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Digital Role-Playing Games as a Novel Approach to Learning Mathematics: A Quantitative Analysis

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Abstract

Taking advantage of our digital era commodities, a plethora of game-based learning activities and educational game genres have been introduced into numerous academic disciplines. However, research has shown that regarding mathematics the variety seems limited; especially for higher level topics, e.g. calculus, there is a lack of immersive games (Anagnostopoulou, 2021). In search of innovative ways for learning mathematics, this study presents an investigation into the use of the immersive features of role-playing games (RPGs) to introduce higher level mathematics to adult learners. As part of a PhD research, an RPG was designed and developed, in such a way that the abstract patterns and structures of mathematics were gradually introduced and intrinsically incorporated into six RPG mechanisms. An experiment was then carried out to examine whether learners can be enabled to gain higher mathematics skills solely by playing the game. Adult learners with a variety of mathematical background knowledge and gaming experience were recruited. The participants were asked to a) complete a pre-questionnaire and test, b) play the game, and finally c) complete a post-questionnaire and test. Data were collected via the questionnaires, observations, and interviews. The experiment yielded positive results regarding game usability, functionality, and effectiveness. This paper reports only on the quantitative analysis from the questionnaire data, whereas the qualitative analysis was published in a separate paper (Anagnostopoulou, 2023). The quantitative results suggest learning and understanding of mathematical processes concerning basic differentiation rules was significantly increased by playing the game. There was a statistically significant increase in mathematics scores after playing the game. The effect size was large for users with low to medium mathematical background skills, whilst the effect on those with high mathematical skills was small. Recommendations for future improvements as well as avenues for further research are proposed.

Key words: higher level mathematics; game-based learning; immersive games; mathematics games; adult education.

Introduction

The study presented in this paper involves exploring ways through which higher mathematical concepts can be incorporated into immersive games, in such a way that learning occurs without disrupting the gameplay flow and players' entertainment.

Research has shown that various disciplines are using highly interactive games as a teaching and learning method. Examples include: River City (Nelson et al., 2004), for application of scientific principles to modern societal challenges; Quest Atlantis series (Barab et al., 2005), for scientific reasoning, decision-making, language, and social studies; Arden (Castronova, 2007), for social science and economic theories, as well as Shakespeare's works; Ed-Wonderland (Hung, 2011), for English vocabulary; Humatan (Kannan, 2012), for human anatomy; and CMPRPG (Susaeta et al., 2010) for ecology. However, in terms of mathematics, the game closest to offering an immersive and highly interactive experience is Zombie Division (Habgood, 2007), a single-player action role-playing game created to teach prime numbers to children.

It seems that mathematics learning stands out from other subjects, especially at higher levels, as mastering a topic still often requires traditional hands-on methods like pen and paper exercises. It seems challenging to use digital games for advanced mathematics learning without disrupting immersion and the player's experience. By examining the available computer games, which were built to teach mathematics, Anagnostopoulou (2021) discovered that there is a lack of immersive games for higher level mathematics. The gap represents game-based learning with a high interactive player experience that would cover a level equivalent to Key Stage 3 (KS3) to Key Stage 5 (KS5) UK mathematics curriculum, corresponding to 14-18 year old students. While KS3-KS4 does not cover calculus, this paper reports only on calculus (KS5), although it could have been any topic.

The purpose of this study was to address this gap by making use of previous research on highly interactive educational games that enhance player experience. From the list of games with high immersion (Johnson et al., 2014), the role-playing games (RPGs) genre was selected. The study concentrated on identifying and demonstrating methods through which the environments and features of RPGs could be used as educational tools, paving the way for alternative and innovative approaches to teaching and learning higher mathematics. As an example, the mathematical content chosen to be incorporated in the game for this current study was the process of differentiation, in particular, the power rule of differentiation, derivatives of trigonometric and exponential functions, as well as the addition law of differentiation.

'The Red Circle' is an RPG, implemented by a designer (the author) and a developer, using Unity Engine, a powerful cross-platform game development tool used to create 3D interactive experiences and simulations. The gameplay is set in the medieval scenery of a virtual world, with which the player can interact by means of controlling an in-game character. The storyline accounts for the player to magically spawn in an unknown village, within which all the villagers are trapped, as an evil spirit blocked the only gateway. The player is set with the task to fight the evil spirit and free the villagers by unblocking the gates. On their journey, they need to build a sword and learn fighting techniques, following a series of quests that direct them to their final task.

Since the primary goal of the game is fun, mathematics is intrinsically incorporated in the journey, in direct relation with the story and quest lines, in a way that does not distract the player from their enjoyment. Having played the game, travelled through the virtual world, and completed the endeavours set, the player enhances their skills on the mathematics topics embedded, as the results of this study reveal.

This paper focuses only on the quantitative analysis of the research. Comparing learning outcomes and efficiency against other approaches to teaching was beyond the scope of the research.

Game design background

A brief account of the background which influenced the design and development of the Red Circle game is provided below.

Game-based learning (GBL)

Games appear to own the elements and competencies to stimulate learning, which is both innovative and based on a variety of pedagogical principles. They can be used to provide an environment where Papert's (1991) constructionism can be implemented, as the learner has a variety of methods to take control of their knowledge (Tang et al., 2007). Storytelling is a main feature in 'serious games' (Tang et al., 2007), as it provides the context for gameplay. Learners play the game following its mechanics, rules, and goals while at the same time they engage with the learning material included within. Moreover, in-game learning can be transferred to real world context (Oblinger, 2004).

GBL was chosen as an active, hands-on process in which educational content is integrated into a game environment. It should not be confused with gamification, which describes the addition of game elements in an educational subject (Dichev & Dicheva, 2011). The Red Circle gameplay consists of differentiated mechanics, where challenges are gradually introduced (scaffolding), thus addressing the individualisation of each player. Feedback is immediate and contextualised during the activities, enabling the player to assess their learning and repeat the activities needed to enhance their knowledge and achieve the objectives.

Digital role-playing games (DRPG)

To address the highly interactive player experience requirement, a DRPG environment was chosen for the gaming content, as the genre offers high immersion due to a combination of multifaceted elements. Among seven game genres, DRPGs score high in the player's experience scale in relation to immersion, flow, relatedness, challenge, competence, and autonomy (Johnson et al., 2015). Moreover, they enhance critical thinking and motivation (Chen and Wu, 2021). Additionally, the genre offers a means of description and guidance for the game's content, enabling a gradual unfolding of the design process. According to Anagnostopoulou (2022), DRPGs features and activities were integrated into the Red Circle gameplay to incorporate mathematical content. These activities included unlocking chests by turning the lock, interacting with in-game assets, like pigs and ores to pick up materials, engaging in combat, collecting items, crafting weapons, communicating with non-player characters to get quests, etc.

