Who Stole the Book of Kells? Description and Player Evaluation of a Cryptography Game for Primary School Students

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Abstract: Several studies suggest the need to develop technology skills from a young age. The development of computational thinking enhances multidisciplinary abilities, such as abstracting and decomposing a problem into smaller parts to find a solution. Among various tools, educational games can be implemented to efficiently stimulate the development of technology skills in primary school students. The current paper describes an educational game designed to motivate players to learn and reflect on cryptography, a collection of computer science techniques adopted for data protection. *The Code of Kells* is a mystery game that aims to support the development of computational thinking and maths abilities for primary school students. In this collaborative game, 10-12 years old players use cryptography techniques to discover who stole the Book of Kells – an ancient manuscript kept in the Trinity College Library in Ireland. To identify the criminal's identity, the players should work on teams and follow a map of Dublin city to collect encrypted clues hidden in popular locations, such as Phoenix Park and Dublin Castle. The participants should follow guidelines provided by a cipher sheet that illustrates cryptography techniques such as Caesar's Cipher, Polybius Cipher, Pigpen Cipher and the Morse Code. Each clue leads the player closer to the revelation of who stole the book of Kells. In this study, 80 primary school children (10-11 years old) evaluated *The Code of Kells* by sharing their experience through an adapted version of the Game Experience Questionnaire (GEQ). Nine dimensions of the questionnaire were assessed considering children’s previous mathematics and literacy scores, besides their levels of maths anxiety. Results suggest that children with higher mathematics performance positively perceived the game and found it challenging. However, results also indicate that maths high achievers students also felt tense while playing. Students with high levels of maths anxiety perceived the game as a sensory and imaginative immersive activity.

Keywords: game-based learning, computational thinking, cryptography, primary school, ciphers.

1. Introduction

In the current digital 21^{st}-century world context, even those who do not intend to work as computer scientists might be required to develop some level of digital literacy (Wing, 2006). Therefore, schools have been attempting to embrace a curriculum that includes the development of computational thinking skills, a set of human understanding and perceptions of the process computers use to solve problems (Weintrop *et al.*, 2016). According to Wing (2008), computational thinking goes beyond only being able to write a computer program but includes using abstraction and decomposition to tackle complex problems, and should its development motivated since the early years of education. Previous research suggests that teaching cryptography, a collection of techniques used for data protection, can foster children’s computational thinking. This can be due to cryptography promoting a natural and meaningful way of helping students build up problem-solving skills and strategic thinking (Koblitz, 1997). Cryptography learning can also increase the ability to abstract and decompose a problem into smaller parts to quickly find a solution – skills shared with other areas of education, such as mathematics (Klembalski, 2009).

Among various tools, educational games can be used to support computational thinking skills and cryptography learning in primary school. Some advantages of using games include promoting cooperation, learning engagement, and the development of problem-solving strategies (Baek, 2010) and stimulating collaborative work among players (Sun, Chen and Chu, 2018). A variety of skills can also be obtained through games for technology and maths education and communication, such as problem-solving and critical thinking (Checa-Romero, 2016).

The current paper describes the development and evaluation of a cryptography educational game designed to motivate players to learn and reflect on the power of ciphers in data protection. The game is followed by a narrative that includes historical aspects, supporting gameplay immersion and interdisciplinary learning.

2. Research Background

The current paper describes the development and evaluation of a cryptography mystery game designed for primary school children (8-12 years old). This section attempts to shed light on the research background that supports using this type of learning tool to support mathematics learning and the development of skills such as computational thinking.

2.1 Cryptography in primary school

Cryptography is the set of techniques used to protect private information, especially by encrypting and decrypting messages that do not allow third-parties to intercept them (Griffiths, 2015). Besides the practical applications on data security, cryptography is also considered a rewarding way to introduce mathematics and computer science topics into the classroom, besides stimulating pupils' problem-solving skills (Borelli *et al.*, 2002). While solving cryptography puzzles, students need to use several interdisciplinary abilities and personal experiences, making the challenge highly engaging (Kaur, 2008). Due to the challenge and fun embedded in puzzle-solving, children's interest in riddles appears even in the preschool-age (Azhmukhamedov, Kuznetsova and Vybornova, 2019). This level of engagement can support the development of computational thinking skills.

