Learning Mathematics Through Play: Design and Development of a Serious Game for Undergraduate Students

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***Abstract*—Learning mathematics requires learners to have a good understanding of the concepts and problem-solving skills. However, mathematics is often associated with complexity and rarely perceived as connected to real-world applications. Educational games have the potential to make learning more enjoyable, motivating learners by offering challenges and control over their learning experience. Despite the growing research on mathematical games, existing educational games dominantly target primary and secondary levels, with limited focus on undergraduate calculus topics such as differentiation and integration. Visualizing mathematical concepts such as differentiation and integration through real-life scenarios and providing space for learners to learn while playing can be a suitable practice to persuade learners to learn mathematics. The aim of this study is to design and develop a game prototype that covers the topic of differentiation and integration. Method of instructional design: Analysis, Design, Development, Implementation, and Evaluation (ADDIE) is used to develop the game prototype, focusing on the systematic construction and expert validation. The serious game called CalcQuest Adventure was developed and distributed to eight experts to evaluate its suitability as a tool for learning the mathematical concepts of differentiation and integration. A verified instrument called the Suitability Evaluation Questionnaire (SEQ) is adapted in the study to evaluate CalcQuest Adventure. The result shows that the overall mean score is 3.85, which indicates positive feedback from experts. The findings contribute to the practical design insights for educators and developers by illustrating how real-life problems can be visualized and embedded into serious games for undergraduate calculus learning.**

***Keywords*—Mathematics education; game design; differentiation and integration; calculus; STEM**

I. Introduction

Mathematics helps to understand the complexities of the world, such as the patterns in nature, economic systems, and formulating predictions. Learning mathematics requires learners to have a good understanding of the concepts and problem-solving skills. Mathematical concepts explain how certain rules are applied and the reasoning behind them. Understanding the concepts enables learners to apply appropriate problem-solving strategies. This skill involves critical thinking that allows them to break down difficult problems into simpler parts. However, mathematics is often associated with complexity and disassociated to the real world [1, 2]. Thus, their perception is becoming one of the global issues, as many learners choose not to pursue mathematics. Convinced actions are required to change their perception and encourage learners to have more interest in learning mathematics. Creating an enjoyable learning environment has been shown to be one way to encourage learners to have a better understanding [3, 4]. Visualizing mathematical concepts in real-life scenarios and providing space for learners to learn while playing may support learners' engagement with mathematics. Educational games can make learning more enjoyable while motivating learners by offering challenges and control over their learning experience [3, 5]. Moreover, gaming is a popular activity among young people, and games appeal more to Millennials and Gen Z than movies [6]. Therefore, the use of game technology as an interactive learning media has the potential to eliminate boredom and fear of learning mathematics, especially for Millennials and Gen Z.

Even though educational games are an excellent teaching tool, there is a limited number of mathematics games that are designed for upper-level topics specifically for undergraduate students [4, 7]. Most mathematics games aim for pre-school to primary level that only cover basic calculation. Upper-level topics mostly presented in the form of textbooks, traditional video or slide presentation [8, 9]. Topics like differentiation and integration, which are often considered difficult topics are limitedly available in a more enjoyable form to learn [10]. Presenting the topic as the content of educational game and visualizing the topic to real-life scenarios may able to make learner comprehend easily. It has potential to help the learner to understand the mathematical concept of differentiation and integration and improve their problem-solving skills while playing. However, the studies that focus on designing and developing mathematics games for undergraduate students are limited [4, 7].

Despite the increasing adoption of educational games in mathematics education, most existing studies and applications continue to focus on basic mathematical skills at the primary and secondary levels. Research that addresses game-based learning for undergraduate calculus topics, particularly differentiation and integration, remains limited. This gap indicates a need for instructional tools that support conceptual understanding of

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advanced mathematical topics through interactive and engaging learning environments.

