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Exploring the Acceptance and Impact of a Digital Escape Room Game for Environmental Education Using Structural Equation Modeling

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Abstract

This study explores the utilization of digital escape rooms for promoting environmental education. The goal is to investigate the effectiveness of this technology in enhancing users' environmental knowledge and eco-friendly behaviors in their daily lives. For this purpose, a digital escape room was developed and used as a testbed for this research. Structural Equation Modeling (SEM) was used to evaluate its acceptance and impact on environmental education. As such, this study examines how the game's perceived ease of use, enjoyment, and usefulness affect learning engagement, environmental knowledge, and, consequently, environmental behavior. A sample of university students was used to assess these relationships, and the results indicate that the digital escape room positively influences users' environmental knowledge and encourages eco-friendly behaviors.

Keywords: digital escape rooms; environmental education; structural equation modeling; technology acceptance

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1. Introduction

Environmental education is essential for raising awareness, knowledge, and attitudes among the general public to protect the environment and make sustainable use of natural resources [1]. It draws on multiple disciplines to promote responsible environmental behavior grounded in knowledge of ecological processes, human-environment interactions, and sustainable practices [2]. With the urgency surrounding climate change, biodiversity loss, and environmental degradation, environmental education has become more widely acknowledged as a fundamental aspect of fostering the future generation's ability to view and interact with the world in more sustainable ways [3,4].

The rapid advancement of technology has spread to all areas of education, providing interactive, engaging, and personalized learning experiences that have transformed conventional teaching and learning practices [5]. This evolution has not left environmental education unaffected. Over the past decade, the integration of digital tools in environmental education has gained significant attention as educators seek to enhance students' awareness, motivation, and engagement with sustainability issues. Digital technologies provide students with opportunities for immersive and experiential learning of complex environmental issues through simulation, gamification, and virtual experiences within the context of environmental education [6,7].

Recent educational systems are exploring ways to improve environmental education by utilizing digital tools to engage learners more deeply in the subject and foster closer collaborations, as well as problem-based learning [8–11]. As such, game-based learning has emerged as a powerful pedagogical strategy that promotes active learning, student engagement, and learning outcomes [12,13]. Within this landscape, digital escape rooms have emerged as a promising gamified approach [14–16]. Through them, students can complete challenges, puzzles, and tasks that generally require critical thinking, problem-solving, and domain-specific knowledge. Using digital escape rooms for environmental education can be a powerful way to provide hands-on, inquiry-based, and interdisciplinary lessons that challenge students to assess the particular challenges of localized environments while reinforcing global issues related to sustainability and conservation [17–19].

As the use of this technology continues to grow, gaining insights into the acceptance and effect of digital escape room games in education, particularly in environmental education, will help evaluate their effectiveness as a teaching tool [20]. Acceptance signifies the extent to which students and educators are willing to adopt and utilize this technology in their learning process, while impact reflects the effect of these games on learning objectives, encouragement, and engagement. This can help researchers assess the potential impact of digital escape rooms on environmental education and the importance (or otherwise) of embedding them in a wider pedagogical setting.

To effectively assess the acceptance and influence of educational digital tools, robust evaluation methods are needed [21]. Among these methods, Structural Equation Modeling (SEM) is one of the most widely adopted methods in educational research. SEM can examine complex relationships between variables, such as perceived usefulness, engagement, motivation, and learning outcomes [22]. By allowing researchers to test theoretical models and validate hypotheses, SEM offers a robust framework for assessing the impact of digital educational interventions.

The purpose of this study is to examine the acceptance and impact of digital escape rooms for environmental education using Structural Equation Modeling. This study examines key factors influencing students' acceptance of the game, as well as its impact on engagement, motivation, and learning outcomes. By employing SEM, this study provides empirical support for the effectiveness of digital escape rooms in enhancing environmental education and offers practitioners and policymakers insights into embedding gamification within environmental curricula.

2. Related Literature

The effectiveness of environmental education has been widely examined in various studies, highlighting the need for innovative pedagogical approaches that engage learners in active and meaningful experiences. Studies have shown that traditional methods of environmental education, such as straightforward lectures and textbooks, may not be sufficient to promote deep comprehension and behavioral adaptation [11,23–26]. Instead, experiential learning tactics, including digital and game-centered learning, have been recognized as more effective in nurturing environmental awareness and inspiring action [6–8,17,18].

Digital tools have revolutionized education by offering collaborative and learner-focused environments for developing students' knowledge. Studies have demonstrated that gamified learning, augmented reality, and online simulations can substantially enhance students' motivation, involvement, and retention of environmental information [27–31]. Specifically, gamification has been found to positively influence learners' problem-solving abilities, collaboration, and environmental consciousness [31–33]. Scholars have emphasized the part of virtual escape rooms in improving cognitive and emotional learning outcomes by immersing students in scenario-based challenges that necessitate critical reasoning and teamwork [12–20,32,34,35].