Concreteness fading

Concreteness fading is a term used to describe a step process, where learning begins with the use of concrete materials and then gradually fades to more abstract notions, moving from contextualised and perceptually rich visualisation to more iconic visualisation (Fyfe et al. 2014). An equivalent fading mechanism was used to introduce derivatives throughout the gameplay. The mathematical content was presented to the learner in a gradual process through a series of quests. Shapes were used as virtual concrete manipulatives, which progressively faded away to pure mathematical symbols. (Anagnostopoulou, 2022). For example, a three-step process of the derivative of $y = 4x^3 \Rightarrow \frac{dy}{dy} = 12x^2$ is presented in Figure 1:

Figure 1: Three-step fading process.

However, in the current project, for reasons of chunking the knowledge of higher mathematics and providing the chance for further training, revision and repetition, the fading process from shapes to mathematical expressions was constructed in five stages incorporated into six mechanics, as shown in Table 1.

Table 1. Six mechanics with five steps of fading.

Mechanics	Name	Fading Level	Content
1	Chests	1	Purely shapes
2	Pigs	2	Introduction of a few numbers
3	Ores	3	Mixture of numbers and shapes and introduction of trigonometric
4	Fight	3	and exponential functions
5	Mushrooms	4	Mainly mathematics symbols with few shapes
6	Anvil	5	Purely mathematics symbols

Intrinsic motivation of learning

Intrinsic motivation is defined as the doing of an activity for its inherent satisfactions rather than for some external result. When intrinsically motivated, a person is moved to act for the fun or challenge entailed rather than because of external prods, pressures, or rewards.

Most RPGs possess intrinsic motivation features for most players through the game design, social interaction, and gamers' psychological characteristics (Herodotou, 2009). According to the intrinsic motivation of learning taxonomy (Malone and Lepper, 1987), the more motives a designed learning environment contains the more effective it is. Moreover, endogenous learning is necessary i.e., activities that are directly correlated to learners' motivation (Habgood, 2007). The taxonomy introduced by Malone and Lepper (1987) is based on two intrinsic motivational parameters, individual and interpersonal. Individual motivation refers to challenge, curiosity, control and fantasy content, whereas interpersonal motivation is related to socialising factors, specifically cooperation, competition and recognition.

In line with the intrinsic motivation of learning theories, the prototype in this research focuses on individual motivation aspects as it is a single-player game. The Red Circle unfolds in a captivating fictional world, immersing players in a fantasy setting, while integrating educational content into intriguing quests. Players are granted autonomy to interact with the environment, engage in conversations with non-player characters, follow quest lines, or freely explore the map. Throughout the game, players encounter a variety of tasks, puzzles, and activities, each designed with clear goals and outcomes, which offer frequent feedback to challenge and motivate the player.

Methodology

To investigate the quality of the learning environment of RPGs regarding the mathematical content as well as the effectiveness of the RPG features used, two research questions and one hypothesis are presented within the scope of this paper, which correspond to the quantitative analysis of the overall research.

Research questions

1. What is the impact of RPG-based learning on the development of higher-level mathematics skills among learners?
2. What means can be devised to effectively teach higher level mathematics via game-based learning?

Research hypothesis

An RPG based around a quest structure with concreteness fading techniques will enable learners to increase their understanding and skills of higher mathematics in the area of differentiation.

Procedure

After The Red Circle prototype was designed and developed, it underwent Alpha and Beta testing to ensure that it runs as intended and detect possible bugs or glitches as well as provide indicative results (Anagnostopoulou, 2022). Once the game was ready for release, participants were recruited using a pseudo-random process. A pseudo-random sample is used, where completely random sampling is not always feasible, or is not appropriate to a given situation. In this situation, random participants were selected from groups of varying age, prior mathematical background, and prior gaming experience in order to ensure a more inclusive sample.

The research was conducted in two different environments: the Informatics computer lab at the University of Sussex for about two thirds of the participants, and remotely on their own computers for the rest. The study followed a three-step process. The participants were asked to complete a pre-questionnaire and test, designed specifically for the research to assess their mathematical and gaming backgrounds. They then played the Red Circle game (intervention), and their gameplay time was recorded. Finally, they were asked to complete a post-questionnaire which included qualitative data and a test designed to assess the participants' mathematics learning. Data were collected over a three-month period. The three steps of the experiment were completed in a single session, during which each participant spent 15 minutes on the pre-questionnaire and test, approximately 1 hour playing the game, and 15 minutes on the post-questionnaire and test. Upon collection of data, descriptive as well as inferential statistics were used to draw conclusions in relation to the research hypothesis.

Due to the nature of the experiment, there were no obvious disadvantages or risks, apart from spending participants' time, which was about 1.5 hours in total. The study did not involve underage participants. Since the sample was pseudo-random and unrelated to the research, there was no possibility of coercion or conflict of interest. Participants were recruited through email, where the nature of the experiment and ethical considerations were explained. Student participants were initially contacted through an email sent to their University of Sussex student accounts. For the remaining participants, a snowball sampling method was employed, starting with emails sent to acquaintances with diverse backgrounds in mathematics and gaming. The study was approved by the Science and Technology Cross-Schools Research Ethics Committee of University of Sussex with project reference numbers ER/EA434/1 for the Alpha testing phase, ER/EA434/2 for the Beta testing phase, and ER/EA434/3 for the main study.

Sample

As this game has the potential to be utilised by any adult learner of mathematics, the study was interested in sampling a wide range of learners. The experiment was conducted with 148 participants, ranging in age from 18 to 60 years old. The participants also had diverse backgrounds regarding their prior mathematical knowledge and gaming experience, including low, medium, and high levels in both categories, to serve the scope of the experiment.

The pseudo-random sample was inclusive enough as, although most of the sample (63%) was between 18 to 24 years old corresponding to the university student participants, the rest of the age groups (27%) were approximately evenly distributed (Figure 2). Most of the participants were males; however, there was a good representation of the other gender groups. There were equal group sizes of high and low prior mathematical background of the participants, while there also was a considerable amount of medium mathematics knowledge subjects. Regarding the distribution of prior gaming experience, approximately half of the sample had high gaming experience, and the other half evenly distributed between low and medium gaming experience.