Therefore, this study aims to explore the research activities in designing an educational game for undergraduate students, specifically on the topic of differentiation and integration. The primary objective of this study is to design and develop a serious game prototype for undergraduate calculus topics, namely differentiation and integration. It is represented by visualizing the mathematical concept interactively using graphics and animation by depicting a real-life scenario. The methodology used to develop the game prototype is the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) method. This method is suitable for the research as the system requirements are clearly identified before development begins, reducing ambiguity and minimizing potential design errors. The iterative processes where continuous testing, validation, and improvement are significant for refinement. Evaluation of the suitability of the prototype as a learning tool using expert validation, contributing to the limited body of research on educational games for advanced mathematics topics. At this stage, this study focuses on design and suitability evaluation through expert validation and does not aim to measure student learning outcomes. At the end of this study, a discussion on the results of the study is explained, and some recommendations for future study are defined.

II. Previous Studies

Mathematics is a broad subject covering geography, science, politics, and society, and every aspect of life is affected by mathematics. It implies that mathematics is a critical need for sound work in life, irrespective of the field of study or profession of practice of anyone [2, 11]. Educational games, known as a combination of education and playful experience, can motivate the students to learn mathematics, which is mentioned to be a challenging subject [3, 12]. The games are increasingly used as educational resources for students because it is the most engaging and enjoyable virtual environment [10]. Despite the advantages of educational games, research emphasizes the scarcity of mathematics games specifically designed for advanced topics, particularly at the undergraduate level [10]. Most existing games target basic mathematical skills suitable for younger audiences, creating a gap in resources for more complex topics such as differentiation and integration, which are often perceived as challenging.

Motivation, self-confidence, and perceived usefulness of mathematics are some positive attitudes that correlate with learning outcomes. Previous studies highlight the importance of creating supportive learning environments that nurture positive attitudes [2]. Significantly learning by visualizing the equations into graphics and incorporating games into learning is one of the ways for providing a supportive learning environment [3, 13]. Mauntel & Zandieh [3] in their study found that combining game-based and dynamic geometry tools supports the transition of conceptual understanding to real-scenario application in learning mathematics. Their game, named Vector Unknown, created a motivating and exploratory environment, allowing students to experiment and strategize while learning vector concepts. The study shows that students developed richer and more flexible ways of thinking and learning mathematics.

Another perspective that is important in learning mathematics is looking at the view of the teacher. Observation from the teacher during the learning process can be a good input in creating a positive learning environment. According to Matic [7], who explored the perception of teachers on computer games, discovered that teachers generally view computer games as useful tools for enriching mathematics instruction. However, based on the analysis of their survey, most teachers clarify that there is a shortage of resources in terms of suitable games for learning. The teacher-centered research design revealed that future initiatives should focus on empowering teachers through training and developing constructivist game tools in teaching mathematics [7]. This finding is consistent with the research method and results shared by Salainti & Neman [13], where they found that computer games create a more enjoyable learning environment, with noticeable increase in student attention and enthusiasm during lessons. They also concluded that teachers are open and optimistic about integrating computer games in learning. Matic [7] and Salainti & Neman [13] ask teachers' opinions about the use of computer games in teaching subjects in classrooms and both studies applied teacher-centered research design approach.

Studies by Mauntel and Zandieh [3], Anagnostopoulou [10], Matic [7] and Salainti and Neman [13], have significant differences on methods used. Mauntel and Zandieh [3] and Anagnostopoulou [10], primarily focus on learners' engagement, motivation, and conceptual understanding through direct interaction with game-based environments. These studies applied student-centered design in evaluating the game using the Game Experience Questionnaire and Players' Experience of Need Satisfaction to capture students' responses during gameplay. While Matic [7] and Salainti and Neman [13] emphasize teachers' perceptions of usability, classroom feasibility, and instructional value rather than individual learner experience. Student-centered approaches provide rich insights into engagement and learning processes. However, this approach often fails to notice limitations related to curriculum alignment and classroom implementation. In contrast to teacher-centered approaches that are more focused on instructional integration and resource suitability, this study adopts the method, aiming to evaluate the suitability of a calculus-focused game prototype.