Digital escape room games have gained attention in recent years as powerful tools for promoting active learning and engagement. Earlier studies on digital escape rooms have highlighted their capacity to foster collaboration, knowledge retention, and critical thinking [12,14,32,34,35]. Educational escape rooms have been successfully applied in various disciplines, including science, technology, engineering, and mathematics (STEM) education, as well as social sciences and language learning. In the field of environmental education, digital escape rooms offer a promising approach by allowing students to engage with real-world environmental issues and solutions in an immersive and engaging manner [17–19].

The complex models exploring digital learning have elucidated the effect of engagement on acceptance. Various theoretical frameworks, including the Technology Acceptance Model, the Unified Theory of Acceptance and Use of Technology, and the Self-Determination Theory, have illuminated factors like perceived usefulness and ease that influence students' willingness to adopt tools [36–39]. When learners find digital education engaging and beneficial, acceptance increases, bettering experiences and outcomes.

Structural Equation Modeling, applied extensively in educational research, assesses interrelationships among acceptance, involvement, and results comprehensively. Previous environmental education studies utilizing SEM have provided illuminating insights into the effectiveness and motivation, as well as knowledge and behavioral intentions regarding sustainability [6,7,40,41].

As interest in gamification and digital escape rooms grows, further investigation into their acceptance and impact on environmental education is needed. Building on past work, this research employs SEM to examine relationships between key acceptance determiners, engagement levels, and learning outcomes for an escape room designed for environmental education. The findings aim to contribute to the growing body of knowledge on gamified learning, offering practical recommendations for educators and designers seeking to implement digital escape rooms in green curricula.

3. System Overview

The digital escape room developed for this study aims to promote environmental awareness and sustainability by fostering users' green skills. The game provides users with challenges related to waste management, renewable energy, and environmental conservation. It offers a 3D environment, navigated through a standard computer screen, where players engage with puzzles related to sustainable practices, such as recycling. Thus, the game focuses on enhancing users' understanding of the impact of their actions on the environment. As players progress through the game, they not only improve their environmental knowledge but also develop eco-friendly habits. The goal is to encourage users to interact with the challenges and adopt green behaviors in both the virtual and real worlds.

In order to provide a well-designed digital escape room interface that promotes a positive user experience and effective learning outcomes, the game was developed based on key principles of usability [42]. As such, an intuitive navigation system was employed, including easily clickable elements and simple movement controls. Moreover, the game incorporates responsive feedback and clear instructional guidance to support users in understanding their tasks and completing them successfully. Furthermore, puzzles follow a logical sequence, where each task builds upon previously acquired knowledge/skills, helping to maintain engagement and learning progression [43].

Regarding the educational aspect of a digital escape room, it is essential that the puzzles align with educational content and provide a clear and engaging narrative [43]. Another key characteristic is the progressive challenge levels that encourage problem-solving and critical thinking. Moreover, user-friendly navigation and feedback mechanisms play a crucial role in supporting autonomous learning [43].

The digital escape room game developed for this study was structured around the above principles. In particular, three-dimensional design was used, as it enables richer visual representation and enhanced spatial perception. Compared to 2D first-person formats, which are often limited to flat imagery and narrow fields of view, the 3D setting allows learners to explore a more vivid and dynamic virtual world. This heightened sense of space contributes significantly to the overall atmosphere and realism of the game environment. Moreover, a point-and-click interaction system was implemented to strike a balance between immersion and ease of use. This approach simplifies user controls by enabling learners to interact with the environment using only the mouse, facilitating intuitive navigation without the complexity of managing multiple movement axes, as typically required in conventional first-person games. As a result, the gameplay becomes more accessible while maintaining strategic depth in exploration and interaction.

The game was designed with the aim of developing green skills through a sequence of interactive puzzles and challenges. As such, the game serves not only as a platform for entertainment but also as an educational tool that fosters meaningful learning. The green skills selected for teaching through the game focus on environmental issues commonly encountered in everyday life, such as waste management, water conservation, and renewable energy. At the beginning of the game, players are introduced to concepts of green skills, and then they are involved in a series of puzzles that test their understanding and ability to apply this knowledge. This approach enables deep cognitive processing and practical application. The design of each puzzle was aligned with specific learning outcomes derived from the targeted green skills. The challenge in game development was to balance the pedagogical value and engaging gameplay, ensuring that learners remain motivated to continue exploring and learning through their interaction with it.

The digital escape room game consists of two main rooms, each requiring a set of puzzles to be solved in order to escape. The first room focuses on waste management and water conservation, while the second one is on renewable energy. The game flow is as follows: Firstly, the game presents users with a puzzle to solve (Figure 1). Based on this, players must take the appropriate actions to complete the challenge (Figure 2). Afterward, the game proceeds with a short quiz to evaluate the environmental knowledge acquired (Figure 3). When players solve all the puzzles in the first room, they move on to the second one. After completing the challenges in the second room, the game is over, providing users with a final assessment that summarizes their performance and the environmental concepts they have learned. Moreover, motivational messages are provided to encourage users to take action in their daily lives.

