

The study proposed a new model integrating the TPB and PMT and evaluated the predictive power of these models. This amalgamated model was found to surpass traditional theoretical frameworks in its ability to predict science teachers' intentions to adopt gamified VR, showcasing a satisfactory predictive power. Further analysis revealed nuanced interactions between the model's constructs and the intentions to adopt gamified VR. Significant relationships were identified among attitudes, perceived behavioral control, perceived severity, and perceived vulnerability, each contributing positively to the intention to adopt this technology. Moreover, the study emphasized significant disparities across demographic groups including professional status and gender, which had discernible effects on the adoption intentions. Specifically, differences were observed in the paths from attitudes to intentions, perceived vulnerability to intentions, and response cost to intentions concerning professional status. Regarding gender, distinctions were evident in the paths from attitudes to intentions and response cost to intentions.

5.2 Implications

5.2.1 Theoretical implications

The current study offers both theoretical and practical implications for understanding the determinants of teachers' intentions to utilize gamified VR technology in educational settings. This research marks the first integration of the TPB and PMT to investigate this subject. Previous studies have validated the application of PMT in explaining cognitive and motivational responses to perceived threats and benefits among educators (e.g., Al-Emran et al., 2023; Arpaci, 2023), while TPB has been extensively used to assess behavioral intentions across various educational technologies (e.g., Al Breiki et al., 2023; Greisel et al., 2023; Hamad et al., 2024; Liu & Wang, 2024 Zabasta et al., 2024). In this study, we devised a conceptual framework that synthesizes TPB and PMT, aiming to provide a comprehensive model to understand the intentions of science teachers regarding the adoption of gamified VR technology. By examining the interrelations between these theoretical constructs, our model was supported by empirical data, illustrating its robustness in explaining the adoption intentions among both pre-service and in-service science teachers. This underscores the significance of combining motivational, cognitive, and threat-assessment elements to enhance our understanding of the technological adoption process. Our findings reveal that the synthesized constructs of PMT and TPB together accounted for a

Table 5 Moderation results by professional status for gamified VR adoption

Groups	Models	χ^2	df	RMSEA	CFI	IFI	TLI	$\Delta\chi^2$	Full-metric invariance
Pre-service and In-service Teachers	Non-restricted model	1950.25	750	0.043	0.93	0.93	0.91	$\Delta\chi2(35)=101.15, p>0.01$ (insignificant)	supported
	Full-metric invariance	2051.40	785	0.043	0.92	0.91	0.91		
Paths	Pre-service Teachers ($n=985$)		In-service Teachers ($n=660$)			Baseline model			Nested model
	β	t-values	β	t-values					
ATT → INT	0.45	9.05	0.55	10.45		χ^2 (800)=2250.47			χ^2 (801)=2255.93[a]
SN → INT	0.24	3.10	0.26	4.65		χ^2 (800)=2250.47			χ^2 (801)=2250.62 [b]
PS → INT	0.23	2.65	0.26	4.85		χ^2 (800)=2250.47			χ^2 (801)=2251.21[c]
PV → INT	0.28	4.00	0.41	7.40		χ^2 (800)=2250.47			χ^2 (801)=2256.22[d]
RE → INT	0.22	2.05	0.45	8.20		χ^2 (800)=2250.47			χ^2 (801)=2256.37[e]
RC → INT	0.31	6.85	0.46	8.90		χ^2 (800)=2250.47			χ^2 (801)=2256.47 [f]
SE → INT	0.33	7.90	0.37	6.55		χ^2 (800)=2250.47			χ^2 (801)=2251.89 [g]

Results of chi-square difference test:

[a] $\Delta\chi2(1)=5.46, p<0.05$ (significant)

[b] $\Delta\chi2(1)=0.15, p>0.05$ (insignificant)

[c] $\Delta\chi2(1)=0.74, p>0.05$ (insignificant)

[d] $\Delta\chi2(1)=5.75, p<0.05$ (significant)

[e] $\Delta\chi2(1)=5.90, p<0.05$ (significant)

[f] $\Delta\chi^2(1)=6.00, p<0.05$ (significant)

[g] $\Delta\chi^2(1)=1.42, p>0.05$ (insignificant)

Table 6 Moderation results by gender for gamified vr adoption

Groups	Models	χ^2	df	RMSEA	CFI	IFI	TLI	$\Delta\chi^2$	Full-metric invariance
Male and Female	Non-restricted model	2002.18	750	0.044	0.91	0.91	0.90	$\Delta\chi^2(35)=85.41$, $p>0.01$ (insignificant)	supported
	Full-metric invariance	2087.59	785	0.042	0.92	0.92	0.92		