Calculus-focused games require learners to understand mathematical concepts through visualization or graphical representation that mimics a real scenario. A study that explores calculus-oriented games, such as the role-playing game developed by Anagnostopoulou [10], demonstrates a shift from procedural practice towards exploration and problem-based learning. Procedural practice in basic mathematics is frequently selected as the content of educational games designed for primary and secondary education levels. These games often emphasize repetitive practice, immediate feedback, and skill reinforcement, making them suitable for foundational learning, but less adaptable to the abstract reasoning required at higher levels of mathematics. Research on upper levels of mathematics games remains limited. This imbalance indicates that basic mathematics games are well established and calculus-focused games are still inadequate, emphasizing the need for further

studies that support higher-order mathematical thinking at the undergraduate level.

Not only are the resources of teaching mathematics using computer games limited, but the calculus topic, like differentiation and integration, has always been non-spotlight. Based on the search on the index-comprehensive and multidisciplinary academic research database, Web of Sciences in December 2023, there is a very limited amount of research done that is focused on teaching differentiation and integration topics. Anagnostopoulou [10] considers this gap and explores a role-playing game (RPGs) in mathematics education that includes the topic of differentiation and integration. The author aims to improve the students' engagement and understanding of the topic by designing an RPG and evaluating the game by adapting and devising Players' Experience of Need Satisfaction (PENS) and the Game Experience Questionnaire (GEQ). The result of the study shows a significant improvement in students' mathematical abilities and a positive attitude towards the subject, also responding to the gap of Matic [7] and Salainti & Neman [13]. The author also suggests that innovative approaches can be particularly effective in adult education settings, where traditional teaching methods may be less engaging.

The evaluation method applied by Anagnostopoulou [10] is similar to the method applied by Alsswey [14] and Rodrigues & Cheiran [15], but different in terms of questionnaire, as they used the Suitability Evaluation Questionnaire (SEQ) to evaluate their applications. SEQ consists of 14 questions that include the user's feelings while playing the game, and a fewer number of questions compared to GEQ and PENS. An optimized number of questionnaires may help respondents to be more focused on answers, committed to responding and reduce the burden on respondents. There are many arguments in the number of items in a questionnaire; however, the suitability of the questionnaire to the objective of the study is the most important factor to consider.

Comprehensive instruments such as the Game Experience Questionnaire and Players' Experience of Need Satisfaction are effective in evaluating the learners' immersive and motivational experiences, as applied by the research in [7] and [14]. However, these instruments are less suitable for early-stage prototype evaluation, where instructional suitability and usability are the main interests. SEQ has been applied in studies focusing on the practical assessment of educational applications, particularly in terms of ease of use, clarity of content, and overall appropriateness for instructional purposes [14, 15]. It is suitable to evaluate educational tools within limited time constraints. Therefore, SEQ is considered appropriate for this study, which adopts a teacher-centered design to evaluate the suitability of a serious game prototype for classroom integration rather than to measure learners' affective gameplay experiences.

Based on the input from previous studies, this research aims to fill in the gap by designing a prototype of a computer game that focuses on the calculus topic, which is differentiation and integration. To evaluate the design of game prototypes, a SEQ is employed through teacher-centered design research. The following section briefly describes the methodology.

III. METHODOLOGY

This study mainly focuses on the process of designing serious game content of real-life scenarios that relate to mathematical theories, which are the differentiation and integration topics. The aim of the game is to assist learners in understanding how differentiation and integration theories can solve real-life problems. The methodology of the study is divided into three phases, as described in Table I. The first phase is the Conceptual phase, which involves literature analysis on similar studies. The result of this phase is the theories and the content scope. The second phase is called the Design and Development phase, which involves specific steps that are frequently applied by application developers [16], which is Analysis, Design, Development, Implementation, and Evaluation (ADDIE). In this process, expert validation is needed to evaluate the low-fidelity design before the real game prototype is developed. A low-fidelity design is a paper sketch that has a game storyline that consists of real-life problems and can be solved by using appropriate mathematical theories. Three experts are appointed to examine the correctness of mathematics theories and how they apply to serious game design. The experts are appointed based on the criteria of having at least five years of experience in teaching calculus for undergraduate students. The third phase is the Game evaluation phase, which is carried out by developing a game prototype based on the finalized outcome from phase 2. Eight experts are appointed to evaluate the game prototype using SEQ to measure the suitability of the game to assist learners in learning differentiation and integration. The selection of experts for this phase followed the same criteria applied in the preceding phase. Accordingly, the three experts involved in the earlier evaluations were invited to participate in the assessment at this stage.