To better understand the game functionality, a detailed description of the first room is given. The first room of the game introduces players to key green skills through a structured sequence of interactive tasks focused on waste sorting, organic waste processing, and responsible water use. Each phase builds on the previous one. The game begins with a brief introductory tip that highlights the importance of recycling (Figure 1a). Players are immediately immersed in a task that requires them to identify and correctly classify scattered waste items into four available bins. The waste types include organic, plastic, and glass, with an additional misleading bin designed to introduce cognitive conflict and prompt critical evaluation of item classification (Figure 2). Players select waste items using a left-click and must deposit each into the appropriate bin by dragging it over and clicking again. Correct choices are rewarded with visual animations (i.e., the bin opens, and the item disappears from the inventory), while incorrect actions trigger corrective voice and subtitle feedback from the in-game character, John. All incorrect actions are logged and reflected in the final performance evaluation, encouraging careful decision-making.

After successful sorting, the player is presented with a multiple-choice quiz that assesses their understanding of proper recycling practices (Figure 3). When answering correctly in this quiz, a compost bag is displayed, representing the processed result of the organic waste collected earlier (Figure 4). This item becomes part of the player's inventory and introduces the next stage of interaction.

To further emphasize the circular value of organic recycling, the player must now locate and interact with three empty plant pots positioned in the upper-right section of the room. By using the compost bag, the player fills each pot individually, triggering a distinct visual animation that signals the completion of the action (Figure 4). If the compost bag is not in the inventory, the pots remain inactive, reinforcing the narrative link between proper waste disposal and environmental restoration. The compost bag contains just enough material to fill all three pots, after which it is automatically removed from the inventory.

This intermediate task deepens the player's understanding of the real-life impact of composting, illustrating how food waste can be transformed into a useful resource for plant growth. Upon filling all three pots, the player receives a new tip leading into the next and final part of the room's sequence.

In the third and final task, the focus shifts to water conservation. The player must locate a watering can hidden near a sink on the lower side of the room and add it to their inventory. To fill the can, the player interacts with the sink, initiating both a real-time animation of running water and a hidden timer that tracks water usage (Figure 5). A sound effect enhances immersion. This design element emphasizes the environmental consequences of excessive water consumption.

If the player fails to stop the water flow promptly after the can is full, the system records excess water waste, which negatively impacts their final score. Continued inaction prompts verbal intervention from John, and if the threshold is exceeded, the task resets, reinforcing the lesson through consequence-based repetition. Players must then fill the can again—this time being mindful of how quickly they close the tap.

With a filled watering can, players return to the three composted plant pots and water each one individually. Successful interaction causes each pot to visually "grow" a plant, symbolizing the transformation of waste and water into new life (Figure 5). This highlights the tangible outcomes of sustainable behavior. If the can is empty or missing, the pots remain inactive, and John provides contextual verbal feedback to guide the player.

Once all plants have been watered, a final multiple-choice quiz appears, testing the player's knowledge of water conservation (Figure 3). A correct answer completes the room. The previously locked door becomes interactable, and an animated transition leads the player into the second room of the game.

The digital escape room game combines entertainment with education, offering an innovative way to engage users in learning about environmental issues. The design and structure of the game are based on gamification principles, making the environmental skills taught both easy to understand and meaningful. This approach helps players apply the knowledge they have gained to real-world actions that protect the environment.

(**a**) (**b**)

(**c**) (**d**)

Figure 1. Puzzle presented to players: (**a**) recycling puzzle, (**b**) organic recycling, (**c**) water conservation, and (**d**) renewable energy.

Figure 2. Recycling puzzle gameplay.