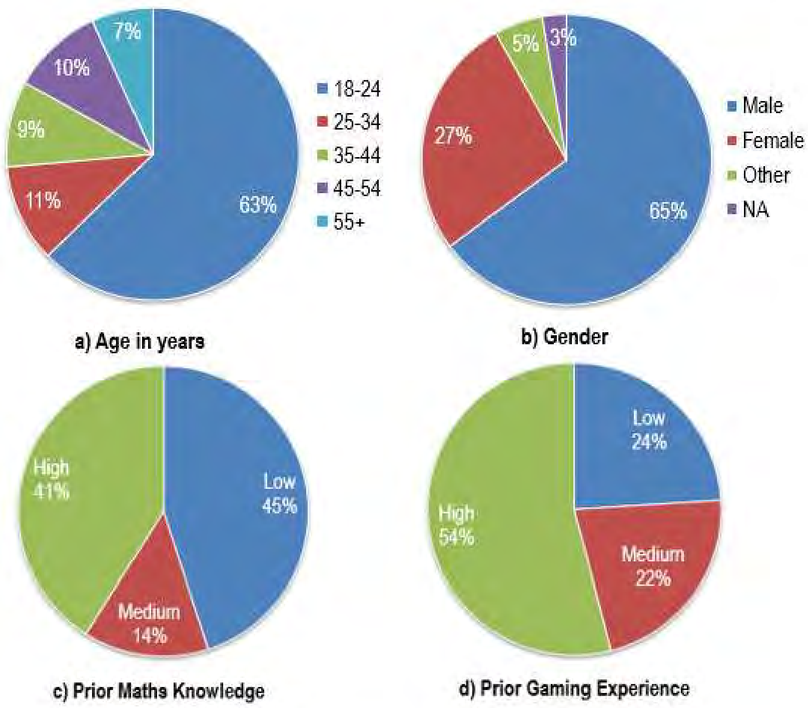

Figure 2. Distributions of a) Age, b) Gender, c) Prior maths knowledge, d) Prior gaming experience.

Data collection

Quantitative data was collected through two questionnaires and two tests, which were administered via Qualtrics survey tool.

A pre-participation questionnaire was designed to assess the participants' background regarding their mathematical and gaming experience. Among other questions which are beyond the scope of this paper, 13 of the mathematics questions addressed in the pre-questionnaire were also repeated exactly in the post-participation questionnaire for statistical analysis purposes. Note that the participants completed the questionnaire and the game in the one session, and they did not receive answers to the questions from the pre-test nor did they have access to the pre-test while completing the post test.

The post-test consisted of four parts:

a) puzzle-shaped multiple-choice questions, a sample of which is presented in Table 2,
b) simple function multiple choice questions (Table 3),
c) function combinations multiple choice questions (Table 4), and
d) a free answer question (Table 5).

Table 2. Sample of the puzzle-shaped multiple-choice questions.

For each of the following questions, tick all correct combinations:	
	○ 
	○ 
	○ 
	○ 
	○ 

Table 3. Sample of the simple functions' multiple-choice questions.

Tick the correct answer	
$\frac{d}{dx}(e^x) =$	◯ xe^x ◯ xe^{x-1} ◯ e^x ◯ e ◯ I don't know

Table 4. Sample of the function combinations multiple-choice questions.

Tick the correct answer	
$\boldsymbol{\frac{d}{dx}(\cos x - 7x^4 + 6)} =$	◯ $-\sin x - 28x^3 + 6$ ◯ $\sin x - 28x^3 + 6x$ ◯ $-\sin x - 28x^3$ ◯ $-\sin x - 7x^3 + 0$ ◯ I don't know

Table 5. Free answer question.

Differentiate the following:
$y = 4x^3 + \sin x - e^x - 5x^2 + 2x + 3$

Results

This section reports on the quantitative analysis of the data collected. The terms used in the analysis and tables are listed below:

Pre-test/scores: refer to the mathematical questions that have been answered by the participants before they played the game.

Post-test/scores: refer to the mathematical questions that have been answered by the participants after having played the game.

Maths components: refer to four components (puzzles, simple functions, combinations, and free answer) of the post-test.

Low, medium, high maths (maths groups): refer to the participants' mathematical knowledge, as determined by the pre-questionnaire scores (low: <30%; medium: 30%-70%; high: >70%).

Low, medium, high game (gaming groups): refer to the participants' gaming experience, as determined by the pre-questionnaire scores (low: 0-1 out of 5; medium: 2-3 out of 5; high: 4-5 out of 5).

Distribution of pre- and post-scores

The distribution of the participants' pre-scores is shown in the histogram of Figure 3. It can be seen that, although the mean value of scores is approximately central, the results are highly spread out. The three groups of the different mathematical background of the participants are evidently represented. Data is approximately bimodal representing 43 participants with low prior mathematics knowledge who scored 0%, 45 of high prior knowledge who scored full marks and 60 participants in between.

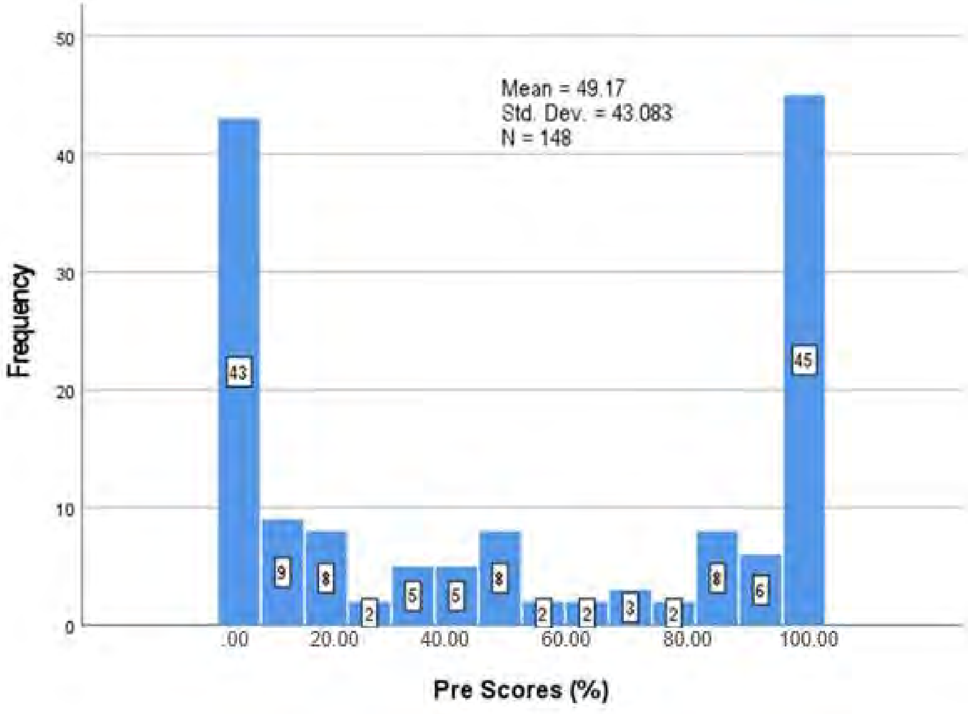

Figure 3. Histogram of the pre-scores.

