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Playing non-educational logic puzzles as STEM incidental learning activities:

An analytical approach based in entertainment and engagement value

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Abstract

Game-based learning can be a powerful tool to improve students' motivation, information retention and problem-solving skills. Problem-solving skills are key when it comes to programming, as well as various mathematics domains, and there is a strong connection between the ability to solve puzzles and the ability to solve industry problems. Nonetheless, many of the currently available educational games fail as either learning activities or game experiences. Logic puzzle games' focus falls upon the game rules, thus compelling the player to employ logic notions to solve them. Hence, the gameplay fully revolves around the complexity of a logic paradigm, stemming from the effects of the core game mechanic. Therefore, we focus on well-designed and entertainment-centred logic puzzles and investigate their potentiality as incidental learning activities. Instead of postulating game design features that may be useful for education, we reverse-engineer four high user-rated puzzle games with a logic-derived gameplay and propose learning outcomes and assessment methods for each of them as learning activities. Provided that well-constructed puzzles are thought to be capable to train the user's mind and improve their problem-solving skills by challenging them with unusual dilemmas, and that playing games satisfies the player's need for achievement and keeping up with the challenge is a key reason for playing games, our aim is to understand if rationale-defying, yet entertainment-centred puzzles, can produce valuable incidental learning outcomes, thus correlating the acquisition of metacognitive problem-solving strategies to playing puzzle games.

Keywords: Puzzle, Logic Puzzle, Educational Game, Game-based Learning, Learning Objectives, Cognitive Abilities, STEM Learning, Logical Thinking

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Chapter 1

Introduction

This paper is concerned with incidental learning through puzzle games. In this introductory chapter, we describe the motivation for the study by examining the influence of puzzle games in the global games market. We also present the research question that the paper is concerned with and outline the structure of the paper.

1.1 Motivation

As video games have become increasingly popular, the global games market's value has increased at a rapid rate. As demonstrated in the yearly global games market reports by Newzoo, the global games industry was valued at 63.3 billion dollars in 2012. In contrast, the most recent report shows that the industry is valued at 159.3 billion dollars in 2020 [1].

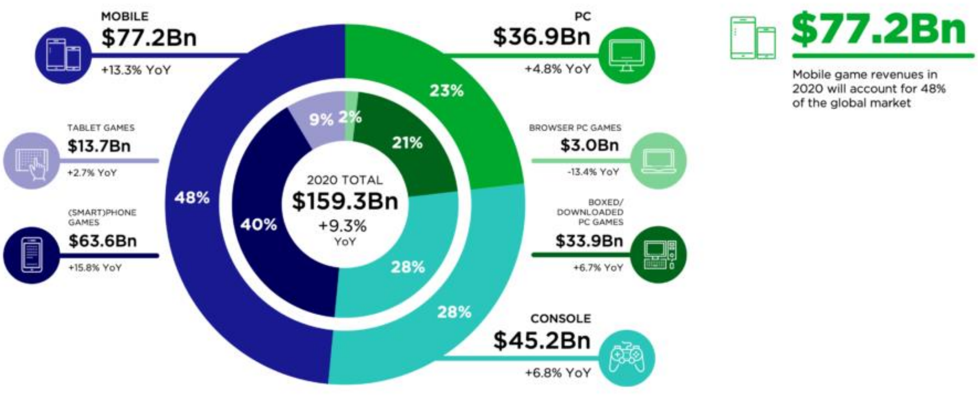

Figure 1: Graphic from Newzoo's 2020 Global Games Market Report (April update).

Due to its convenience and ease-of-use, mobile is currently the most popular platform to engage in a gaming activity, and as mobile game users tend to play on-the-go, there is a growing divergence between the type of gameplay popular on mobile devices and computer/console games. To indulge with a console or computer game, the player must typically be quite committed, as these games require a lot of time and attention from the user. The mobile platform, however, offers a variety of casual, short, or level-based video games, which the user can easily interrupt and later resume. Partially due to the sheer global uptake of the use of smartphones, but also plausibly due to the ease of playability for mobile games, the mobile market's revenue share in the global games market has been growing since the launch of mobile platforms such as App Store and Google Play in 2008, while the console and PC games' shares have been slowly decreasing. According to Newzoo, whilst the mobile, console, PC and web markets took up 18%, 43%, 30% and 9% of the games market share in 2012, respectively, in 2020, they are currently worth 48%, 28%, 21% and 2% of the market's value. The 2020 report further states that mobile "remains the largest segment in 2020, with revenues of $77.2 billion and growing +13.3% year on year"; on the other hand, "browser game revenues will continue to decrease as more gamers convert to mobile gaming" and "will decline -13.4% year on year" [1, p. 14].

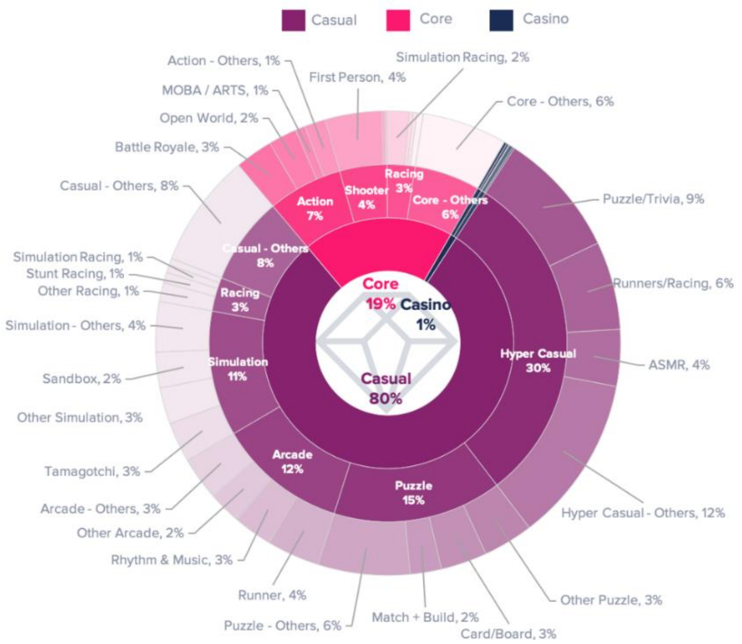

Figure 2: Share of global downloads by gaming genre in the first half of 2020, combining iOS and Google Play (iOS only for China). Source: App Annie.