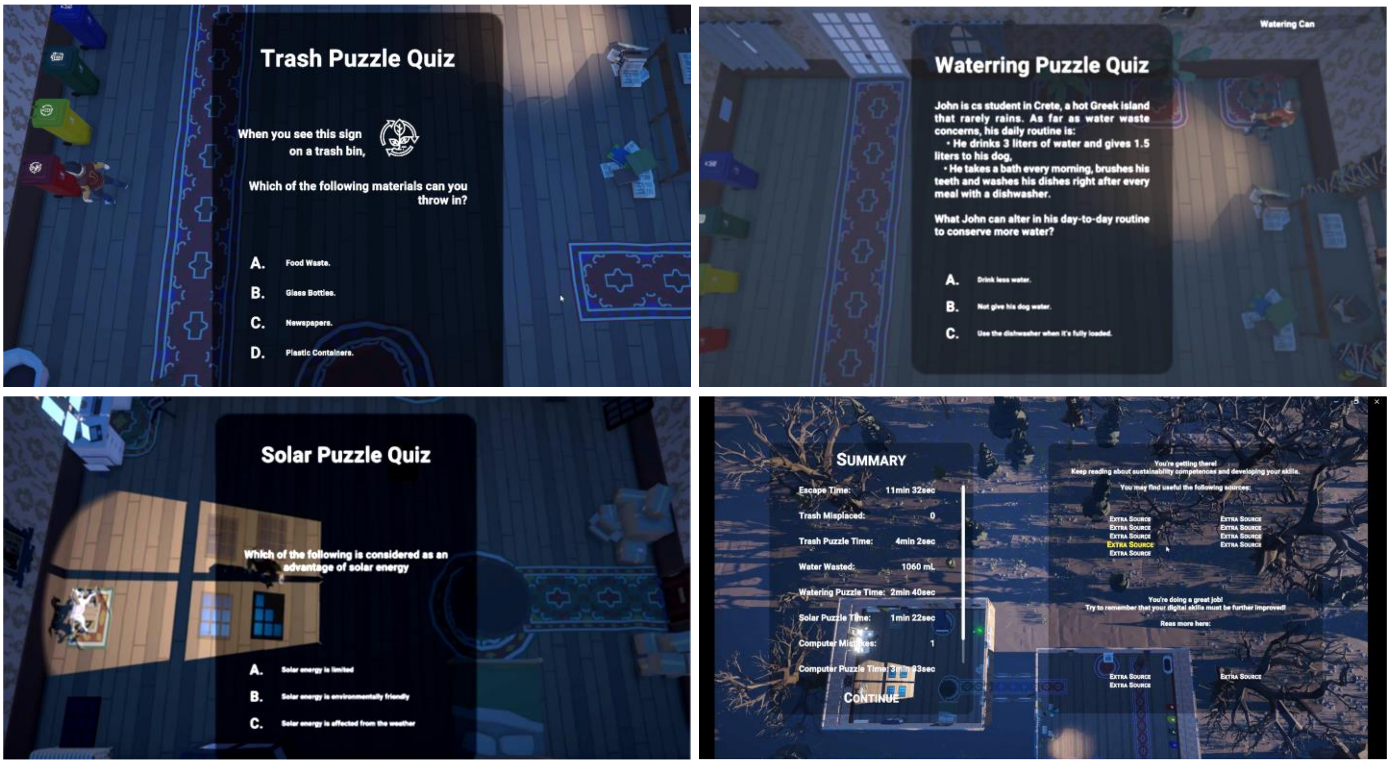

Figure 3. Evaluating environmental knowledge gained through game interaction.

Figure 4. Organic recycling puzzle gameplay.

Figure 5. Water conservation puzzle gameplay.

4. Materials and Methods

This study aims to examine how the use of the presented digital escape room can support environmental education, enhance users' environmental awareness, and promote eco-friendly behaviors. To achieve this, the convenience sampling method was employed to select students from the university where the authors work. This method was preferred since it is both effective and efficient, facilitating easy sample selection and the implementation of the experiment. However, in order to ensure validity and generalizability, diversity in the sample was achieved by including both undergraduate and postgraduate students from various academic backgrounds, genders, age groups, and ecological behaviors. Thus, the sample consisted of 120 university students. The demographic characteristics of the participants are illustrated in Table 1. Regarding the categorization of computer skills, participants were asked to self-assess their computer skills as basic, intermediate, or advanced based on their familiarity with computer use and navigation in digital environments. Likewise, ecological behavior was self-assessed as low, medium, or high based on their engagement in environmentally friendly actions, such as recycling, conserving energy, reducing waste, or making sustainable consumption choices. This self-assessment approach was defined by the authors and was chosen for its simplicity.

The sample consisted of 60 undergraduate and 60 postgraduate students. The majority (65%) of participants' ages ranged from 18 to 24; a smaller percentage (27.5%) were aged between 25 and 34, and 7.5% were 35 years or older. Regarding students' gender, 55% of them were female, while 45% were male. Moreover, most participants (70%) came from urban areas, while 30% were from non-urban areas. In total, 25% of students study Health and Care Sciences, 45% study Engineering, and 30% study Economics and Social Sciences. Concerning their computer skills, 22.5% of them had basic skills, 32.5% had intermediate skills, and 45% had advanced skills. Understanding the range of computer proficiency levels is crucial for understanding how users with different skill levels engage with the digital escape room game. This is particularly important, as they must navigate through the virtual environment, solve complex puzzles, and interact with various elements within the game. Regarding participants' ecological behaviors, the majority (55%) applied limited environmentally friendly practices in their daily lives, while 30% showed medium ecological behavior, and only 15% exhibited high ecological behavior. This diversity in environmental awareness is significant for examining whether participants' ecological behaviors were positively affected after interacting with the game.