Comparing the pre-scores (Figure 3) to the distribution of post-scores shown in Figure 4, it is evident that the participants' mathematics skills were significantly improved after playing the game. The mean is considerably increased to 87.63%, while the variability is halved. The minimum score has now been shifted from 0% to 15.38% corresponding to only one person, while more than half participants scored 100%.

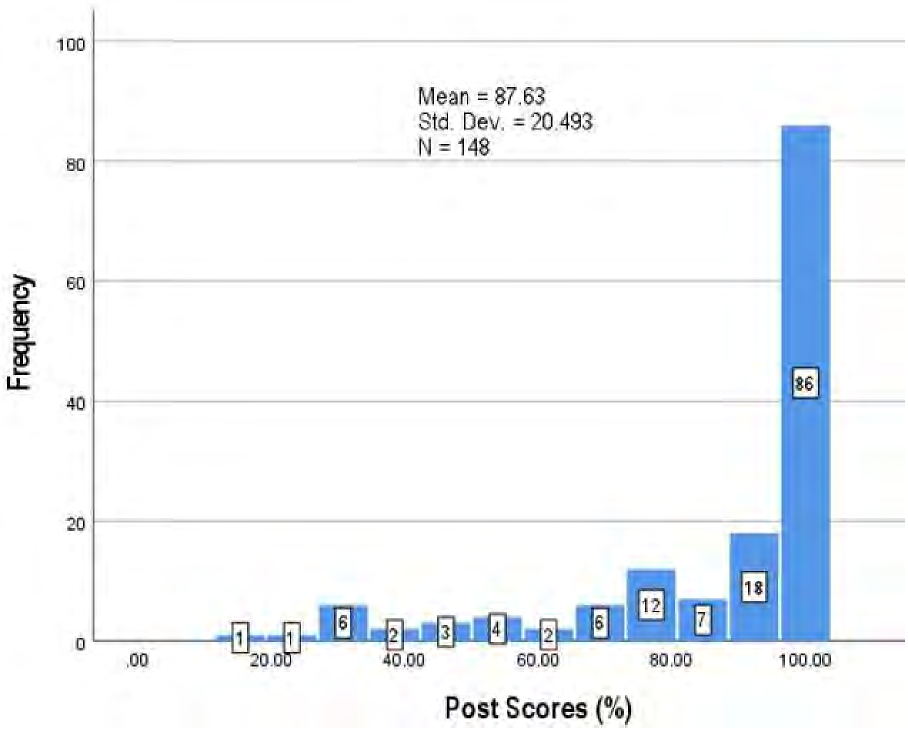

Figure 4. Histogram of the post-scores (148 participants).

Of the 148 subjects who participated in the study, playing the game elicited an increase in the post-scores of 102 participants compared to their pre-scores, two participants had a decrease in their scores and 44 participants saw no change. These 44 participants were players with strong mathematical background knowledge, hence scored full marks in both tests. There was a statistically significant median increase in mathematics scores for the mathematics test before playing the game (46.15) compared to the mathematics test taken after playing the game (100.00).

Distributions of pre- and post-scores for different variables

The results for the pre- and post-scores for different variables (mathematical background, age range, gaming experience, and playtime) are presented below.

According to mathematical background

Breaking the results into the individual mathematics groups (low, medium, and high) Table 6 reveals the following information.

Table 6. Comparison of the mean pre- and post-scores with respect to mathematics groups.

Prior Maths Experience	Size	Pre-scores Mean (SD)	Post-scores Mean (SD)
Low	67	5.86(9.48)	74.40(24.04)
Medium	20	50.00(10.73)	95.00(9.43)
High	61	96.47(6.52)	99.75(1.38)
Total	148	49.17(43.08)	87.63(20.49)

By comparison of the means, it is evident that the low mathematics group significantly improved their mathematics scores. The medium mathematics group recorded a substantial increase in their scores, while a slight increase was noted for the high group, as expected.

The statistical significance of the above descriptive results is presented in Table 7.

Table 7. Statistical testing for the pre- and post-scores with respect to mathematics groups.

Group	Size	Hypothesis	Test	Statistical outcome	Result
Low Maths	67	H_0: μ = 0 H_1: μ ≠ 0	*t*-test $p < .05$	$t(66) = 22.214$ $p < .001$ Cohen's $d = 2.714$	H_1
Medium Maths	20	H_0: μ = 0 H_1: μ ≠ 0	*t*-test $p < .05$	$t(19) = 17.085$ $p < .001$ Cohen's $d = 3.820$	H_1
High Maths	61	H_0: μ = 0 H_1: μ ≠ 0	*t*-test $p < .05$	$t(60) = 3.765$ $p < .001$ Cohen's $d = 0.482$	H_1
Whole Sample	148	H_0: Δ(median) = 0 H_1: Δ(median) ≠ 0	Sign $p < .05$	$z = 9.71$ $p = .0001$	H_1

Regarding the whole sample, there was a statistically significant median increase in mathematics scores for the mathematics test after playing the game compared to the mathematics test taken before playing the game. The participants with low prior mathematics background scored higher in the post-test than in the pre-test with a statistically significant increase between means of 68.542, with a large strength in the effect size as Cohen's d value implies. The medium mathematics participants recorded a statistically significant increase of 45.000 in their post-test with a large strength in the effect size. Those with high mathematics background knowledge also demonstrated a statistically significant increase in their post-test, however of smaller size (3.279) and a small strength in the effect size.

According to age

Regarding how the age of the participants affected their mathematics scoring, Table 8 reveals the following:

Table 8. Comparison of the mean pre- and post-scores with respect to age groups.

Age in years	Size	Pre-scores Mean (SD)	Post-scores Mean (SD)
18-24	93	62.70(42.59)	89.83(20.42)
25-34	16	34.13(32.39)	88.46(18.20)
35-44	14	14.29(29.85)	78.02(24.11)
45-54	15	32.82(35.78)	87.69(16.65)
55+	10	20.77(34.98)	79.23(22.37)
Total	148	49.17(43.08)	87.63(20.49)

The age group of 18-24 years old, which corresponds to university students, showed a measurable increase in their scores, while the rest of the groups revealed significant progress, with the group of 35-44 years old demonstrating the greatest change.

According to gaming experience

The pre- and post-scores were analysed with respect to the subjects' prior gaming experience. Table 9 shows that all groups demonstrated a statistically significant increase in their mean scores, with the low gaming group exhibiting the greatest progress.