The mobile platform provides the users with a wide range of games and has been taking on the legacy of the web game industry. In fact, many web game developers are now shifting their focus towards mobile games. Besides, similarly to their popularity on web browsers, puzzle games are the second most popular genre in the mobile platform.

Video games have become an important factor in our everyday lives, providing users with increasingly accessible leisure tools. Besides their entertainment function, many games can also challenge their users. Puzzles are one of the fundamental ways in which games can challenge players, as they encourage reasoning by providing their user with a series of simultaneously enjoyable and rationale-defying tasks. C. Linehan, Z. H. Morford and B. Roche further define puzzle games as "those video games where problem solving is the central mechanic" [2, p. 184].

Puzzles have a wide applicability and are often incorporated in other game genres. In fact, non-puzzle AAA titles frequently make use of puzzle challenges as a form of play to increase the entertainment value in specific game interactions. The Action RPG *The Elder Scrolls V: Skyrim (2011),* the Strategy RPG *Divinity: Original Sin II (2017),* or even the expansion pack *World Adventures (2009)* in the Life Simulation game *The Sims 3* are examples of this practice. This wide-ranging use of puzzles can be partially justified by their efficacy in the creation of challenge through the definition of a goal and a set of rules and placing value in the player's actions. Besides, puzzles can act as mental challenges, which can add significant variety to a mainly action-based game [3].

1.2 Research question

Through a survey of the literature, this study will examine the extent to which logic puzzle games can influence a player's cognitive abilities and provide learning outcomes, even if the games were not created for educational purposes. To address this question, the study will review available evidence to assess how engagement and entertainment value influences the learning and cognitive outcomes associated with the process of play, and to investigate a possible correlation between non-educational logic games, cognitive ability, and mathematics-based logic processes which are vital in various STEM fields. To better understand what constitutes a valuable game-based learning experience, we will conduct a search on educational games and evaluate by analysis their performance as game-based activities. Fundamentally, we will discuss their positive and negative aspects, and assess if they are entertaining as games and valuable as learning activities.

1.3 Document roadmap

The rest of the paper is structured as follows:

In chapter 2, we examine puzzle games and what makes a good puzzle, and further discuss the evolution of puzzle games' playability. We also consider the impact of games in emotional management, and in cognitive and educational outcomes.

In chapter 3, we describe the research methodology that was employed in the search for potentially valuable logic games and key components in effective educational games, and the criteria for selecting these games.

From chapters 4 to 7, the chosen games, namely *Four Color Theorem (2019), Hexologic (2018), Rullo (2016) and Dynetzzle (2014)*, are described, their potential learning objectives and learning evaluation methods are proposed, and their influence on learning and cognitive enhancements is further examined.

Chapter 8 concludes the research by correlating the acquisition of metacognitive problem-solving strategies to playing puzzle games, thus evaluating puzzle games as a tool for incidental learning and describing the future work.

Chapter 2

Puzzle Games: Experience and Learning

This chapter defines the methodology for the study. We first review definitions of puzzle games from the literature in order to arrive at a working definition for the paper. We further define a set of rules to evaluate puzzle games as incidental learning tools. Then, we assess the available evidence on how puzzles and games can be beneficial to improve players' learning outcomes and cognitive abilities.

2.1 Puzzle games under lenses

A puzzle demands that the player stops to think. However, it should not completely stop the process of play; integrated into the game environment, a puzzle allows the player to feel that their actions are part of the overall game structure. According to J. Schell [3], there are ten principles of puzzle design, that can be used to create good puzzle challenges in any game genre and are listed below:

1. It should be obvious for the player what the goal of the puzzle is; if not, the player might quickly lose interest and abandon play.
2. How to commence manipulating a puzzle should be clear for the player. When unsure of what to do, the player might decide not to play the game.
3. A player will likely become more engaged with a puzzle if they can sense they are progressing and slowly arriving at a solution. Nevertheless, if instead they feel stuck, they might become frustrated.

4. Although it is not particularly relevant in digital puzzle games, it is important for a puzzle to provide the player with a sense of solvability, related to the sense of progress.
5. Successful puzzles adhere to the maxim of gradually increasing difficulty, keeping the player in the flow.
6. Adding various pieces to the puzzle can assist the player with the process of solving it without entering a frustration state; if the player finds themself with no way out of a puzzle step, they can shift to another.
7. When solving smaller parts of a puzzle helps reveal a greater picture, the player will feel more involved in the game.
8. While removing part of the puzzle in a given interaction, hints can be very helpful to renew a frustrated player's hope and curiosity.
9. Providing the player with an answer can be useful to overcome player frustration in puzzles. Nonetheless, this rule is not relevant in digital games, as playthrough videos will eventually be uploaded online by players.
10. Puzzles where the answer is either obvious or seems impossible to understand will likely exclude most players from the game.