TABLE I. RESEARCH FRAMEWORK

Phase	Method	Expected result
Conceptual analysis	Literature study on Similar studies on existing mathematics games Mathematical concepts	Scope - differentiation and integration
Design and Development	ADDIE method Three experts to validate the low-fidelity design	Serious game prototype design
Game Evaluation	Eight experts to measure the suitability	Validated mathematics game prototype

A. Instrument

The instrument is adapted originally from Gil Gomez [17], called the Suitability Evaluation Questionnaire (SEQ). The questionnaire is used to evaluate the user experience with the product, such as satisfaction, acceptance, and security of use. The SEQ includes a short feedback questionnaire and focuses on the product's suitability for the users, consisting of 14 questions that include the user's feelings while playing the game. The questionnaire is scored from 1 to 5, with 1 indicating "not at all" and 5 indicating "very much", or 1 indicating "very easy" and 5 indicating "very difficult".

B. Expert Evaluation of Low Fidelity Design

Recruited experts are from the mathematics field who have good experience in teaching calculus, specifically differentiation and integration topics.

A low-fidelity design in the form of a paper sketch is given to the experts to evaluate the content of the game. Their responsibility is to ensure that all mathematical theories are correctly applied to specific real-life problems. They need to agree and disagree with 25 checklist items that describe the storyline of the game. Table II shows an example of questions. At the end of the checklist, experts can add further comments/ suggestions, and it is not compulsory. The size of the respondents is suitable for this study according to Paz [18].

TABLE II. EXAMPLE OF CHECKLIST ITEMS

Num	Question	Image Num	Theory	Agree (Yes/No)
1	A ladder slides down a tree. If the bottom moves away from the wall at 2 m/s, find how fast the top is falling when the bottom is 3 m from the wall and the ladder is 5 m long.	1a	Acceleration Differentiation	
2	If the ladder starts falling from rest and accelerates due to gravity, model the velocity function and find the acceleration at t=2 seconds.	1b	Acceleration Differentiation	
3	If the radius of the cylinder decreases over time, determine the time when the radius becomes half its initial value.	2a	Volume Differentiation	

C. Expert Evaluation of the Game Prototype

A total of eight mathematical experts are recruited for the study to evaluate the game prototype. The number of respondents is enough for this study, according to the heuristic evaluation method [18]. The SEQ is designed using Google Form and the survey link is shared to all experts together with a game installer. The respondent needs to play the game as long as they need, then they need to fill in the survey form. The result from the survey is analysed using descriptive analysis and a table of improvement actions is adapted from Ramli [19] and applied to categorize the results based on mean score. Table III shows the improvement action.

TABLE III. IMPROVEMENT ACTIONS BASED ON MEAN SCORES

Score	Action
0.00 - 1.66	Design must be improved
1.67 - 3.33	Design can be improved
3.33 - 5.00	Design is maintained

IV. RESULTS

This section describes briefly the result of the study on phase 2 and phase 3 that consists of: 1) suggested design of low-fidelity interface, 2) evaluation result for low-fidelity design and 3) evaluation result on game prototype using SEQ. Hence, the results are divided into two parts, namely design and evaluation of low-fidelity interface, and game evaluation result based on the research framework, as shown in Table I. The first phase of the methodology is carried out by utilizing the literature review process that concludes the scope of the research, which is differentiation and integration.

A. Design and Evaluation of Low-Fidelity Interface

A paper sketch of interfaces and a storyboard are designed using the ADDIE method. The paper sketches, also known as low-fidelity, are designed to mimic real-life scenarios purposely to present the real-world problem that can be solved by using mathematical theories, specifically differentiation and integration. Fig. 1 shows the example of low-fidelity interface designs, while Fig. 2 shows the design of interfaces for the homepage, menu, and game contents included in the example. For the interface, 1. Menu page and 2. Game map, shows the main pages that include the introduction of the game. For the interface, 3. Level 1 illustrates the real situation of a ladder leaning on a tree and to add a storyline to the game, there is a cat on top of the tree that needs to be saved. However, the ladder may slide from the tree, and this is where the differentiation theory, which is acceleration, is applied to describe how fast the ladder falls down. The players need to calculate using the differentiation (acceleration) theory by having certain conditions, like the height of the ladder and the tree. Interface Level 4 and Level 5 show the example of low-fidelity design for differentiation theory of volume and integration theory of heat.