2.2 Cryptography and storytelling

The use of secret codes to protect information dates from way before digital technology became part of our daily lives – for instance, ciphers can already be found in the Bible (Borelli, 2002). In a book about the history of cryptography, Simon Singh describes how Mary, Queen of Scots, was beheaded after her plans of killing Queen Elizabeth were discovered (Singh, 1999). The plan details were coded using a substitution cipher, which made the text meaningless for those who did not know how the content was encrypted. However, they were intercepted and decrypted by an England spymaster, leading to the execution of the Scottish queen. This episode took place in 1586, and still nowadays, with some additional complexity, substitution ciphers can be used in data protection. The history of cryptography allows teaching ciphers with the aid of storytelling. This powerful tool can make complex topics more meaningful by providing a context, allowing children to connect the concepts learned to other areas of childhood (Casey, Kersh and Young, 2004). An essential component of historical approach-based education is the immersive feature of learning through a narrative. Children tend to learn better when immersed in a story (Manwell and Sullivan, 2013), and games are a vital tool to provide this immersive feeling. An engaging narrative is one of the elements that can make a game immersive, especially when it shows just what is needed at a given time without presenting all possible characteristics of the game at once (Mendonça, Mustaro and Mackenzie, 2012).

3. Methodology

The present paper provides the description and classroom evaluation of a cryptography educational game created for 8-12 years old primary school students. The evaluation includes a pre-gameplay phase when the teacher shares the students' maths and literacy scores to inform the researchers about their previous knowledge in those fields. During the pre-gameplay, researchers also use psychometric scales to collect students' levels of maths anxiety, a collection of negative feelings associated with activities that involve the manipulation of numbers and calculations (Jansen *et al.*, 2013; Caviola *et al.*, 2017). Then, as the topic can be new to many children, an introductory cryptography workshop takes place, where the researcher explains some ciphers. The workshop is followed by a team-based gameplay session where the students play a cryptography mystery game. Students self-report their playing experience using a validated questionnaire during a post-gameplay session. The following sections describe each phase of the classroom evaluation and detail how the user-testing data is analysed.

3.1 Cryptography introductory workshop

The evaluation of the Code of Kells takes place in a primary school classroom. The session should last one hour and be guided by a researcher, with the possible support of the teacher. The session starts with a 15-minutes cryptography introductory workshop. The initial minutes involve the history and the importance of developing ciphers, where the researcher introduces examples of secret messaging used before the adoption of cryptography. One example given to the students relates to the Ancient Chinese, who used to send secret messages by writing those on a piece of silk (Singh, 1999). The silk would then be scrunched in a ball covered with wax so it could be swallowed by a messenger, who would carry it in his stomach to the destination. The following minutes of the workshop includes presenting each cipher, demonstrating how they work, and inviting children to try to use the ciphers to read secret messages.

3.2 Gameplay

The game described and evaluated in the present paper is entitled *The Code of Kells*, a team-based multiplayer game where students are invited to solve a mystery. The game has a collaborative element, and all the players should work in teams. Using cryptography techniques such as Caesar's Cipher, Polybius Cipher, Pigpen Cipher and Morse Code, the teams can work on the puzzles that lead to solving the mystery. The game can be adapted for different ages and gameplay durations by including or excluding puzzles and ciphers. Table 1 summarises the different components of the game and is followed by their descriptions.

Table 1 The Code of Kells game components.

The Code of Kells – Game components		
Material	**Mechanics and Rules**	**Game ambiance**
- Digital slides - Game sheet - Cipher's sheet - Map of Dublin - Blank papers - Pencils	Players should get together in teams and solve encrypted puzzles. The first team to solve each puzzle is awarded. The team who solved more puzzles wins the game.	The narrative takes place in the Trinity College Dublin library and describes the theft of the Book of Kells

For this pilot study, the Code of Kells is presented in digital slides projected to the students. Before playing, students are invited to join their classmates in teams according to affinity. Each team receives a game sheet where their names and team name can be inserted, a map of Dublin city, and a cipher's sheet containing short explanations about each cipher used in the game. Teams are also provided with blank sheets of paper and pencils to be used to elaborate their responses to the puzzles.