However, the game mechanics are the most valuable aspect when it comes to puzzle games. In fact, the dynamics in puzzle play are entirely constructed on the basis of the key mechanic. Hence, to create a successful puzzle game, we propose that a few more features should be considered, namely:

1. Simplicity – The game should revolve around a core mechanic. This mechanic should be simple enough to be manipulated in various ways throughout the game, in order to allow content variety.
2. Progression – Each new element in the game should be properly introduced. As can be stated in successful puzzle games such as *Portal (2007)* and *Braid (2008)*, the challenge drops whenever a new interaction is introduced, thus allowing the user to familiarize themselves with it before facing it in high-complexity puzzles. Linehan et al. have further proven this effectiveness [2].
3. Complexity and variety – It is crucial to add variety and complexity to the game throughout the gameplay. Nevertheless, the developer should assure that each

new non-introductory level has fewer solution paths than the previous level, independently of the amount of interactable objects in the play area. The solution does not necessarily need to have more steps than the solution for the previous challenge, as long as these steps are notably more challenging.

2.2 The evolution of Puzzle Experience

The first digital puzzle games emerged from arcades. Examples include *Tetris (1984)* and *Qix (1981)*. As was the convention for arcade games, these puzzle games were fast-paced and included action elements. However, as games moved to the comfort of people's homes, puzzle games evolved and now tend to provide the player with a very different experience, and it is fair to say that the typical puzzle game experience has shifted from hectic to serene. Many of the recently successful puzzle games invest in a calm and soothing environment, where the player can solve challenging puzzles while remaining amused and relaxed. When comparing these recent puzzle game environments to the first digital puzzle games, for instance, a clear ambience shift can be noted. While *Qix* and *Tetris* created a very high-intensity ambience, numerous modern puzzles, such as *FEZ (2012), The Witness (2016)*, *The Gardens Between (2018), Black (2018),* and *NABOKI (2019),* aim at projecting a relaxation effect onto the player. To achieve this effect, game developers tend to cast aside time restrictions, unnecessarily difficult instructions and game actions, or even defeat conditions; instead, they focus on a simple and clean user interface and on an atmospheric effect, provided by the game aesthetics. The previously mentioned games are a few examples of successful puzzle games that make use of these features.

Puzzle games, defined by C. Linehan et al. as games in which the fun is derived primarily from learning and applying specific skills to progress [2], have evolved and can now be categorized into several sub-genres, with different objectives. Examples include tile-matching puzzles, logic puzzles, narrative puzzles and many others [4]. In this research paper, the focus will be on logic puzzles. Provided that these games tend to be an abstraction from more general puzzle games, by removing game world components such as character control and prioritizing the element of reasoning in the process of play, we propose an analysis of logic puzzles' effects on learning and improving cognitive abilities, based on their strong logic component. The foundation for this potentiality derives from the historical use of logic challenges, typically presented through non-digital forms, such as paper exercises, to improve cognitive abilities.

Logic games evolved from paper formats, such as *Kakuro (1966)* and *Sudoku (1984)*, to digital forms, from where successful games such as *World of Goo (2008)*, *Interlocked (2011)*, *Hook (2014), Monument Valley (2014), The Gardens Between* and *Black* emerged. When it comes to logic puzzles, a relaxation feeling is extremely valuable to keep the player in the flow as they unravel difficult puzzles. Hence, many logic puzzles tend to immerse the player in a glorified relaxation feeling and/or educational experience.

2.3 Psychological influence of a game

Immersion, as described by B. G. Witmer and M. J. Singer, consists of "a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli" [5, p. 227]. Involvement, on the other hand, is further defined by the same authors as a mental state that is experienced "as a consequence of focusing one's energy and attention on a coherent set of stimuli" [5, p. 227]. The game mechanics and challenge in a game can cause the player to experience involvement, whereas the aesthetics immerse the player in the game. Moreover, the combination of immersion and involvement can further allow the player to experience presence.

Another psychological effect that can be motivated by a game is the feeling of flow. According to M. Csikszentmihalyi, "Flow is the result of intense concentration on the present, which relieves us of the usual fears that cause depression and anxiety in everyday life" [6, p. 112]. This feeling can be achieved in a game when the experience of play reaches a balance between the challenge associated with the game and the abilities of the player [7].

The presence or absence of sound and music in games has been proven to impact subjective experience, such as immersion, tension, flow, negative and positive affect and challenge factors [8]. The game environment can also project emotions onto the player. In fact, "If a game has the capability of evoking the player's fantasy and makes him feel that he is somewhere else or doing something exotic then that game is more enjoyable than a game which does not do so." [9, p. 39]. Besides, suspense has also been judged as an important feature to increase player enjoyment [10]. However, any delay in providing the player with feedback about their in-game actions has been proven inefficient [11] [12].

Subjective experience is central to explanations of the appeal of games; however, "players' motives for playing games provide an alternative perspective on understanding player engagement" [12, p. 778]. Players' motivations for playing a game will reflect on their engagement while performing the activity. Moreover, playing games satisfies players' need for achievement and keeping up with the challenge is a key reason for playing games.

2.3.1 In emotions

Players often resort to games as an entertainment medium, using them for emotion regulation purposes and to cope with their psychological state [13] [14]. In fact, several positive aspects are frequently linked to games [15]. R. Koster further stated that a study published in the *New England Journal of Medicine* in June 2003 considered games as mental challenges capable of delaying the developments of Alzheimer's; other activities, such as playing musical instruments, learning new languages, and dancing also yielded similar effects [16, p. 232]. As reinforced by J. Schell [3], games can be used as a tool to vent anger and frustration, cheer up, gain perspective, build confidence or to relax. In general circumstances, games allow us to detach ourselves from our real-world problems, thus allowing us to confront and eventually solve them with more ease.

Game aesthetics support immersion. Thus, relaxation-inducing aesthetic choices can greatly influence the player's psychological state. In some games, as the dynamic audio and visual assets immerse the player in the game world, they can relax to a soothing soundtrack and achieve an almost-meditational state. *The Gardens Between* and *Black* are examples capable of causing this aesthetic appeal. The audio-visual assets in *The Gardens Between* create an immersive scenario, enhanced by a fully animation-based storytelling experience (with no text or narration), environmental particle effects which the user can interact with, and a visual ambience shift throughout the levels. Similarly, but in a minimalist and much simpler fashion, *Black* immerses the player by synchronizing in-game animations and player actions with an iconic background music. As corroborated by B. Witmer and M. Singer, “Presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another” [5, p. 225]. According to C. Jennett et al., players’ presence and immersion can be measured through five factors, divided into “person factors (cognitive involvement, real world dissociation, emotional involvement) and game factors (challenge, control)” [17, p. 654].