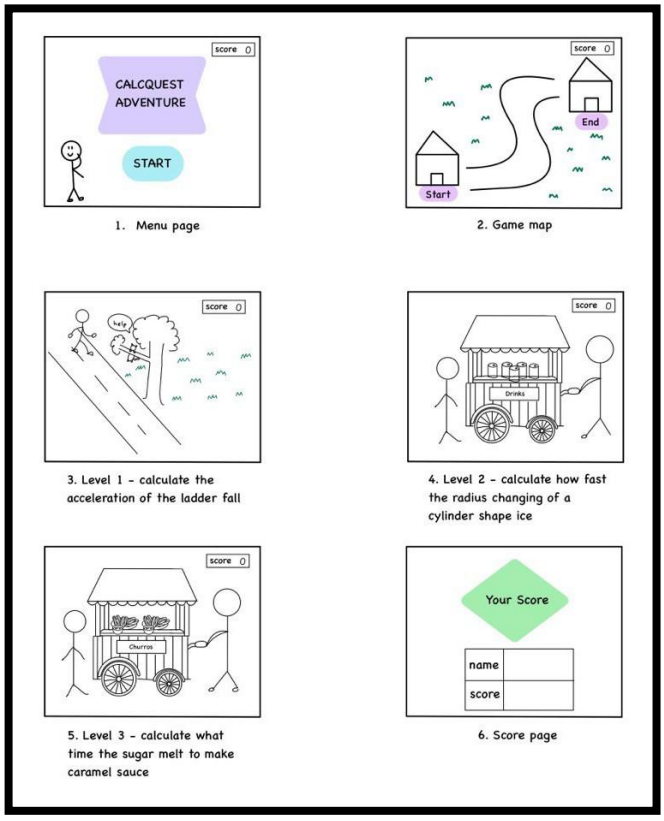

Fig. 1. Examples of low-fidelity interface designs for CalcQuest Adventure.

The recruited experts reviewed the description of each interface in the low-fidelity design and answered the questions by agreeing or disagreeing with the statements. The evaluation of low-fidelity design took around 3-6 weeks, and all experts

returned the feedback within acceptable time. Based on the feedback of all experts, it shows that there was no disagreement with any of the 25 statements in the checklist neither nor further arguments or suggestions from the experts. It can be concluded that all experts agree with the theory applied.

Based on the positive result of low-fidelity design evaluation, a game prototype is developed by using Scratch software and the duration of development took around 10 weeks. The game prototype is called CalcQuest Adventure and Fig. 2 shows the examples of game scenes. The main character, Jordyn, represents the player to experience the real-life scenario and handle all the challenges that need to be solved using the differentiation and integration theories. In order to make the game fun to play CalcQuest Adventure is designed by including game elements like game mechanics, goal, progression, balance, feedback, narrative and aesthetics. The different ways to collect points and answer the questions are examples of challenging fun factor that is included in the game design. For example, in Level 1, players engage in a shooting game for innovative question-solving. Level 2 introduces a catching game, which adds agility and coordination to the learning process. Lastly, Level 3 introduces a drag-and-drop game, requiring a hands-on approach to answering questions. This dynamic and engaging interface meets various learning styles, ensuring comprehensive educational experience at different skill levels.