The game narrative takes place in Dublin, capital of Ireland, more specifically at the Trinity College Library, the largest one in the country. This library holds the book of Kells, a manuscript gospel book written in Latin and dated from 800 years before current era (Bioletti *et al.*, 2009). The story of the game starts by describing a member of the staff nervously calling a team of detectives to communicate a tragedy: the book of Kells was stolen and someone needs to find it. The players are then invited to join this man in the library, who provides a piece of paper left by the criminal, containing a weird collection of letters and a key number (Figure 2).

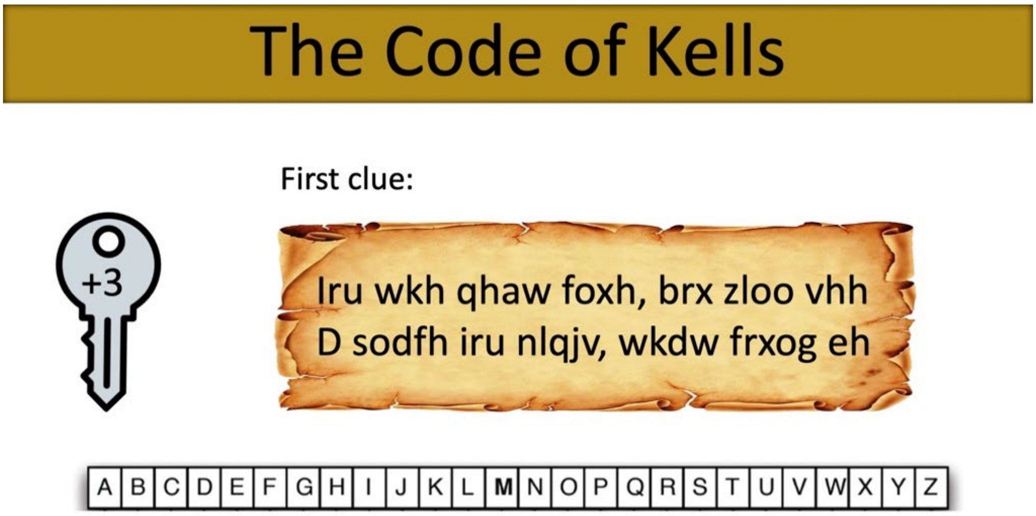

Figure 1: First clue left by the criminal in The Code of Kells.

Based on the cryptography introductory workshop, the players should be able to identify that the message was encrypted using Caesar's Cipher, where each letter is shifted a number of letters to the right (when a positive key number is used for encryption) or to the left (when a negative key number is used for encryption) in the alphabet. The key number on the slide represents the number of letters to be shifted. Using the cipher's sheet, the players decipher the message, which results in a riddle such as the following:

For the next clue, you will see

A place for kings, that could be

After deciphering the riddle, the team of players should check the map and try to identify to which place that clue leads – in the aforementioned case, the clue leads to the Dublin Castle. The first team to guess the next place to be visited receives a sticker on their Game sheet, and all teams move to the Dublin Castle. The narrative unfolds by inviting the teams to check the castle' walls only to find their next clue: a collection of numbers to be deciphered using the Polybius Cipher (Figure 2).