Table 1. Demographic characteristics of sample.

Characteristics		Number	Percentage
Age	18–24	78	65.0%
	25–34	33	27.5%
	≥35	9	7.5%
Gender	Female	66	55.0%
	Male	54	45.0%
Area of origin	Urban origins	84	70.0%
	Non-urban origins	36	30.0%
Studies	Undergraduate	60	50.0%
	Postgraduate	60	50.0%
Academic background	Health and Care Sciences	30	25.0%
	Engineering	54	45.0%
	Economics and Social Sciences	36	30.0%
Computer skills	Basic	27	22.5%
	Intermediate	39	32.5%
	Advanced	54	45.0%
Ecological behavior	Low	66	55.0%
	Medium	36	30.0%
	High	18	15.0%

The research model constructed to investigate the acceptance and impact of digital escape rooms in environmental education consists of the following 6 latent variables:

- Perceived Ease of Use (PEoU): It refers to the degree to which users believe that the game is easy to use. This variable is important for the acceptance of digital escape rooms. Three-dimensional environments need to have user-friendly interfaces in order to facilitate users during their navigation and interaction with game elements.
- Perceived Enjoyment (PE): This refers to the level of pleasure users experience while playing the game. This variable plays a crucial role in motivating users to engage further with the learning process and making it more enjoyable.
- Perceived Usefulness (PU): This refers to users' perception of how beneficial the game is for environmental education. This variable is important for the adoption of digital escape rooms. Users who believe that the game is a valuable tool for learning about environmental issues are more motivated to use it. Moreover, the likelihood of withdrawing from the learning process is reduced.
- Learning Engagement (LE): This refers to the extent to which users engage with the game and the educational content. This variable plays a key role in the effectiveness of digital escape rooms for environmental education. In particular, the more engaged users are with the game, the more likely they are to explore the environmental material and apply it in real-life contexts.
- Environmental Knowledge (EK): This refers to the increase in users' knowledge about environmental issues resulting from their interaction with the game. This variable is key in assessing the educational impact of digital escape rooms. Users who

acquire a better understanding of environmental issues through the game are more prone to taking action to protect the environment.

- Environmental Behavior (EB): This refers to the changes in users' behavior regarding environmental protection after playing the game. This variable is essential in evaluating the impact of digital escape rooms on users' actions toward environmental conservation. Specifically, those who become more aware of environmental issues through the game may adopt more eco-friendly practices in their daily lives.

The relationships between the latent variables are depicted in Figure 6, indicating the following hypotheses:

H1. *The ease of use of the game positively influences the enjoyment users experience (PEoU → PE).*

H2. *The ease of use of the game positively influences the perception of its usefulness (PEoU → PU).*

H3. *The enjoyment of the game positively influences the users' engagement with the environmental education content (PE → LE).*

H4. *The perceived usefulness of the game positively influences the level of engagement with the environmental education content (PU → LE).*

H5. *The level of engagement with the environmental education content positively influences users' environmental knowledge (LE → EK).*

H6. *The level of engagement with the environmental education content positively influences users' environmental behavior (LE → EB).*

H7. *Environmental knowledge positively influences users' environmental behavior (EK → EB).*

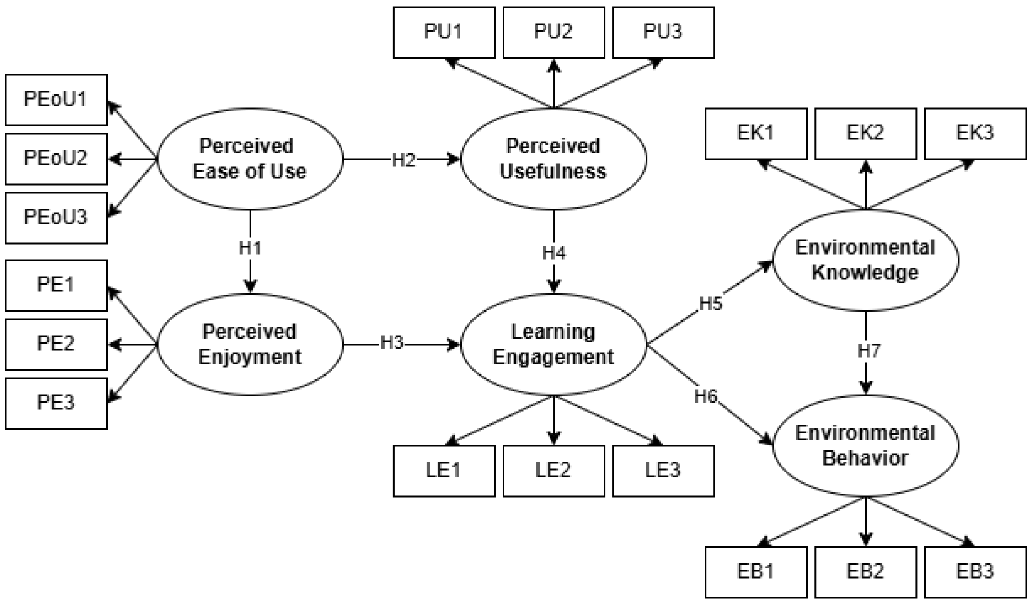

Figure 6. Research model: hypotheses and expected relationships.