Another potential benefit from the use of games can be the production of knowledge through educational outcomes. The way we learn can easily be compared to a game experience: by completing a series of challenges with incrementing difficulty, students can achieve goals and be graded, and move on to an interrelated subject coated by a new context. Besides, in the specific case of engineering and programming-related courses, students are often faced with puzzle-like problems. To solve them, they are typically required to dissect the main question into smaller parts, so they can construct a proper answer through code, considering all the relevant variables. As stated by A. Rojas-Salazar, P. Ramírez-Alfaro, and M. Haahr, regarding the study of games for learning to manipulate binary trees, “serious games have the potential to serve as a learning tool that accomplishes both objectives: to link new information with previous knowledge and to facilitate active learning” [18, p. 1].

2.3.2 In knowledge

Learning is a continuous process provided by interacting with different materials, and as a highly interactive entertainment medium, games can act as tool to provide students with these materials [19]. What makes a game enjoyable is its built-in learning process; a game becomes more enjoyable as we learn how to master it [16] [20]. Provided that a game is well designed, and the player can continuously achieve flow throughout their experience, as the completion of each game phase results in learning outcomes, then the player’s experience should also become more enjoyable as they learn more about the game. According to Hamari et al, “Drawing on flow theory, perceived challenge and skills (the main two elements of flow) are hypothesized to predict engagement and immersion, which in turn are believed to predict perceived learning” [21, p. 171]; in the state of flow, the user will become fully immersed in the task and thus produce greater learning outcomes. Aside from the game design elements, primarily displayed through game mechanics, the challenge a game provides is yet another factor that deeply influences its entertaining and engagement value, and a game which provides the player with a meaningful learning experience can also become more entertaining as the challenge grows.

The learning process associated with STEM (Science, Technology, Engineering and Mathematics), especially when it comes to the logical reasoning involved with computational tasks in the fields of Mathematics, Engineering and Technology, requires a deep understanding of abstract concepts, capability in algorithmic thinking, and logical reasoning [22]. Furthermore, and as supported by J. Holvikivi, "many studies indicate that ability in logical reasoning is not separate from overall intellectual capacity and that students who master reasoning and problem-solving tend to perform better in any science subject" [23, p. 367].

A study, led by S. Klymchuk and conducted on university students taking a second-year engineering mathematics course, revealed that "almost all participants believed that solving puzzles enhanced their problem-solving skills (97%) and generic thinking skills (97%). Most participants (82%) indicated other benefits for them apart from enhancing problem-solving and generic thinking skills" [24, p. 1115]; these benefits were described as "fun breaks" or "good ways to escape" stressful activities, or even as an incentive to the mind's performance.

Apart from the widespread belief that puzzles increase motivation, this form of rational thinking might also be linked to the development of professional skills, by engaging with students' emotions, creativity and curiosity, and enhancing their general thinking skills [24]. As reported by J. Holvikivi, "Reasoning is a central component of cognition that depends on theories of comprehension, memory, learning, visual perception, planning, problem solving, and decision making" [23, p. 368]. Besides, both mathematical and logical thinking are cognitively demanding and "heavily dependent on working memory and inhibitory processes" [25, p. 104]. Moreover, "Mathematics and logical thinking also share the requirement to be able to retrieve and apply normative rules, to draw conclusions on the basis of given premises, and to process abstract or symbolic content"

[25, p. 104]. Studies such as these suggest that education in mathematics improves logical reasoning, and that the development of mathematical and logical skills might be related. Thus, the creation of suitable digital puzzle games that follow good game design rules and logic puzzle principles could fulfil this motivation of increasing cognitive and mathematic skills while simultaneously acting as an accessible leisure tool.

2.4 Educational and non-educational games on Math learning

As the video game industry grows, and smartphones have become a ubiquitous and indispensable accessory, video games are also becoming more popular amongst children and teenagers, especially through the use of mobile platforms.

As they can act as powerful tools to increase motivation and engagement, video games have great potential when it comes to learning. As already discussed, a player can experience flow when there is a perfect equilibrium between their skill and the challenge faced in the game's action; this sensation allows the player to become further involved with the activity. The same happens in an educational scenario: if the student's knowledge is higher than the challenge in the exercises they are assigned with, they might become bored; otherwise, if the student has fallen behind and finds the assignments too hard, they might feel frustrated. The optimal learning experience can be achieved through a state of flow. Besides challenge, immersion in games is also a crucial factor when it comes to measuring engagement. Hence, if a game has well-designed mechanics, a specific educational scope, and the game's aesthetics produce a pleasant and harmonic ambience, then it is likely that this game can act as a tool for learning.

Well-constructed puzzles are thought to be capable to train the user's mind and improve their problem-solving skills by challenging them with unusual dilemmas [24] [26] [27]. Besides, problem-solving skills are key when it comes to programming, as well as various mathematics domains. Logic puzzle games' focus falls upon the game rules, thus compelling the player to employ logic notions to solve them. Hence, the gameplay fully revolves around the complexity of a logic paradigm, stemming from the effects of the core game mechanic. For this reason, logic puzzles are very useful as a puzzle subgenre, and especially relevant when it comes to practicing logic theorems and problem-solving.