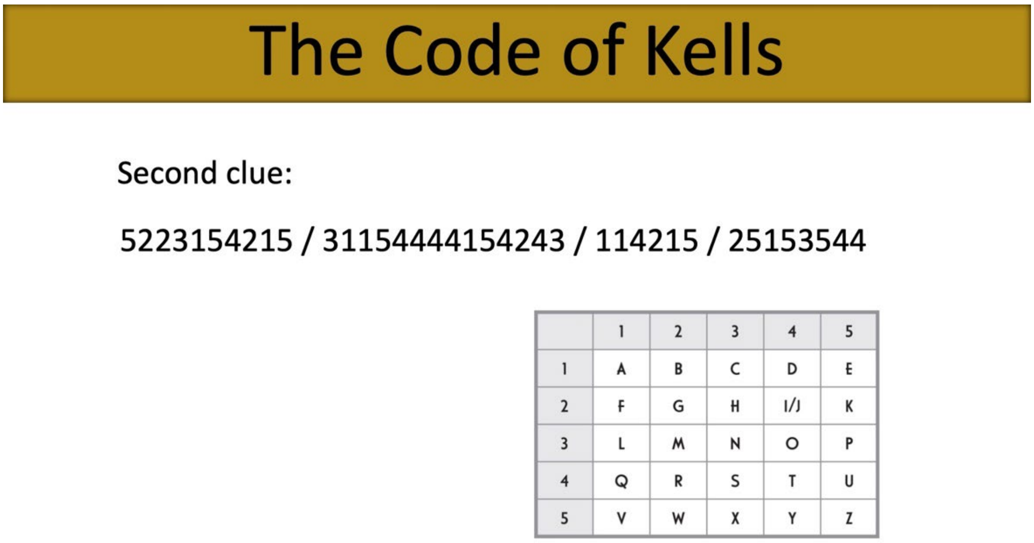

Figure 2*:* Second clue left by the criminal in The Code of Kells.

The game follows with the teams of players collecting and deciphering new riddles, and visiting different places that are relevant to the history of Dublin city. Finally, the teams reach the president of Ireland's house, where the president's dog hold the final clue that results in the following riddle:

A green jacket

Covers his arms

Do not ever steal

His Lucky Charms

The players then discover the criminal's identity: the Leprechaun, a fairy-like creature very popular in the Irish mythology.

3.3 Data collection

The current study is part of a research project that aims to evaluate the potential of games on maths learning. In this project, students are identified by random IDs to guarantee data anonymisation, so researchers have no access to students' real names. In the pre-gameplay phase, two main sets of data are collected. First, teachers provide details about students' previous grades on standardised tests for mathematics and literacy, ranging from 1 to 10. Later, researchers meet the students and invite them to answer the Abbreviated Mathematics Anxiety Scale (mAMAS), a scale developed and validated by (Carey *et al.*, 2017) to assess maths anxiety in primary school children. The scale consists of a self-report questionnaire with nine items. Children use a 5-point Likert scale to indicate how anxious they feel when dealing with maths situations, where one is equal to low anxiety, and five equals high anxiety. The higher the final score, the more anxious the child is. The minimum score is 9, resulting in a low level of maths anxiety, and the maximum score is 45, which results from a high level of maths anxiety. Students are then invited to share their experiences while playing the Code of Kells in the post-gameplay phase. This occurs by answering a modified version of the Game Experience Questionnaire (GEQ) (IJsselsteijn, de Kort and Poels, 2013), a tool developed to evaluate the players' perceptions considering several dimensions. Questions describing the player's experience while playing the game are presented, and the respondent should select the level of agreement (from 1, do not agree at all, to 5, extremely agree) As the original questionnaire is not designed for primary school children, an adapted version was adopted in this study. Table 2 shows the GEQ questions selected for the adapted version, besides what measures of game experience they measure. Some questions had their language simplified to adapt to the audience's level of literacy.

Table 2*:* Selected questions and dimensions included in the adapted version of the GEQ

User-experience dimension	Question (adapted from GEQ)
Behavioural Involvement	I felt important for my team
Challenge	I thought it was hard
	I felt pressured
	I felt challenged
	I had to put a lot of effort into it
Competence	I felt clever
	I was good at it
Negative affect	It gave me a bad mood
	I thought about other things while playing
	I felt bored
Positive affect	I felt content
Psychological Involvement - Empathy	I felt connected to my team
	I enjoyed working on a group
Psychological Involvement – Negative Feelings	I felt jealous about the other members on my team
Sensory and Imaginative Immersion	I was interested in the game's story
Tension/Annoyance	I felt annoyed
	I felt frustrated

3.4 Data analysis

The results collected from the data provided by the teachers and the mAMAS questionnaire are manually inputted into a password-protected digital database. The analysis is carried out through statistics techniques using the software IBM SPSS Statistics 21. The statistical analysis considers relevant tests for descriptive statistics, frequencies, and statistical significance to evaluate what individual aspects influence students' experience while playing *The Code of Kells* game considering the different dimensions of the adapted GEQ.

4. Results

This section describes the study's results considering the descriptive statistics and inferential analysis.