In order to measure the effect of the latent variables, three indicators were assigned to each variable. As such, the survey consisted of 18 questions, as shown in Table 2. The questions were based on prior, validated studies related to the application of SEM in digital technologies and environmental education [33,44–46] and were adapted properly to the context of digital escape rooms. To ensure content validity, the questionnaire was reviewed by six experts, namely four with backgrounds in educational technology and two in environmental science. These experts evaluated the clarity, relevance, and appropriateness of the items. Moreover, a 5-point Likert scale was used to rate users' experience with the game. Thus, responses ranged from 1, meaning "totally disagree," to 5, meaning "totally agree". The questionnaire was delivered to participants online at the end of the experiment period, with a 100% return rate. The analysis of collected data was performed using Partial Least Squares Structural Equation Modeling (PLS-SEM). In particular, the path weighting scheme was applied, with 300 maximum iterations and a 1×10^{-7} stop criterion. Firstly, the measurement model was tested to verify its reliability and validity, using composite reliability (CR), Cronbach's Alpha, outer loadings, AVE values, and the Fornell-Larcker discriminant validity criterion. Afterwards, the structural model was assessed to investigate the support for the model's hypotheses. At this stage, a bootstrapping procedure with 1000 subsamples was performed to calculate the path coefficients, t-values, and the significance of the paths.

Table 2. Measurement indicators.

Variable	Indicator	Measurement Question
PEoU	PEoU1	I found the game easy to navigate.
	PEoU2	The instructions in the game were clear and understandable.
	PEoU3	I had no trouble using the game's features.
PE	PE1	I found the game enjoyable.
	PE2	The game was fun to play.
	PE3	I felt entertained while playing the game.
PU	PU1	The game helped me understand environmental issues better.
	PU2	The game was useful in teaching me about sustainability.
	PU3	I believe the game can improve my knowledge of environmental conservation.
LE	LE1	I actively participated in the game's challenges.
	LE2	I was focused on learning during the game.
	LE3	The game kept me engaged throughout the learning process.
EK	EK1	I learned new facts about the environment from the game.
	EK2	The game increased my understanding of environmental protection.
	EK3	I feel more knowledgeable about sustainability issues after playing the game.
EB	EB1	I have changed some of my daily habits to help the environment.
	EB2	I am more mindful of my environmental impact since playing the game.
	EB3	The game inspired me to take action for environmental conservation.

5. Results

Firstly, the reliability and validity of the measurement model were tested in order to evaluate how well the observed indicators represent the latent variables and whether each variable contributes meaningfully to the model. For this purpose, indicator reliability, internal consistency, and both convergent and discriminant validity were examined [47–49]. Indicator reliability was evaluated based on the outer loading. The outer loadings of all indicators were higher than 0.700, showing that all of them were acceptable (Table 3). Internal consistency was assessed using composite reliability (CR) and Cronbach's Alpha. The results indicated internal consistency, as both Cronbach's Alpha and CR values exceeded 0.700 (Table 3). Convergent validity was assessed using the Average Variance Extracted (AVE) method. In this model, AVE values for each variable exceeded 0.500, suggesting adequate convergent validity (Table 3). Regarding discriminant validity, the Fornell & Larcker (1981) criterion [49] was used for its evaluation, examining for each variable if its AVE value is greater than the squared correlations between this variable and all other latent variables. The results confirmed this criterion, supporting the adequacy of discriminant validity (Table 4). In view of the above, the model demonstrates satisfactory validity and reliability without any data violations, confirming its suitability for further use in the analysis.

Table 3. Reliability and validity metrics of the measurement model.

Variable	Indicator	Outer Loading	AVE	CR	Cronbach's Alpha
PEoU	PEoU1	0.832	0.702	0.878	0.821
	PEoU2	0.856			
	PEoU3	0.724			
PE	PE1	0.912	0.647	0.821	0.812
	PE2	0.795			
	PE3	0.803			
PU	PU1	0.874	0.732	0.901	0.868
	PU2	0.768			
	PU3	0.811			
LE	LE1	0.93	0.762	0.85	0.875
	LE2	0.901			
	LE3	0.928			
EK	EK1	0.812	0.698	0.832	0.843
	EK2	0.781			
	EK3	0.805			
EB	EB1	0.682	0.687	0.865	0.802
	EB2	0.779			
	EB3	0.876			

Table 4. Correlation matrix for latent variables in the measurement model.