When playing a logic puzzle, the player will normally be concerned with the puzzle only, rather than worrying about other typical aspects of playing games, present in any other genre or subgenre, such as platforming elements or character control. In fact, as previously stated, the gameplay for titles belonging to this subgenre of puzzle games revolves around a key game mechanic, which is typically simple and capable of producing challenges with wide-ranging complexity. For instance, in the game *The Gardens Between,* the core game mechanic consists of manipulating time. The characters follow a pre-defined path, and it is up to the player to let the course of action happen in its normal order, or in reverse. By stopping, advancing, and reversing the action's course, the player can interact with the game world and manipulate the game objects that are unaffected by the flow of time. Likewise, in the game *NABOKI*, the core mechanic is based on a simple concept: perspective. The player is faced with a three-dimensional object, composed of small cubes. By rotating the camera view, they can unravel new aspects about this composed form and slowly disassemble it. Furthermore, puzzles can also be a factor in retaining and motivating students, and there is a strong connection between the ability to solve puzzles and the ability to solve industry problems [28]. As a result, the creation of game-based logic puzzle challenges for programming and mathematics training can potentially be a valuable pedagogic tool.

Chapter 3

Literature Search Methodology

There is already a great amount of proclaimed STEM-based educational games in the games market, yet research shows that they do not seem to be effective as pedagogic tools [29]. The purpose of this analysis is to:

1. Prove that many educational games are not valuable as learning activities, understand what needs to be changed in available educational games to ultimately produce valuable mathematics and programming-based educational games, and to determine an effective method to search for these valuable games.
2. Understand if entertainment-centred logic puzzle games that are available online can be valuable educational activities.

For this purpose, we are conducting a broad online search on educational STEM-based games and cognitive-enhancing games, and another on non-educational logic puzzles that we will further analyse. The first search will be conveyed on Google, and thus is not platform-specific, whereas the second one will be conducted on Kongregate, a web game portal.

Upon searching for these games online using the keywords “educational programming game”, “educational math game” or “cognitive game”, all searches result in a great number of applications (March 2021). However, only a few of these remain after excluding the games that are not suitable as a pedagogical medium to learn mathematics or programming. According to K. Devlin [29], this initial filtering for mathematics games consists of avoiding:

1. Confusing mathematics itself with its representation (typically through symbols).
2. Presenting the mathematical activity separately from the core game mechanics.
3. Adding to the common belief that math is an obstacle to enjoyment.
4. Reinforcing the perception that math is built on arbitrary facts and rules with no unified logical sense.
5. Encouraging students to answer quickly, without reflection.
6. Contributing to the misbelief that math is intrinsically uninteresting.

The same rules can be considered when it comes to programming games. In essence, the object of learning should be the central mechanic of the game, rather than a side-quest, and the challenges should be designed to be both difficult and fun, by properly regulating the game's complexity at each phase.

From the large initial sample, Devlin observes that only a reduced number of games pass this filtering. Moreover, most of the few remaining games fail on gameplay tests, for either poor game design (the resulting game does not function properly as a game experience), or for lacking educational value (there is a proper game to play, but it does not provide a learning outcome).

A non-platform-specific search was conducted on multiple keyword-based searches. This resulted on a large number of applications; however, by applying the previously defined filters, most were discarded.

The first search, on "educational programming game", presented a list of "coding games". However, most were coding programs that do not match the definition of game (*CodeWars*, *CodeMonkey*, *CodinGame*, and *CheckiO*); instead, they consist of code editors. From the games among these results, only *RoboZZle* steers clear from explicit coding. The user can only "play" the remaining games writing code, either by text commands or by manipulating code blocks. Neither code nor programming concepts are mechanics to the game.

Given that these results displayed only one candidate for game-based learning of programming concepts without coding directly, the educational keyword was removed from the search, narrowing it down to “programming game”. As a result, a new list was displayed, showing games that use programming or programming logic as well implemented game mechanics. Some examples are *Lightbot (2008), Minecraft (2011), Human Resource Machine (2015)* and *Shenzhen I/O (2016).* From this list, only *Lightbot* is labelled as an educational game; nonetheless, the previously mentioned games have been studied for their positive effects in learning programming.

The search for “educational math game” resulted in various games and applications, such as *Prodigy Math Game (2015), Big Brain Academy (2005), DragonBox: Algebra 12+ (2013), Fraction Challenge: Math games (2020), Twelve a Dozen (2014), and MathLand (2018).* The first and last games fail the initial filtering, as they do not use math as the core mechanic, but rather as a side task to play the game; math is only used in *Prodigy Math Game* and in *MathLand* to fight monsters that come in the way of the player’s exploration process. Besides, one of the results, *Big Brain Academy,* is not a math-based game, but rather a cognitive ability game. The fourth result, *Fraction Challenge: Math games,* also fails the filtering process, as it is not game; it simply displays a series of simple mathematical operations and allows the player to choose the correct representation from two possible answers, and further incites the user to answer quickly, without reflection. *DragonBox: Algebra 12+,* on the other hand, can be a useful tool to practice introductory algebra, as it slowly introduces fractions as a game action, even though the mechanic revolves around simply solving fractions, by moving the fraction’s components. Similarly, *Twelve a Dozen,* although not advertised as educational, seems to be both an entertaining game and a valid pedagogical medium to learn basic number operations.

Finally, the search for “cognitive game” displayed a few applications labelled as “brain-trainers”, such as *Lumosity, CogniFit* and *Elevate*. This search also recommends games such as *Sudoku* and crossword puzzles. *Lumosity* and *Elevate* are further labelled in Google Play as educational, and *CogniFit* is labelled as a health and fitness application. These three applications share the same method: providing users with daily challenges, consisting of mini games, to evaluate their cognitive abilities. The only difference between the three applications is the taxonomy they employ for cognition.