Table 9. Comparison of the mean pre- and post-scores with respect to gaming groups.

Prior Gaming Experience	Size	Pre-scores Mean (SD)	Post-scores Mean (SD)
Low	35	25.27(34.43)	80.88(23.40)
Medium	33	53.85(39.22)	93.71(13.39)
High	80	57.69(44.55)	88.08(20.91)
Total	148	49.17(43.08)	87.63(20.49)

According to playtime

Figure 5 shows the distribution of playtime for the sample. Playtime can be approximated to normal distribution, with a mean value ≅ 50 mins, mean = 2.55 corresponding between group 2 (30 - 50 mins) and group 3 (51 -70 mins), with a standard deviation of *SD* = 1.139 corresponding to approximately 20 mins.

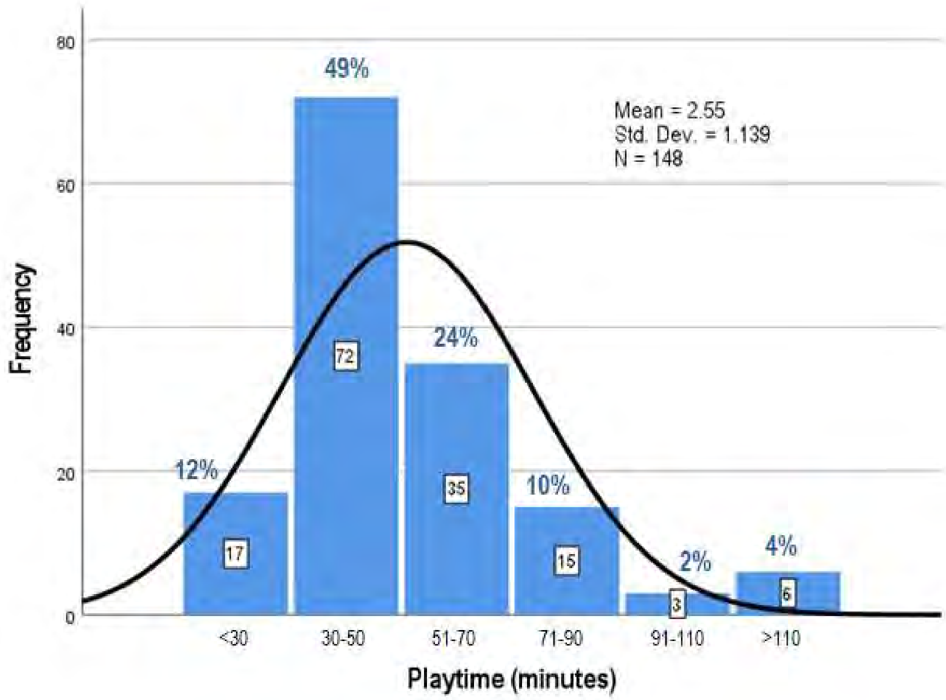

Figure 5. Distribution of playtime for the sample (148 participants).

Low playtime was mainly recorded by the age group of 18 – 24 years, which is comprised of students (63%). Hence, the average value of ≅ 50 mins makes the game suitable to be used in a teaching session. Longer playtime was recorded for higher age groups; among other reasons, it involved exploration of the map and interactions with the non-player characters (NPCs) of the game.

Regarding the effect of playtime in the post-scores, Table 10 indicates the following:

Table 10. Comparison of the mean pre- and post-scores with respect to playtime groups.

Playtime in mins	Size	Pre-scores Mean (SD)	Post-scores Mean (SD)
<30	17	76.92(39.03)	88.69(25.38)
30-50	72	61.75(39.50)	93.59(15.44)
51-70	35	24.40(33.56)	83.52(20.02)
71-90	15	37.44(46.42)	80.51(22.87)
91-110	3	35.90(55.65)	66.67(34.69)
>110	6	0.00(0.00)	65.38(24.20)
Total	148	49.17(43.08)	87.63(20.49)

Although the participants with low playtime (<30, 30-50 mins) scored higher in the post-test compared to those who spent more than 50 mins, examining the difference in the means of the pre- and post-scores indicates that the group of >110 mins playtime exhibits the largest difference of means. This result may indicate that those with higher mathematics knowledge and higher gaming experience could complete the game faster. However, the sample size for the >90 mins groups is too small to provide significant results.

Distributions of Post-scores for different variables

Inferential analysis of the post-scores with respect to mathematics knowledge, age and gaming experience is presented in Table 11.

Table 11. Statistical testing for post-scores with respect to mathematics knowledge, age and gaming experience.

Variable	Size	Hypothesis	Test	Statistical outcome	Result
Maths knowledge	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 78.761$ $p < .0005$	H_1(H-L) H_1(L-M) H_0(H-M)
Age	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 12.025$ $p = .017$	H_0
Gaming experience	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 5.695$ $p < .058$	H_0

Key: distribution equal: distribution of Post-scores among the variable groups is equal; L, M, H: Low, Medium, High maths groups; H-L: between High and Low maths groups.

Regarding prior mathematics knowledge, post hoc analysis revealed statistically significant differences in post-scores between the high and low (p < .0005) mathematics groups, and low and medium (p < .001) mathematics groups, but not between the high and medium mathematics groups (p = .074). The post hoc analysis further revealed statistically insignificant differences in post-scores between all pairs of age group comparison, as well as all pairs of gaming experience groups. Regarding playtime statistically significant difference in post-scores was found between the extreme groups of this variable, i.e. the < 30 mins and > 110 mins (p < .001) groups; the 30 - 50 mins and 51 - 70 mins (p < .001); and 30 - 50 mins and > 110 mins (p < .001).

Distribution of post-scores for the different mathematics components

The distribution of the participants' performance in the individual mathematics parts of the post-test (puzzles, simple functions, combinations, and free answer) is presented next.

Puzzle scores

Figure 6 indicates that the participants scored high in the puzzle section of the post-test with an average of 82.50% (SD=19.55%). 52 people scored full marks, and none scored zero. The minimum score was 20% (n = 2).