Paths	Male (n=651)		Female (n=994)		Baseline model	Nested model
	β	t-values	β	t-values		
ATT → INT	0.31	4.51	0.59	9.41	χ^2 (800)=2310.62	χ^2 (797)=2316.62[a]
SN → INT	0.24	2.64	0.27	4.15	χ^2 (800)=2310.62	χ^2 (797)=2311.37[b]
PS → INT	0.28	2.77	0.26	3.91	χ^2 (800)=2310.62	χ^2 (797)=2312.42[c]
PV → INT	0.36	3.88	0.38	4.96	χ^2 (800)=2310.62	χ^2 (797)=2312.62[d]
RE → INT	0.24	2.52	0.22	3.19	χ^2 (800)=2310.62	χ^2 (797)=2312.67[e]
RC → INT	0.25	2.56	0.51	8.90	χ^2 (800)=2310.62	χ^2 (797)=2316.37[f]
SE → INT	0.39	4.89	0.36	5.41	χ^2 (800)=2310.62	χ^2 (797)=2312.27[g]

Results of chi-square difference test:

[a] $\Delta\chi2(1)=6.00$, $p<0.05$ (significant)

[b] $\Delta\chi2(1)=0.75$, $p>0.05$ (insignificant)

[c] $\Delta\chi2(1)=1.80$, $p>0.05$ (insignificant)

[d] $\Delta\chi2(1)=2.00$, $p>0.05$ (insignificant)

[e] $\Delta\chi2(1)=2.05$, $p>0.05$ (insignificant)

[f] $\Delta\chi^2(1)=6.15$, $p<0.05$ (significant)

[g] $\Delta\chi^2(1)=1.65$, $p>0.05$ (insignificant)

substantial percentage of the variance in intention, which was greater than the variance explained by either theory alone. This suggests that the integrated model offers a superior explanation of teachers' intentions to adopt gamified VR technology. Additionally, the study highlights the importance of including both volitional and non-volitional determinants to comprehensively understand the dynamics of e-learning environments. The comprehensive model developed through this research is not only robust but also adaptable, providing valuable insights for further development across diverse e-learning contexts. These findings align with prior research comparing the efficacy of TPB and PMT, confirming the added value of integrating these models to better understand educational technology adoption (e.g., Al-Emran et al., 2023). This innovative approach facilitates a deeper understanding of the factors influencing educational technology adoption and can inform targeted interventions to promote the effective integration of gamified VR in science education.

The results of this study validate H1 and H2, revealing that constructs from the TPB, specifically attitudes and subjective norms, exert a significant influence on the adoption intentions of both pre-service and in-service science teachers regarding gamified VR integration in classrooms. These constructs collectively explained a significant percentage of the variance in intention, highlighting the impactful role of psychological factors in technology adoption decisions. The results suggest that science teachers who possess strong positive attitudes towards using gamified VR are more likely to believe in its potential to enhance their teaching effectiveness and productivity. Similarly, a teacher's perception of social support and approval (subjective norms) from peers and influential figures within the educational community positively affects their intention to adopt gamified VR. This includes a sense of control over technology choices and positive interactions with colleagues, which are pivotal in shaping their attitudes towards technology integration (Konukman et al., 2024; Schettino et al., 2024). Thus, enhancing teachers' confidence in their ability to effectively use gamified VR, coupled with fostering a supportive environment that encourages technology adoption, is crucial for optimizing educational outcomes. The pioneers in the field, such as Ajzen (1991) who formulated the TPB, have consistently noted that aligning personal beliefs and the surrounding social expectations can lead to higher motivational levels and, consequently, greater success in behavioral adoption. These findings contribute to bridging the theoretical gaps by underscoring the significant influence of TPB constructs on the adoption intentions of science teachers towards gamified VR. Such insights align with previous studies, reinforcing the notion that understanding and leveraging motivational and social dynamics are essential for effective technology integration in education (Al-Takhayneh et al., 2022; Ateş & Garzón, 2023; Ayanwale et al., 2023).