From this filtering process, we can conclude that searching for educational games can be very inefficient, especially when including the "educational" keyword in the search, given that various applications are incorrectly labelled as educational, or even as games. Hence, to properly filter and consequently find relevant games, the user should use a platform-specific application or website, such as Google Play or Kongregate, rather than a search engine, as these applications and websites have a tagging system to categorize games by their genre or features. For instance, in Kongregate, the user can quickly find only math-related games. In websites such as Kongregate and Coolmathgames, the taxonomy for games is clearly defined, and thus allows the user to find very specific games with ease. In Coolmathgames, which only contains puzzle games, the games are manually divided into strategy, skill, numbers, logic, trivia, classics (e.g., chess, solitaire, etc.), word games, puzzles (jigsaw), memory, geography, and science. On the other hand, Kongregate hosts games from various genres, and thus has a broader tag system, including tags that are not even related to the mechanics, such as "good music", "cute", or even "unity", that specify the game engine in which the game was made. However, unlike Coolmathgames, Google Play and App Store, which decide the tags for each game, Kongregate allows the developer to tag their own game. Nonetheless, these tags are then verified by users, who can: downvote or upvote them, or even add more tags. The tags only become valid when they reach at least three votes. This player and developer collaboration produces very accurate tags as a result. Therefore, the tagging systems in Kongregate or even Coolmathgames are vastly superior to those utilized in Google Play and App Store, especially when it comes to educational or mathematic-based labels.

The four games which were chosen for this analysis, namely *Rullo, Hexologic, Four Color Theorem, and Dynetzzle,* were found on Kongregate by using the "math" and "puzzle" tags simultaneously. From the list of results, the games were sorted by highest rating and the currently unavailable flash games were removed. Afterwards, the highest rated games were played so as to confirm their puzzle value, and the games that were not assessed as logic puzzle games were removed from the list. Adaptations from classic and famous games, such as *Sudoku*, *Hashiwokakero (1990)* and *2048 (2014)* were also discarded from consideration. Each of the top 10 remainder games were analysed and described in Table 1, and those where the game mechanics rely on math rather than movement mechanics were prioritized. Uncommon and complex game mechanics were further weighted, and purely sum-chain based puzzle games were discarded, as they were very commonly found in this search. Afterwards, the game *Four Color Theorem* was added. This game was previously tagged as a math game but said tag has since been removed by the players as the game does not make an obvious use of mathematical concepts. However, the core game mechanic is purely based on a visual mathematical representation; hence, this game was added to the list. *Four Color Theorem* was also very popular, having a 4.10 out of 5 rating and 220,836 plays count. It has the following tags: Puzzle, Coloring, Mouse Only, Minimalism, Educational, and Painting. It is important to stress that these tags are user-voted, and only become visible when they attain user votes; the developers did not advertise their games as educational, yet the players decided to tag them as educational.

Table 1: Search for four logic puzzles with mathematics characteristics.

Name	Tags	Rating	Number of plays	Year
Hexologic	Math, Mouse Only, Puzzle, Relaxing, Minimalism	4.26	237,470	2018
Rullo	Brain, Math, Puzzle, Mouse Only, Minimalism, Educational	4.03	425,682	2016
10	Puzzle, Math, Block, Mouse Only, Brain	3.94	627,657	2013
Dynetzzle	Puzzle, Mouse Only, Brain, Math, Minimalism	3.91	265,796	2014
Puzlogic Plus	Mouse Only, Puzzle, Sudoku, Math, Relaxing	3.84	123,023	2019
9	Puzzle, Math, Mouse Only, Brain, Educational	3.82	339,558	2014
10 is Again	Puzzle, Math, Mouse Only, Brain	3.73	341,735	2013
Nambers Level Pack	Puzzle, Math, Brain, Minimalism, Mouse Only	3.58	164,052	2016
Nambers	Puzzle, Math, Mouse Only, Brain	3.57	14,246	2015
Finite Moves	Puzzle, Math, Brain, Mouse Only, Educational	3.52	42,373	2015

The games *9 (2014)* and *10 is Again (2013)* were discarded from consideration given that they are both sequels to the game *10 (2013)*, which was also disregarded as it is a chain-sum logic puzzle, and hence a very common type of logic puzzle to find on game websites. As they are not solely concerned with sum operations, the selected games compose a genuinely distinctive and intricate gameplay. Besides, *Puzlogic Plus (2019)* was only discarded for there was already a sufficient number of games with a higher rating to analyse. The games that were chosen for this case study (*Four Color Theorem, Hexologic, Rullo, and Dynetzzle*), on the other hand, are nonetheless perplexing, yet fairly accessible for an average player.

It can be further stated that the chosen games are enjoyable, given their high rating, which indicates a commercial success and that the learning and game play elements have been successfully balanced and approved by the players. Similarly to the research done by C. Linehan et al. [2], instead of postulating game design features that may be useful for education or investigating how multiple participants react to the game experience, we reverse engineer high-rated games with a logic-derived gameplay as a means to understand their educational value.

Four Color Theorem translates the mathematical Four-Colour Conjecture with simplicity, thus creating a very intuitive game; this seemingly trivial colouring game in fact demands the user's attention to identify and arrange patterns and layouts. The second game, *Hexologic*, immerses the player in a soothing atmosphere while they fill in the cells in a hexagonal grid with numeric shapes, in order to obtain a summed value for any specified columns and rows. In the third game, named *Rullo*, the user is faced with a matrix of numbers, and it is their goal to achieve a certain sum outcome in each line and column. This grid is already filled with specific numbers, so the player must decide which numbers stay or are ruled out at each cell. As a result, *Rullo* creates a challenging *Sudoku*-like game experience with an additional element of sums and subtractions. On the other hand, the last game, *Dynetzzle*, is a unique game that puzzles players by challenging their spatial visualization abilities, thought the high-complexity unfolding of three-dimensional objects while simultaneously applying a geometry principle.