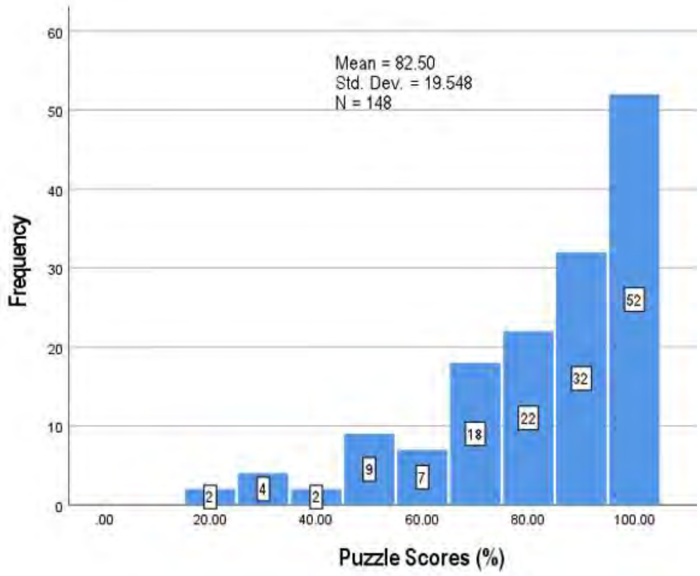

Figure 6. Distribution of puzzle scores for the sample (n = 148).

Simple function scores

Comparing Figure 6 with figure 7, it can be concluded that the sample performed better in solving simple functions (e.g. $\frac{d}{dx}(e^x), \frac{d}{dx}(\sin x), \frac{d}{dx}(4x^3)$), than they did in the puzzle section. The average score was 90.06% with a lower spread of scores (SD = 16.30%). Nobody scored 0%, 95 people got 100%, while the minimum score was 28.57%.

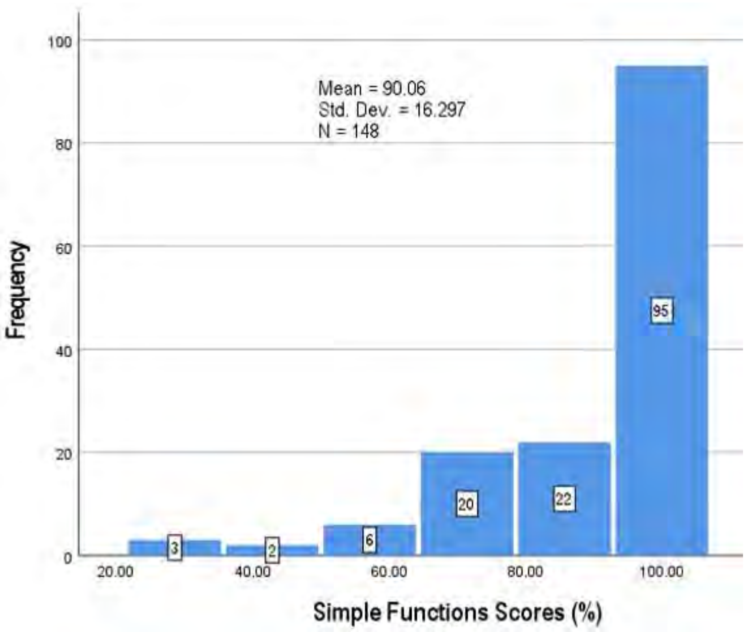

Figure 7. Distribution of simple functions scores for the sample (n = 148).

Combination scores

In the combinations part (Figure 8), functions such as $\frac{d}{dx}(4x^3 + \cos x - e^x)$, 78 participants got full marks, nobody scored 0% and the minimum score was 18.18%. The mean was high (87.35%) and the spread low (SD = 18.20%).

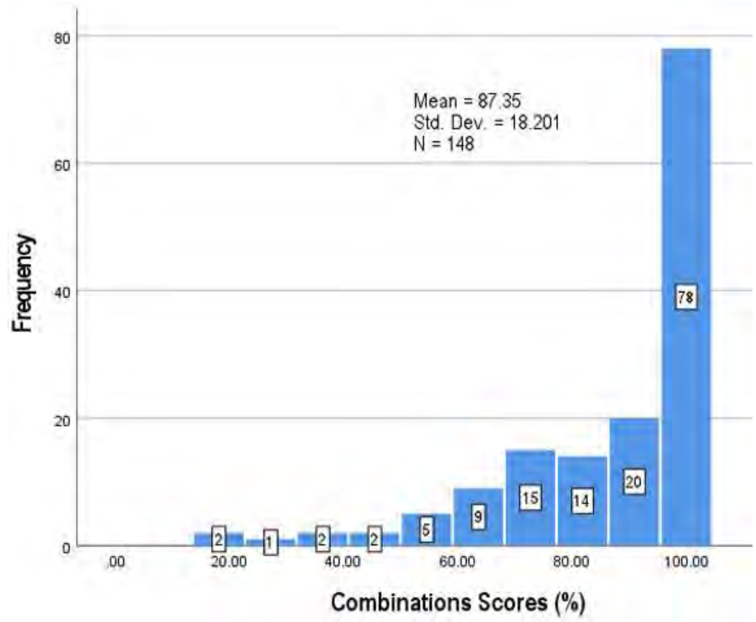

Figure 8. Distribution of combinations scores for the sample (n = 148).

Free answer scores

The free answer question was a question that the participants had to type their answers rather that select the correct one out of multiple choices. As seen in Figure 9, although the mean score is high (83.56%), the spread is the highest of all the 4 parts (SD = 29.42). Ten participants scored 0%, while 95 scored full marks.

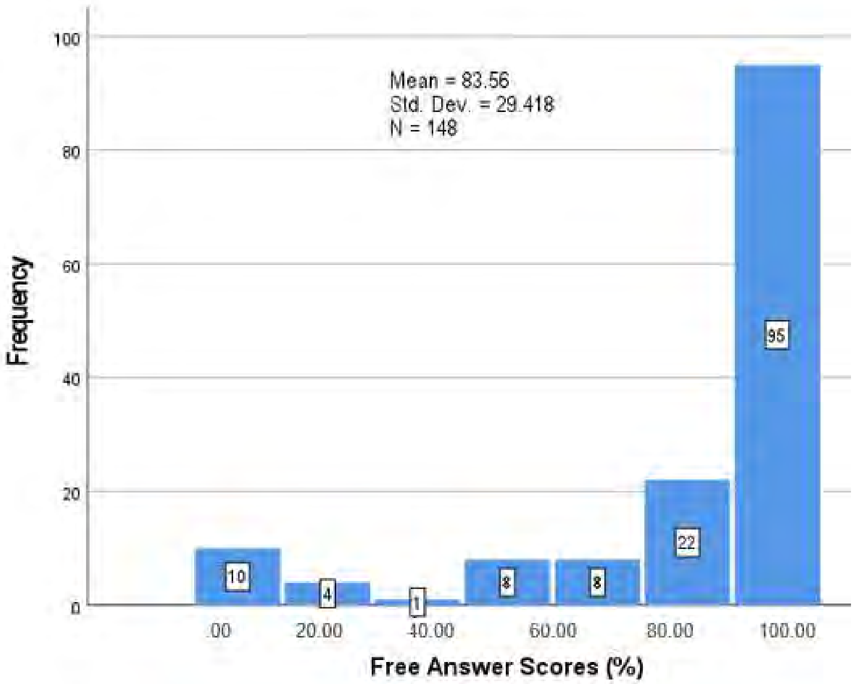

Figure 9. Distribution of free answers scores for the sample (n = 148).