4.1 Descriptive statistics

The participants were recruited through the larger project that this research is part of. Researchers contacted the school and informed them about the user-testing procedures. Once the schools agreed to participate in the research project, parents' consent and students' assent documents were provided. The researchers then visited the school to collect data about students' levels of maths anxiety and previous scores in maths and literacy. Later, one of the researchers visited the school for the evaluation of *The Code of Kells*. The present paper describes a session that took place in five classrooms (four 4th class and one 5th class) from two schools located in south Dublin city. A total of 80 students participated in the experiment. Two of the participant classrooms were part of a girls-only school, resulting in a sample of 59 female students and 21 male students.

The evaluation session took place during an one-hour visit to each classroom, where students participated of the cryptography introductory workshop, followed by the Code of Kells gameplay session, and a 10 minutes session when students were invited to answer the adapted GEQ. During the gameplay, the participants were grouped in teams by affinity, but were also allowed to move around the classroom, getting closer to the smart board in case they wanted to have a better look at the game puzzles (Figure 3).

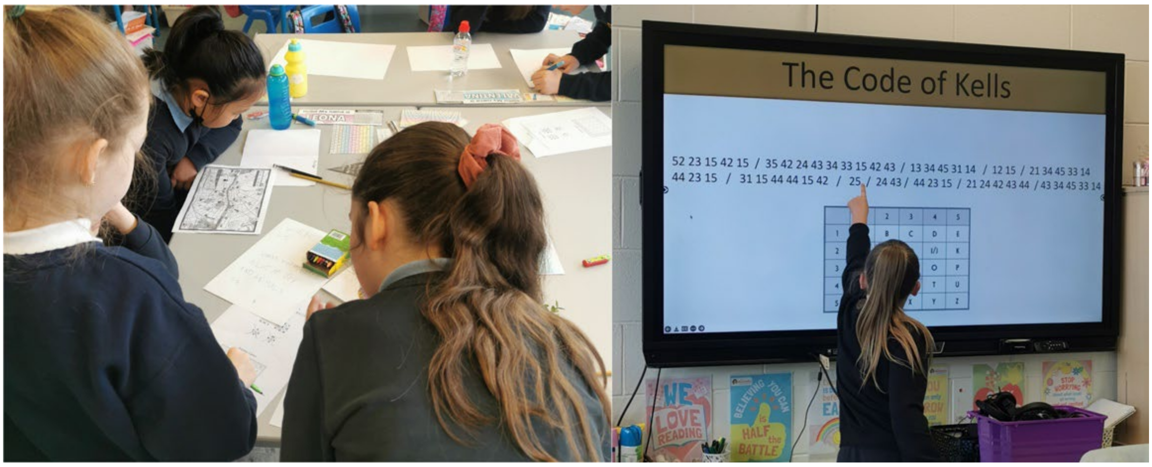

Figure 3*:* Classroom evaluation session of The Code of Kells.

Data cleaning was performed to remove users with missing values, resulting on the data analysis of a sample of 72 participants. Table 3 shows the means and standard deviations of the pre-gameplay individual metrics (mAMAS, literacy and maths scores), besides the means and standard deviation for each dimension of the adapted GEQ, applied during the post-gameplay phase. The dimensions with higher mean scores are, in descending order, Sensory and Imaginative Immersion (3.65) and Positive affect (3.31). Dimensions that represent a negative gameplay experience had low mean scores, such as Negative affect (1.30) and Psychological Involvement – Negative Feelings (1.49).

Metrics	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Maths score	0	10	5.49	2.29
Literacy score	0	10	4.86	1.83
mAMAS score	9	45	20.53	6.83
Positive affect	1	5	3.31	1.29
Sensory and Imaginative Immersion	1	5	3.65	1.13
Negative affect	1	5	1.30	0.72
Competence	1	5	2.69	1.31
Challenge	1	5	2.70	1.06
Tension/Annoyance	1	5	1.94	1.13
Psychological Involvement - Empathy	1	5	2.90	1.43
Psychological Involvement – Negative Feelings	1	5	1.49	0.99
Behavioural Involvement	1	5	3.22	1.44
Number of participants	72			