Educational games are explicitly designed with learning objectives in mind, and only after defining the specific learning objectives do the designers create the game mechanics and, consequently, make a game. Nonetheless, given that, according to Devlin [29], many educational games fail on their game component, as they do not create a fun game activity – and sometimes they do not fit the definition of game either –, it is logical to analyse incidental learning in available games that were not formally designed for learning (e.g. no learning objectives were defined prior to their creation) but have been proven to be entertaining by users, either through high user ratings, a high number of play sessions, or both. Thus, we will be analysing user-approved logic puzzle games, that were not created for educational, but rather entertainment purposes, and proposing plausible learning objectives that could have been defined prior to the creation of the games, based on their game mechanics and play experience. The chosen games are free and available online, and, as web games, they are appealing, for they are usually short (and hence not time-consuming) and straightforward. Fundamentally, each game will firstly be described, and their game mechanics will be analysed; then, depending on the mechanics and play experience, we will conduct a reverse-engineering process to determine what learning objectives could have been defined for the game if it had been created with an educational purpose and purposely shaped as a medium for learning a specific subject or to acquire a set of skills. For this effect, we will be applying B. Bloom's taxonomy [30] for defining learning objectives, since this taxonomy seems to be an effective way to categorize learning objectives adequately. One limitation to this theory, nevertheless, is that it is specifically designed for institutional teaching from primary to high school, and thus does not fully align with informal or incidental learning forms, such as logic puzzle games. After applying the taxonomy for defining the learning objectives of each game's activity, we propose assessment activities so that the efficiency of each game as a learning tool can be evaluated.

Chapter 4

Game Analysis: Four Color Theorem

Four Color Theorem is a free web-based logic puzzle game concerning the Four-Colour Conjecture, proven by the mathematicians Keneth Appel and Wolfgang Haken in 1976 by means of computational calculations. It states that "every map drawn on a sheet of paper can be colored with only four colors in such a way that countries sharing a common border receive different colors" [31, p. 153]. Figure 3 contains two coloured maps. The first map is composed of four regions, and must be coloured with four colours, as all the regions are contiguous; however, the second map contains six regions, and yet can still be coloured with only four colours, as not all regions of the map share an edge.

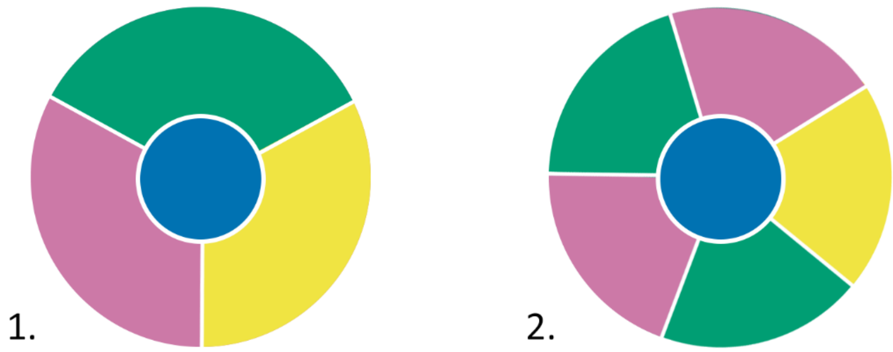

Figure 3: Representation of the use of the Four-Colour Conjecture in two different maps. Map 1 contains four regions, whereas map 2 contains six; nonetheless, both maps should be coloured with four different colours so as to comply with the theorem.

According to Rick Hudson, “The four-color problem is arguably the most influential question in the development of graph theory” [32, p. 42], and its “origins were a driving force in establishing graph theory as an independent branch of mathematical study” [32, p. 65]. In fact, this problem was solved by Appel and Haken through the instrumentality of Graph Theory, in virtue of transforming each map into a planar graph. Consequently, as many mathematicians "devoted a great deal of effort to the Four-Color Conjecture”, “much of what is now known as Graph Theory – the geometry of wiring diagrams and airline routes – grew out of the work done in attempting to prove it" [31, p. 162]. The computational usefulness of the Theory of Graphs as we currently know it – for navigation, data mining, image segmentation, clustering, and image capturing to name a few – was largely provided by the Four-Colour Conjecture.

The game *Four Color Theorem* is divided into forty levels, where each level presents a map, which consists of a plane divided into various regions. To move onto the next level, the player must colour this map with the least number of colours as possible, provided that they cannot use the same colour to fill adjacent regions. The player is allowed to use up to five colours, where the fifth colour is offered to assist the player in the levels that require a minimum of four colours for completion. At each level, there is a minimum performance threshold to move onto the next level, thus assisting the players who might be struggling to complete it; however, to achieve a perfect score, the player should use only the necessary colours. Figure 4 displays levels 20, 28, 34 and 40 of the game, respectively. From these images, we can observe that the game has an uncomplicated and colourful appearance, and a simple User Interface, containing buttons to access the levels menu, reset the level, progress onto the next level (which only becomes available once the player reaches the minimum threshold in the progress bar), switch the current painting colour, and to mute or unmute the music and sound effects in the game, which sound cheerful and light-hearted. Besides, it can be further noted that the complexity increments as the user progresses through the levels – not only in the sense of incrementing the number of regions, but also in a sense that the regions commence sharing more edges.