According to mathematics background

Regarding the distribution of mean scores in the 4 individual parts with respect to the players' prior mathematics knowledge, Table 12 shows a uniform distribution of the results, with the lowest mean that of the low mathematics groups when they answered the free question. It is also worth noting that although the high mathematics groups scored above 99% in all abstract mathematics parts (simple functions, combinations, free answer), they did not do equally well in the puzzle part (mean = 82.50%).

Table 12. Comparison of the mean scores with respect to mathematics groups.

Prior Maths Knowledge	Size	Puzzles Mean (SD)	Simple Mean (SD)	Combinations Mean (SD)	Free Answer Mean (SD)
Low	67	75.22(21.70)	79.53(18.81)	74.90(19.52)	66.42(35.94)
Medium	20	93.00(12.18)	95.71(9.38)	91.82(13.48)	92.50(15.74)
High	61	82.50(15.95)	99.77(1.83)	99.55(1.98)	99.45(2.99)
Total	148	82.57(19.55)	90.06(16.30)	87.35(18.20)	83.56(29.42)

According to gaming experience

The participants' prior gaming experience revealed an approximately uniform distribution of the mean scores in all gaming groups (Table 13). A slightly lower mean score was observed in the low gaming group when they completed the free answer test.

Table 13. Comparison of the mean scores with respect to gaming groups.

Prior Gaming Experience	Size	Puzzles Mean (SD)	Simple Mean (SD)	Combinations Mean (SD)	Free Answer Mean (SD)
Low	35	82.29(18.48)	86.94(17.45)	81.82(20.21)	73.81(34.37)
Medium	33	86.97(16.67)	92.64(14.78)	91.74(13.89)	92.42(18.21)
High	80	80.75(20.97)	90.36(16.36)	87.95(18.45)	84.17(29.87)
Total	148	82.50(19.55)	90.06(16.30)	87.35(18.20)	83.56(29.42)

Statistical significance of the results

The significance of the above observations is further analysed. Table 14 summarises the statistical results among the four parts of mathematics questions.

Table 14. Statistical testing for post-scores with respect to the four individual parts.

Part of Post maths test	Size	Hypothesis	Test	Statistical outcome	Result
Puzzles-Shapes	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 20.801$ $p < .001$.	H_1(H-L) H_1(L-M) H_0(H-M)
Simple Functions	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 68.623$ $p < .001$.	H_1(H-L) H_1(L-M) H_0(H-M)
Combinations	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 85.448$ $p < .0005$.	H_1

Free Answer	148	H_0: distribution equal H_1: distribution not equal	Kruskal-Wallis $p < .05$	$\chi^2(2) = 60.523$ $p < .001$	H_1(H-L) H_1(L-M) H_0(H-M)

Key: distribution equal: distribution of scores among the maths groups is equal; L, M, H: Low, Medium, High maths groups; H-L: between High and Low maths groups.

The post hoc analysis revealed statistically significant differences in puzzle, simple functions and free answer scores between the high and low mathematics groups, and low and medium mathematics groups, but not between the high and medium mathematics groups. Statistically significant differences were also observed in combinations scores among all groups.

Difference in preference of mechanics

Figure 10 below, presents the players' preference regarding the 6 mechanics in the game, which served to introduce the process through which the virtual concrete manipulatives of shapes gradually fade to the abstract notion of mathematical symbols (Mechanics 1: full concreteness – Mechanics 6: full abstractness).

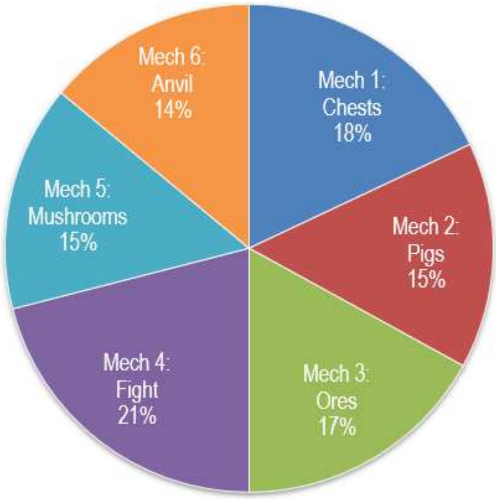

Figure 10. Preference of mechanics for the sample (n = 148).

The distribution of preferences is relatively even across the six mechanics, indicating a smooth transition between the fading stages. There is a slightly increased preference noted for Mechanics 4, the Fight, which is unsurprising given that players generally prefer combat in games (Castronova, 2007; Anagnostopoulou, 2024). Additionally, Mechanics 6, the Anvil, which scored lower in players' preferences, involves full abstractness. A possible explanation for this could be found in the limitations of gameplay. Originally, the design included eight fading mechanics instead of six, to ensure the consolidation of learning and an easier transition from stage 5 to greater abstraction. However, due to limited time and resources, the mechanics had to be reduced to six. Furthermore, the constraints on gameplay time during the experiment might have prevented players from sufficiently repeating quests and mechanics to enable a smoother transition to abstraction, despite the inclusion of the Red Circle game.

Statistical significance of the players' preferences of mechanics

Friedman's ANOVA tests were run to determine whether there were significant differences in the preference of mechanics among the groups of participants with different mathematics and gaming backgrounds (i.e. the mathematics and gaming groups defined earlier). The results indicated that there was statistically significant difference between the unequal means regarding the preference of mechanics for all the categories of the mathematics groups, as well as the low and high gaming groups, whereas the medium gaming group preference was not statistically significant.

Conclusion

This paper outlines the quantitative outcomes of a study aimed at exploring effective methods for integrating fundamental rules of derivatives into an RPG digital game. Based on the above results, it can be inferred that the game effectively facilitated learning of differentiation. Statistical findings validate the research hypothesis and questions, demonstrating that the mathematical content can be successfully conveyed through a gradual fading process presented in discrete chunks.