	PEoU	PE	PU	LE	EK	EB
PEoU	0.842					
PE	0.518	0.763				
PU	0.299	0.222	0.835			
LE	0.423	0.573	0.312	0.795		
EK	0.389	0.415	0.242	0.374	0.792	
EB	0.228	0.37	0.467	0.503	0.378	0.788

Given the reliability and validity of the measurement model, hypothesis testing was then conducted to assess the bivariate relationships between the latent variables in the structural model. Through this evaluation, the acceptance of digital escape rooms for environmental education and its impact on users' learning and behavior were explored. The structural model obtained from this evaluation is illustrated in Figure 7. The results showed that all paths between latent variables had a *p*-value of less than 0.050 (Table 5). This indicated that all hypotheses defined in this study were supported, showing that the proposed relationships between the latent variables were statistically significant.

In particular, learning engagement and environmental knowledge had a significant impact on environmental behavior, as evidenced by the relationships LE → EB (H6) and EK → EB (H7), which had the highest path coefficients ($\beta = 0.554$ and $\beta = 0.603$, respectively) and extremely significant p-values ($p = 0.000$). The usefulness of the game in environmental education also had a strong positive influence on learning engagement, confirming H4 with a beta coefficient of 0.351 and a p-value of 0.013. Moreover, strong significance was observed in the relationships PE → LE (H3), with $\beta = 0.242$ and $p = 0.021$, and PEoU → PE (H1), with $\beta = 0.322$ and $p = 0.024$, showing that the enjoyment of the game positively influenced the learning engagement, while the ease of use of the game had a strong impact on users' enjoyment. Slightly weaker, but still significant, effects were observed for learning engagement on environmental knowledge (H5, β = 0.215, $p = 0.032$) and the ease of use of the game on its usefulness in environmental education (H2, β = 0.294, $p = 0.045$).

Table 5. Structural path analysis.

Hypothesis	Path	β	Std. Dev.	t-Stat.	*p*-Value	Supported
H1	PEoU → PE	0.322	0.146	2.286	0.024	Yes
H2	PEoU → PU	0.294	0.145	2.012	0.045	Yes
H3	PE → LE	0.242	0.155	2.309	0.021	Yes
H4	PU → LE	0.351	0.135	2.593	0.013	Yes
H5	LE → EK	0.215	0.168	2.175	0.032	Yes
H6	LE → EB	0.554	0.125	4.423	0.000	Yes
H7	EK → EB	0.603	0.114	5.455	0.000	Yes

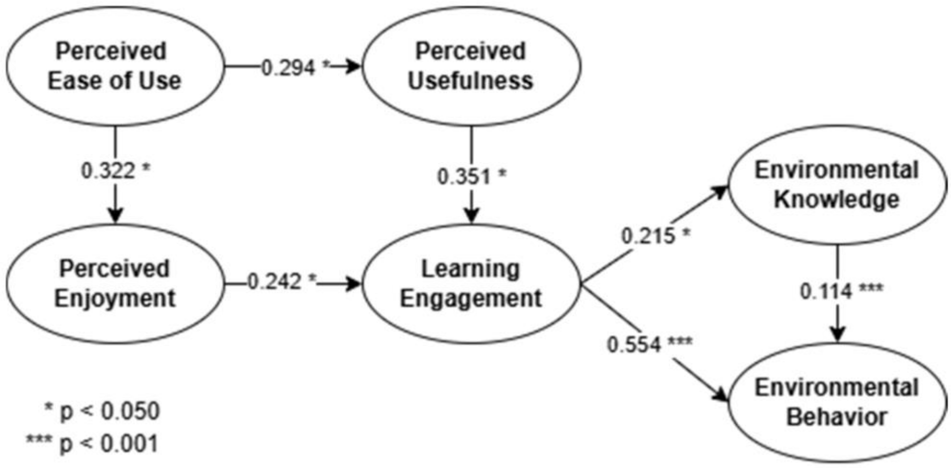

Figure 7. Structural model: relationships between variables.

6. Discussion

This study investigates the effectiveness of digital escape rooms as a tool for environmental education, using the developed system as a testbed. The analysis of the structural model reveals that all seven hypotheses presented in this research were supported, indicating a positive impact of this technology on users' environmental knowledge and behavior. As such, the presented digital escape room can be used as a tool to promote environmental awareness and motivate users to take action toward environmental conservation.

The findings reveal the importance of learning engagement and environmental knowledge in fostering users' sustainable habits, as the relationships between these two factors and environmental behavior were strongly significant. This suggests that as users engage more with the game and learn more about environmental issues, they are more likely to adopt eco-friendly behaviors in their everyday lives. This conclusion is further supported by the ecological behavior data, which showed that 55% of participants initially reported a low level of environmentally friendly behavior. The observed positive association between environmental knowledge and behavior implies that the game experience may have influenced these participants to reconsider and potentially improve their daily practices. However, learning engagement showed a moderate effect on environmental knowledge compared to its impact on environmental behavior. This suggests that knowledge may be influenced by factors beyond users' engagement in the learning process, such as the clarity and relevance of the content.