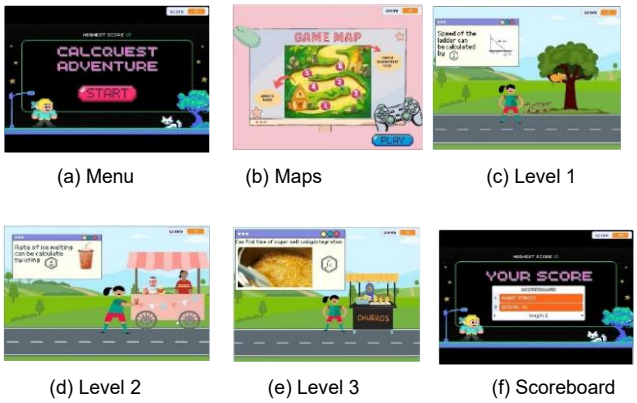

Fig. 2. Game scenes from CalcQuest adventure.

B. Game Evaluation Result

A total of eight mathematical experts participated in the study. The results from the survey are retrieved from the Google Form distributed within the game installer file. Table IV shows the results generated by SPSS 5.0. The overall mean score is 3.85 and referring to Table III, the design of CalcQuest Adventure falling under the “Design is maintained” category, where by the design is maintained and generally well-received by users with mean scores above 3.33 across most items. The highest value of mean score is 4.25 which is for item 8, addressing that the game is helpful for students’ learning. This result indicates that "CalcQuest Adventure" has the potential to become a valuable learning tool.

Items 7, 9, and 10 of the SEQ are negatively oriented, with higher scores reflecting increased discomfort or difficulty. Therefore, these items were reverse-scored during the analysis to ensure consistency in score interpretation across all instrument items, whereby higher scores uniformly represent more positive outcomes. Based on the analysis, the lowest value of the mean score is 3.00 for item 7, suggesting minor issues that may affect user comfort. Mean score 3.0 falls under category 2 which is the design that can be improved but not compulsory. No other item from the questionnaire has mean score less than 3.33 indicating CalcQuest Adventure giving positive user experiences. Aside from that, the total average of standard deviation from the eight mathematics experts is 0.7851 indicating a relatively low level of variability in the scores, the feedback consistent and stable performance across respondents.

Fig. 3 is a graphical representation of the relationship between mean values and the number of items, serving as a visual representation of the data derived from the SPSS analysis that is shown in Table IV. The visual graph provides a clearer visualization of the trends observed in the corresponding Table IV. It can be seen that almost all item distributed on the right side of the graph indicate the positive feedback from all experts.

TABLE IV. DESCRIPTIVE ANALYSIS

Item	Questions	Mean	Standard Deviation	Action
1	How much did you enjoy your experience with "CalcQuest Adventure"?	4.125	0.6409	Design is maintained
2	How immersed did you feel being in the environment of “CalcQuest Adventure"?	4.000	0.7559	Design is maintained
3	How successful were you in understanding through “CalcQuest Adventure"?	4.125	0.8345	Design is maintained
4	To what extent were you able to control “CalcQuest Adventure"?	3.875	0.8345	Design is maintained
5	How real is the virtual environment of “CalcQuest Adventure"?	3.750	0.8864	Design is maintained
6	Is the information provided by "CalcQuest Adventure" clear?	4.125	0.8345	Design is maintained
7	Did you experience any discomfort during your experience with “CalcQuest Adventure"?	3.000	0.9258	Design can be improved
8	Do you think that “CalcQuest Adventure" will be helpful for your students' learning?	4.250	0.7071	Design is maintained
9	Did you find the task difficult?	3.625	0.5175	Design is maintained
10	Did you find the “CalcQuest Adventure" interface difficult to use?	3.625	0.9161	Design is maintained