Based on the findings of this study, the research questions can be answered as follows:

1. What is the impact of RPG-based learning on the development of higher-level mathematics skills among learners?

Game-based learning centred around RPG games has shown the potential to facilitate the acquisition of higher-level mathematics skills among participants. The research outcomes relate to how well the game helps improve mathematics learning. The increase of the participants post-scores in derivatives indicates that playing the game significantly boosted participants' mathematical skills, particularly for learners with low or no prior mathematics knowledge. It needs to be reminded that the scope of the present study is not to compare the effectiveness of game-based learning against traditional or other learning approaches. It merely demonstrated that immersive GBL could also work for higher level mathematics; in fact, in an engaging, motivating, and fun way, as the qualitative analysis concluded (Anagnostopoulou, 2023).

As anticipated, participants with a high mathematics background demonstrated a slight increase in their scores, affirming that the gameplay did not hinder or disrupt their existing knowledge. Although the group with medium prior mathematics knowledge experienced a notable improvement in their scores, the most intriguing result was observed among participants with low or no prior mathematics knowledge. The increase in their post-test scores was significant, with none of them scoring zero marks, and over half of the sample (58%) achieving full marks in the post-test. This is particularly noteworthy considering that initially 29% of the participants scored zero marks and 30% scored full marks in the pre-test. Statistical analysis further revealed that neither the age of the participants nor their prior gaming experience played a significant role in their scores. These results demonstrate that the game effectively enhances mathematics learning across various age groups and levels of mathematical and gaming experience, making it a valuable tool for diverse learners.

Furthermore, there was a noticeable correlation between the gaming experience of participants with a strong mathematical background and their performance in the puzzle section of the test. It was observed that those with greater gaming experience achieved higher scores in the puzzle section. One possible interpretation of this result is that experienced gamers have improved their problem-solving abilities through gaming experiences, which are known to cultivate a range of cognitive skills. However, since this correlation was found to be moderate, nevertheless significant, further research is warranted to explore this finding in greater detail.

The analysis of playtime data yielded interesting findings. The approximately 50 minutes of the mean gameplay time makes the game highly suitable for integration into teaching sessions, especially considering the observed low playtime was mainly recorded by the age group of 18 – 24 years, which is mainly comprised of students. Statistical analysis indicated significant differences in the mean ranks of the post-test scores between the extremes of the playtime groups. Specifically, significant differences were observed between fast players and slow players. Fast players tended to achieve higher scores, although within a narrower range between pre- and post-scores, indicating higher level of experience in both gaming and mathematics. On the other hand, slow players, while potentially obtaining lower scores than their faster counterparts, exhibited a more substantial increase in their achievements. This highlights the importance of considering individual gameplay pace.

2. What means can be devised to effectively teach higher level mathematics via game-based learning?

The mathematical content can be effectively delivered through a gradual fading process, presented in chunks. Leveraging the features of role-playing games, mathematical tasks seamlessly blend into the quest structure of a narrative. The participants showed approximately equal preference in the mechanics presented in game, demonstrating a smooth transition through each fading stage. It is recognised that the transition could be smoother towards the last stage of abstractness by adding one or two more steps, as was originally designed but due to limitations in time and resources could not be implemented.

Although learners with a high mathematical background did not contribute significantly to the research based on the difference in their mean scores between the pre- and post-tests, they did reveal an important finding that warrants further investigation. Interestingly, a significant portion of these participants did not perform well with the shape questions (mean score 82.5%) compared to the symbol questions (simple functions, combinations, free answer) where they scored above 99%. It is worth noting that this issue cannot be attributed to a design flaw, as the participants with low and medium mathematical proficiency performed equally well on both the shape and number questions. It appears that while these learners were familiar with the rules of derivatives, they lacked a deeper understanding of the underlying mechanism of differentiation. Their knowledge was limited to applying memorised techniques to familiar problems, but some struggled when faced with unfamiliar problems that required a deeper understanding of the process. A possible reason could be that their learning was based on surface-level memorisation rather than a comprehensive grasp of the process, hindering their ability to apply their knowledge effectively in new situations. This argument aligns with Lockhart's (2012) criticism of traditional mathematics teaching methods. He argues that the current approach to teaching mathematics focuses too much on memorisation, procedures, and rules, rather than emphasising the creative and intuitive aspects of the subject. The overemphasis on standardised testing and the pressure to produce correct answers stifle students' curiosity and intrinsic motivation to explore and understand mathematical concepts deeply. Lockhart argues that mathematics should be taught as an art form, encouraging students to engage in mathematical thinking, problem-solving, and exploration.

Limitations and future suggestions

The Red Circle game stands as a pioneering example providing a practical demonstration of how advanced mathematics can be integrated into a game-based learning environment. However, since this is the first study in the area, further research is needed on several issues that were not addressed due to limitations. As Castronova (2007) pointed out, the development of a proper educational RPG game requires a great deal of time, resources, and funding. The present study was a part of a PhD thesis, the game was built by only one developer and one designer, therefore limited by time and resources. Consequently, a small sample size relative to the entire adult population was used, which may affect the generalisability of the findings. With a proper group of researchers, designers, and developers this single player game could be transformed to multiplayer to also account for the social aspect and learning through zone of proximal development (Vygotsky, 1978), as scaffolding can occur when more skilled players provide guidance, support, and feedback to help others progress (Peterson, 2016). Furthermore, multiplayer environments can account for interpersonal motivation, an intrinsic motivational factor introduced by Malone and Lepper (1987).

The research addressed the challenge of consolidating advanced mathematical knowledge through the implementation of a fading process. The integration of gameplay mechanics that require the application of mathematical principles allowed players to reinforce their understanding of key concepts over time. The inclusion of different difficulty levels and adaptive feedback systems ensures that the game accommodates learners of varying skill levels and promotes individualised learning experiences. However, the limited participation testing time did not allow including the original eight mechanics as set out in the initial plan. Since playtime is not an issue any longer, the next step for the current game is to add two more mechanics to allow players repeat tasks and use trial and error methods, hence progress at a better individual pace.

The aim of this study was to find ways to make immersive game environments work for the teaching and learning of advanced mathematics, similar to their successful application in various other disciplines. A reasonable future recommendation would be to compare the effectiveness of learning through the game with other teaching methods. There is already an ongoing research set in place, aiming to contrast the current results with those from a traditional 50-minute lesson on derivatives delivered in classroom.

Further future suggestions include expanding the mathematics content, to include mechanics for more differentiation rules, such as the product, quotient and chain rules of differentiation or even explore how to incorporate different mathematics topics, like trigonometry, integration etc., or to create content that assists students with deeper understanding of mathematical concepts.

Overall, this project advances the understanding of how immersive games features can be effectively leveraged as an educational tool to enhance digital game-based learning and paves the way for future research and development in this area. The research was awarded a PhD (Anagnostopoulou, 2024) and received the best thesis award in ECGBL 2023, where the qualitative results were presented (Anagnostopoulou, 2023).

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