The ease of use of the game played an important role in users' experience. In particular, it showed a positive correlation between users' enjoyment and the usefulness of games for environmental education. However, since 45% of our sample reported advanced computer skills, perceptions of ease of use may differ in populations with lower levels of digital literacy. Designing user-friendly 3D environments, such as digital escape rooms, which are accessible via conventional computer screens, is essential for helping users, especially those with basic computer skills, navigate the virtual world and solve the challenges they face. As such, a user-friendly interface can enhance user satisfaction and engagement while assisting users in facing technical difficulties. This also contributes to their perception of the game's educational value since a well-designed interface improves their overall learning experience.

Another interesting result that emerged from this evaluation is that learning engagement is highly affected by both the game's usefulness and users' enjoyment of playing it. The positive relationship between perceived usefulness and learning engagement indicates that when users consider the game as a valuable learning tool, they are more motivated to engage with it. Likewise, the strong correlation between perceived enjoyment and learning engagement highlights the importance of enjoyment in encouraging users to engage with the educational content.

Overall, the results of this study emphasize the acceptance and positive impact of the evaluated digital escape room on environmental education. In particular, the findings support the hypothesis that when users perceive the game as enjoyable, easy to use, and useful for learning about environmental issues, they are more likely to engage with the content and apply the knowledge they have acquired in real-world situations. Thus, the presented digital escape room demonstrates great potential for promoting environmental education and motivating users to take action to protect the environment. However, further research is needed with more diverse user groups to confirm the broader applicability of these findings.

The aforementioned findings align with previous studies that highlight the effectiveness of digital games in fostering environmental attitudes and behaviors. In [46], the authors demonstrated that digital game-based learning (DGBL) environments like EnerCities can lead to measurable changes in students' attitudes and behavior concerning environmental sustainability. Their evaluation procedure was based on a PLS-SEM model similar to the one employed in our study. Likewise, the study presented in [45] found that environmental awareness significantly influences pro-environmental behavior among students, confirming the emphasis of our model on environmental knowledge as a key factor that affects eco-friendly behavior. Moreover, in [33], the authors used a gamified learning platform (Edcraft) to enhance recycling intention among youth. Their results indicated that motivation significantly influenced attitude and intention and that gamification positively moderated this relationship. These findings are consistent with our results, which showed that perceived usefulness and learning engagement are key factors of behavioral intention.

7. Conclusions

Environmental education enables students to understand and explore environmental issues, motivating them to take action to protect the environment. Digital escape rooms provide an innovative approach to environmental education by combining entertainment with learning. This kind of game offers users the opportunity to engage in environmental challenges that simulate real-world situations. In this context, this research explores the effectiveness of this technology in enhancing environmental knowledge and promoting eco-friendly habits in daily life.

The findings of this study highlight the potential of the evaluated digital escape room as a tool for promoting environmental education. The SEM analysis shows that when users perceive the game as enjoyable, easy to use, and valuable for learning about environmental issues, they are more likely to engage with the content and apply the knowledge in real-world situations. Moreover, this study reveals the significant role of learning engagement and environmental knowledge in shaping users' environmental behavior. As players engage more with the game and acquire new environmental knowledge, they are more likely to adopt sustainable practices in their daily lives. This research also highlights the importance of designing user-friendly and enjoyable educational experiences to maximize their impact.

However, this study presents several limitations that should be considered in evaluating the results. First, the sample was derived from the same university and included a relatively high proportion of participants with advanced computer skills. This may limit the generalizability of findings, particularly to populations with lower digital literacy. Second, while the measurement indicators were based on previous studies and reviewed by experts, the questionnaire was not fully validated through a separate factor analysis. Third, this study focused on participants' self-reported perceptions and behaviors without analyzing their actual performance during the game. Such data could provide additional insights into learning outcomes. Lastly, the structural equation model was applied solely in the context of the specific digital escape room developed for this study. As a result, the generalizability of the findings to other systems or educational games may be limited.

Part of our future work will be to extend the research model by adding more indicators to the instrument, thereby strengthening its validity and providing a more accurate measurement of latent variables. Moreover, we plan to incorporate additional variables and introduce new hypotheses, aiming to highlight further significant relationships. Future research will also include performance-based evaluation metrics to provide additional insights into the learning process. Finally, we intend to use a larger sample of participants with more diverse demographic characteristics to enhance the generalizability of the findings, as well as conduct a multi-group analysis to investigate how user characteristics influence the acceptance and impact of the digital escape room in environmental education.

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