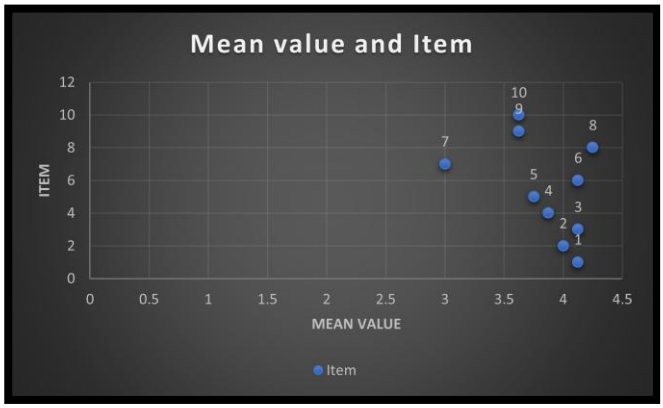

Fig. 3. Mean value vs. item

V. Discussion and Conclusion

This study aimed to design a mathematics game prototype for undergraduate students focused on enhancing the understanding of differentiation and integration. Mathematics is often perceived as abstract and disconnected from real-world, as it is frequently viewed by students as a challenging subject with limited practical relevance. This perception has contributed to a global decline in mathematics-engagement among undergraduate students. Thus, the use of game-based learning as a pedagogical tool to make mathematics more engaging, enjoyable, and applicable to real-world contexts can be the solution. However, limited resources of games designed for upper education level restrained the resolution. The goal of the study is to fill in the gap by providing a game that covers the topic of calculus specifically differentiation and integration and relate the mathematics theories to real-life problems.

CalcQuest Adventure, a game prototype developed using the ADDIE instructional design model is designed to mimic the real-life problem and players solve the problems using the theories of differentiation and integration. The game prototype underwent an expert evaluation phase twice, first during the early phase by creating a low fidelity interface design in the form of paper sketch and second during the last phase, where eight experts are recruited to assess the design using a validated instrument known as the Suitability Evaluation Questionnaire (SEQ).

The feedback data, presented in the form of mean scores and standard deviations, offers valuable insights into the perceived strengths and limitations of the game. The evaluation comprised ten items, each rated on a 5-point Likert scale. Nine out of ten evaluation items received mean scores above 3.34, confirming that the game's design is well-maintained across several dimensions. Experts reported high enjoyment (item 1), a strong sense of immersion (item 2), and clear instructional content (item 3). These results suggest that CalcQuest Adventure succeeds in making mathematics more relatable and engaging, a critical step in addressing student disengagement from the subject. Furthermore, the game was perceived as helpful for students' learning (item 8), highlighting its potential as a supplementary educational tool.

One notable exception was the item regarding user discomfort, which scored a mean of 3.00. Although this value still falls within an acceptable range, it indicates that some aspects of the user experience may require further refinement to improve player comfort. It is very crucial to choose evaluation method and a significant type of evaluation that cater to usability must be carried out in order to get the detail issues on this matter [20]. However, this score does not undermine the overall merit of the game. The standard deviation values, ranging from 0.51 to 0.93, reflect moderate variability among expert opinions, suggesting general consensus while acknowledging some differing perspectives [21]. These findings are important for iterative improvements to the game design.

In summary, the expert evaluation supports the conclusion that CalcQuest Adventure provide valuable insights into the quality and effectiveness of a game design, particularly during the prototype and formative evaluation stages. By leveraging experts' knowledge and experience, the SEQ helps identify design strengths and weaknesses before conducting large-scale user testing specifically on the topics of differentiation and integration. Based on the result of analysis, the game prototype offers a learning experience that may enhances students' understanding on the topic. With an overall mean score of 3.85, the results indicate expert approval, validating the game's readiness for classroom implementation. Previous study on education field shows that range of 3.41 to 4.20 reflects a high level of engagement and satisfaction [18]. Higher levels of engagement and satisfaction in learning may contribute to improved learning outcomes and academic performance [22].

By improving comfort and minimizing usability issues, may enhance the game's effectiveness. According to experts, CalcQuest Adventure demonstrates that game-based learning can serve as a tool in learning mathematics for upper education level. Further research needs to be done to improve the design of the game and more suitable evaluation has to be carried out in order to create a suitable tool to learn mathematics, especially for undergraduate students. Future work may explore both content refinement and game engine optimization, particularly through the integration of more advanced algorithms to improve overall system performance and user experience [23]. This study contributes to the limited body of research on serious games for undergraduate calculus by demonstrating the feasibility of expert-validated game design for differentiation and integration

Declaration

All data analyzed during this study are included in this research. The authors declare that there is no conflict of interest. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors' Contributions

The corresponding author conceived the research idea and provided overall guidance. All authors contributed equally to the research activities, game design and development and data analysis. Manuscript writing was led by the corresponding author, with discussion and brainstorming involving all co-authors. All authors read and approved the final manuscript.

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