4.2 Inferential analysis

To understand what influences student's game experience while playing *The Code of Kells*, a Multivariate Analysis of Variance (MANOVA) was performed. For this analysis, three independent variables were considered: students' levels of maths anxiety, score of previous knowledge in maths, score of previous knowledge in literacy. The dependent variables considered in this study are the 9 components collected through the adapted GEQ modules: Positive affect, Sensory and Imaginative Immersion, Negative Affect, Competence, Challenge, Tension/Annoyance, Psychological Involvement – Empathy, Psychological Involvement – Negative Feelings, and Behavioural Involvement. Preliminary assumption testing was conducted with no serious violations noted. Assumption homogeneity of variance was tested by Levene's Test of Equality of Error Variances, and the assumption was met by the data ($p>.05$). Maths score had a statistically significant influence over three dimensions: Positive affect ($F(1, 68) = 7.9$, $p = .007$, partial eta squared = .104), Challenge ($F(1, 68) = 5$, $p < .05$, partial eta squared = .028), and Tension/Annoyance ($F(1, 68) = 9.6$, $p = .003$, partial eta squared = .124). The mAMAS score had a statistically significant influence over one dimension: Sensory and Imaginative Immersion ($F(1, 68) = 8.8$, $p = .004$, partial eta squared = .115).

The results suggest students with higher maths performance tend to have a more positive perception of *The Code of Kells*, and feel more challenged by the game. Furthermore, these students also feel higher levels of tension and annoyance when playing the game. Another suggested result is that students with higher level of maths anxiety have higher levels of perception of *The Code of Kells* as a game that stimulates their sensory and imaginative sense of immersion.

5. Conclusions and discussion

The present study aimed to describe and evaluate users' perceptions of *The Code of Kells*, an educational cryptography game for primary school students. The responses to the adapted GEQ reveal students had a positive experience while playing the game, resulting in high scores on positive dimensions of the questionnaire. However, when analysing what individual metrics influence the user experience in the game, some specific results should be carefully considered. The outcomes suggest students with higher maths scores had a more positive perception of the game. That can be due to the high correlation between students' maths abilities and their computational thinking skills, as demonstrated by previous studies (Qian and Lehman, 2016; Kumar, 2019). In fact, researchers have already demonstrated that connections across the domains of mathematics and computing are made by students (Sand *et al.*, 2021), and tools similar to the game here evaluated might be useful to support students' development of computational skills. The same metrics of maths scores also had a significant impact on students perceptions of challenge. Although being over-challenged can discourage some students, high achievers tend to feel bored with regular school activities (Cleaver, 2007; Freedberg *et al.*, 2019), and might appreciate the extra challenge provided by elaborated puzzles (Reinhold *et al.*, 2020). Curiously, students with higher maths scores also scored higher for the dimension Tension/Annoyance. Further analysis should be conducted to better understand why those students felt tense while playing. One possibility is related to the high level of competition among the teams. Although competition in educational games can be beneficial in increasing student's engagement and motivation (Cheng *et al.*, 2009), competition can also negatively affect a student's self-efficacy beliefs, motivation, and performance (Bandura and Locke, 2003).

Another result to be highlighted is the correlation between high levels of maths anxiety and students' perception of *The Code of Kells* as a sensory and imaginative immersion experience. The storytelling component of the game might influence this perception, especially considering that narrative-based learning leads students to connect the concepts learned to the human experience (Hobbs and Davis, 2012), which can result in making abstract concepts more meaningful and less scary – a very valuable outcome for anxious students.

6. Future Work

The present study has some limitations as the data collection did not include specific questionnaires to evaluate the level of students' computational thinking or focus groups/interviews to retrieve qualitative information about the players' perceptions. In-depth future studies need to be carried out to better understand the potential of the Code of Kells in supporting mathematics and computer science learning. Focus groups will be conducted in the future with the aim of collecting detailed qualitative data of students' perceptions of the game. Furthermore, a digital version of the game is planned to collect game logs metrics, such as the strategies used to solve the puzzles, the time taken to work on them, and the number of attempts. In a digital version, the game could also be easily adapted to have a narrative taking place in other countries' famous libraries, allowing the extension of the interdisciplinary character of the game.

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