The findings from this study confirm the hypotheses related to the PMT from H3 to H7, demonstrating that perceived severity, perceived vulnerability, self-efficacy, response efficacy, and response costs are all significant predictors of teachers' intentions to adopt gamified VR in their teaching. Collectively, these constructs explained a substantial percentage of the variance in intentions, enhancing our understanding of how these factors contribute to the decision-making process regarding gamified VR adoption. This study enriches the theoretical landscape by validating the PMT constructs in the context of educational technology adoption, specifically gamified

VR. It was found that these elements significantly influence science teachers' positive intentions towards using this technology in their courses. This alignment of results with prior research underscores the effectiveness of PMT in explaining motivational and cognitive assessments in technology adoption contexts (e.g., Al-Emran et al., 2023; Arpaci, 2023; Dang-Pham & Pittayachawan, 2015; Miraja et al., 2019). Notably, studies such as those by Bekkers et al. (2023), Chennamaneni and Gupta (2023), Ifinedo (2012), and Raj Sreenath et al. (2024), who applied PMT, suggest that factors such as teachers' beliefs in the significant consequences of not adopting technology, their sense of vulnerability to negative outcomes without it, their confidence in their ability to effectively use the technology, their belief in the effectiveness of the technology to achieve desired outcomes, and their perceptions of the costs associated with adopting the technology, like gamified VR, enhance the likelihood of its adoption.

In the context of this study, the moderating effects of gender and professional status on the adoption of gamified VR in educational settings were analyzed, revealing significant insights. The findings indicated that gender plays a crucial role in the adoption of educational technology, with female teachers showing a greater inclination towards the use of gamified VR. This aligns with earlier studies such as those by Ateş and Yılmaz (2023) and Hanham et al. (2021), and Harnadi et al. (2024), which have noted similar gender-related tendencies in technology usage within educational contexts. However, some studies also contrast with studies like those by An et al. (2024) that did not find gender to be a significant factor. Moreover, differences were observed in the adoption between pre-service and in-service teachers, with age or experience emerging as a significant differentiator. In-service teachers, typically older than their pre-service counterparts, demonstrated different responses to the adoption of gamified VR, which could be influenced by varying levels of experience, familiarity with traditional teaching methodologies, and openness to technological innovations. These observations are consistent with some prior research, such as An et al. (2024) and Harnadi et al. (2024). The study further illustrates that research on the demographic variables of gender and age has been conducted globally across diverse cultural contexts including countries like Australia, China, Indonesia, and Turkey. Cultural differences significantly shape individual beliefs, attitudes, and intentions towards technology, profoundly impacting the outcomes of such studies. The variation in results across different cultural contexts underscores the necessity of considering these differences when interpreting and analyzing the findings (Bedenlier et al., 2020; Lynch et al., 2024). In today's rapidly globalizing world, where technology transcends geographical and cultural boundaries, it is increasingly important to consider the cultural context in which studies are conducted (Arpaci et al., 2020; von Humboldt et al., 2020). Understanding these cultural nuances allows for a more nuanced interpretation of data and aids in the development of culturally sensitive and inclusive educational technologies. Acknowledging these differences enhances our comprehension of how gender, age, and cultural context influence educational technology use, enabling the development of more effective and sustainable strategies to navigate the challenges presented by the dynamic landscape of technology in education.

5.2.2 Practical implications

The findings of this study on the adoption of gamified VR in educational settings offer significant practical implications that can inform the development, deployment, and enhancement of technology integration strategies within the educational sector.

First, the strong influence of perceived self-efficacy on teachers' intentions to adopt gamified VR highlights the need for targeted professional development programs. Educational institutions should consider implementing comprehensive training sessions that not only familiarize teachers with VR technology but also enhance their confidence in using these tools effectively. By addressing the self-efficacy aspect, schools and universities can empower educators, thereby facilitating a smoother transition to incorporating advanced technologies in their teaching practices.

Moreover, the impact of perceived severity and vulnerability suggests that administrators and policymakers need to communicate the potential benefits and drawbacks associated with the adoption or non-adoption of VR technologies clearly. Educational leaders should ensure that teachers understand how VR can enhance teaching and learning outcomes and address any misconceptions about its complexity or usability. Proper communication can help mitigate fears and build a supportive environment for technology adoption.

In addition, since response costs also play a crucial role in technology adoption decisions, educational institutions should strive to minimize financial and resource-related barriers. This could involve negotiating with VR technology providers for affordable solutions or seeking grants and funding opportunities to subsidize the cost of VR equipment and software. Lowering the entry barriers to technology adoption will likely increase teachers' willingness to engage with these tools.

Furthermore, the findings also suggest that the integration of gamified VR should be aligned with institutional support structures. Schools and universities should provide ongoing technical support and resources to assist teachers in troubleshooting issues that may arise during the use of VR. Establishing a dedicated team or point of contact for teachers to address their technical concerns can help maintain the sustained use of VR technologies in the classroom.

Lastly, the positive implications of integrating gamified VR into educational practices underscore the potential for these technologies to make learning more engaging and effective. Educational stakeholders should consider these benefits and work collaboratively to create policies and frameworks that encourage and support the adoption of such innovative technologies. This collaborative approach will not only enhance the educational experiences of students but also contribute to the professional growth and adaptability of teachers in an increasingly digital world.

5.3 Limitation and suggestions for future studies

The current study, while contributing valuable insights into the adoption of VR in educational settings, presents several limitations that necessitate consideration for future research.

Firstly, the reliance on self-reported measures to assess teachers' intentions and perceptions introduces the potential for response biases, such as social desirability or acquiescence bias, which could skew the results. Future studies could mitigate this limitation by incorporating a mixed-methods approach, including qualitative interviews and observational data, to provide a more nuanced understanding of teachers' actual use and experiences with gamified VR.

Secondly, the study's sample was restricted to science teachers in specific educational settings, which may limit the generalizability of the findings. Expanding the research to include teachers from various disciplines and educational levels would help to explore the broader applicability of the theoretical model proposed and to determine whether similar motivations and barriers exist across different teaching contexts.

Furthermore, while this study amalgamated the TPB and PMT to explain teachers' adoption intentions, the exploration of additional theoretical frameworks could provide deeper insights. Future research could benefit from incorporating theories like the Technology Acceptance Model (TAM) or the Unified Theory of Acceptance and Use of Technology (UTAUT), which may reveal other significant factors influencing technology adoption in education.

Moreover, this study was conducted in a specific cultural and technological context, which might influence the perceptions and adoption of technology. Future studies should consider cross-cultural comparisons to understand how cultural differences impact the acceptance and use of gamified VR in education. This would be particularly relevant in a globally connected educational landscape where cultural nuances significantly influence technology adoption.

Lastly, the rapid evolution of technology and its application in educational settings suggests that longitudinal studies could provide valuable insights into the long-term effects and sustainability of gamified VR as a teaching tool. Future research should aim to track changes in teacher perceptions and adoption patterns over time, especially as new features and capabilities of VR technologies become available.

6 Conclusion

In conclusion, this study has made a significant contribution to our understanding of the factors influencing science teachers' intentions to adopt gamified VR in their teaching practices. By integrating the TPB and PMT, this research has developed a robust theoretical framework that effectively captures the complexity of teachers' decision-making processes regarding new technology integration. The findings underscore the importance of perceived self-efficacy, perceived threats, and the perceived costs and benefits associated with gamified VR technology, which collectively play a crucial role in shaping adoption intentions. The study's results highlight the essential role of teachers' psychological and motivational states in the adoption of innovative technologies. Teachers who perceive themselves as capable and recognize the potential benefits of gamified VR are more likely to embrace such technologies. Furthermore, the support from peers and the educational community, as reflected through subjective norms, significantly enhances this likelihood. This indicates that while individual beliefs and perceptions are critical, the social and institutional context also greatly influences technology adoption decisions. Practically, these insights inform educational leaders and policymakers about the critical areas to focus on to facilitate and encourage the adoption of gamified VR in education. Emphasizing training programs that build confidence in technology use, providing adequate resources, and creating a supportive environment are pivotal steps that can lead to successful technology integration. Moreover, the study highlights areas for future research, particularly the need for more extensive and diverse studies to explore the broader applicability of the proposed model across different educational contexts and disciplines. Overall, the study contributes to a better understanding of the dynamic interplay between individual and contextual factors that influence educational technology adoption. It provides a foundation for developing more effective strategies to integrate cutting-edge technologies like gamified VR into educational settings, ultimately aiming to enhance teaching effectiveness and student learning experiences. As the educational landscape continues to evolve with technological advancements, this research serves as a timely guide for navigating the challenges and opportunities presented by the integration of such innovations into mainstream educational practices.

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Data availability The datasets generated and analyzed during the current study are not publicly available due to privacy and ethical considerations but are available from the corresponding author on reasonable request and subject to necessary approvals.

Declarations

Conflict of interest The authors declare no conflict of interest.

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