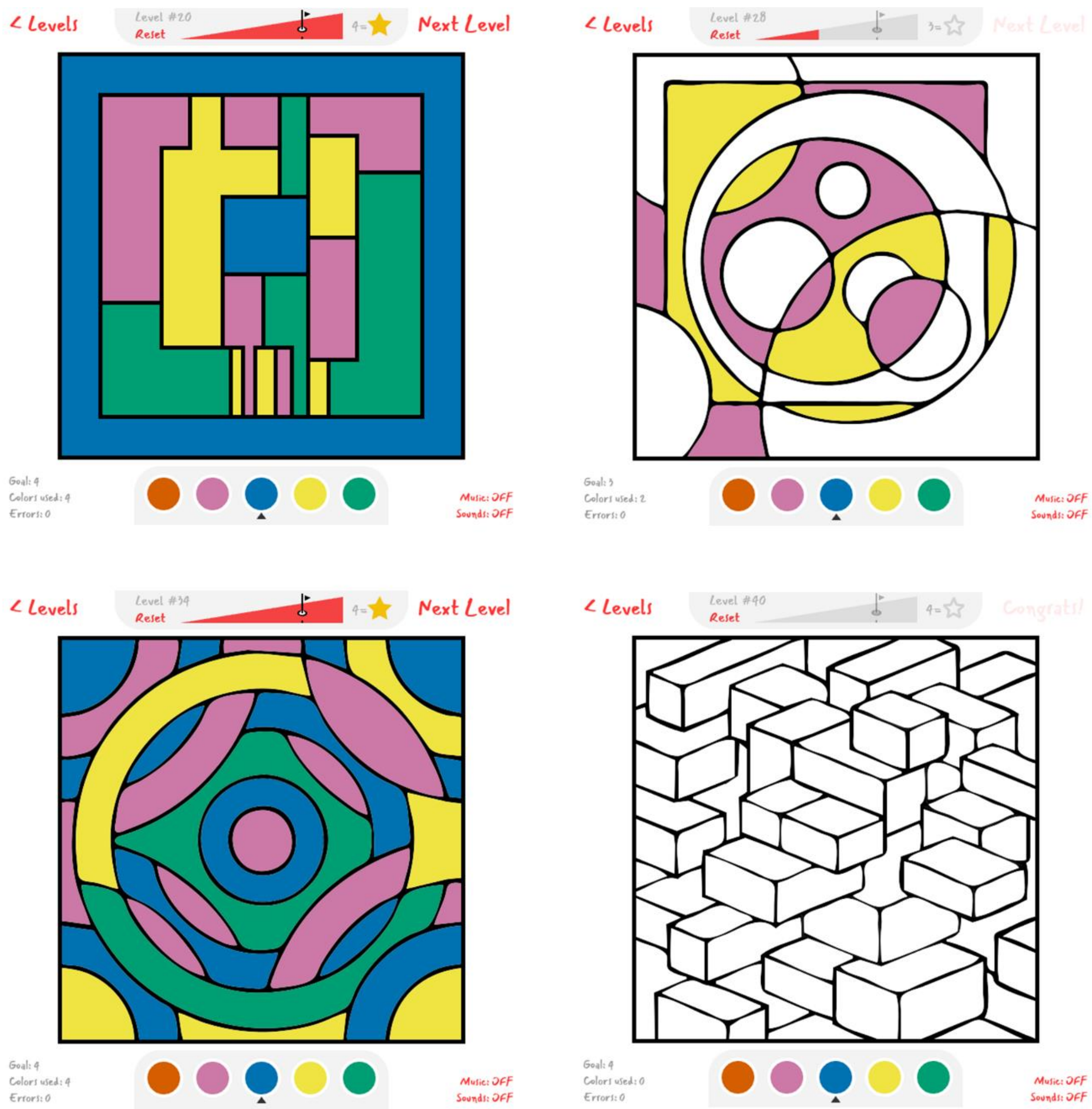

Figure 4: Demonstration of levels 20, 28, 34 and 40 from the game *Four Color Theorem*.

The game is based on a very simple premise and is hence quite straightforward to comprehend. Besides, it is intuitive – similarly to a colouring game, the player must only click on an area to colour it, or double click to remove the paint. All the game actions are based on clicking – there is no need for any mechanical game-playing skillset to enjoy this game. In the same sense as a colouring game does, this game is relaxing as it allows the user to peacefully colour the map in their preferred order and with their choice of colours. Moreover, the puzzling element is capable of creating a challenging exercise and to keep the player in the flow.

As this game relies on the Four-Colour Conjecture's rule, it can plausibly have positive effects on the user's fluid intelligence, specifically when it comes to lateral thinking and visual perception abilities, given that, to win the game, they must deconstruct the map and understand the algorithm to solve it, and employ their problem-solving skills by means of planning their colour use and positioning: no more than the necessary colours should be used to colour the map, and the same colour cannot be used to colour connecting regions. Hence, the user must be able to comprehend and apply the Four-Colour Conjecture, perceive the map regions and their positions in the map space as relative to oneself and in relation to each other, create colour patterns, and identify the optimal quantity of colours, the most efficient pattern for colouring the scene, as well as any errors that might occur where adjacent regions have the same colour. For this reason, we propose, as learning objectives for *Four Color Theorem*, that the player should be able to:

1. Understand the Four-Colour Conjecture (lower cognitive process of comprehension).
2. Operate with the Four-Colour Conjecture (higher cognitive process of application).
3. Identify relationships of adjacency in abstraction from the map itself (lower cognitive process comprehension).
4. Improve generic problem-solving skills (higher cognitive process of application).
5. Evaluate their own application of the Four-Colour Conjecture in order to maximize their colour use efficiency (critical thinking higher cognitive process of evaluation).

Evaluating the player's learning outcomes from this game activity can be quite challenging, because, as the Four-Colour Conjecture is very case-specific, there are not any obvious available tools to evaluate the user's understanding and application of this theorem. In a sense, the game itself could be an adequate tool to evaluate the player, given that it has a threshold to advance in the game, and also a progress bar that measures the accuracy of the user's solution in a percentage. However, using the learning activity to evaluate the user does not guarantee that the user has learned the learning objectives, as it can encourage poor learning strategies, such as memorization.

Another evaluation method could be to present new maps to the player in a paper form; however, a digital medium is much more suitable to test the theorem's application, given that making a mistake on paper requires the user to draw every region again. Hence, an interactive digital version with new maps could be created, and the user would not only fill empty maps, but also be able to rectify inefficiently coloured maps. The base maps contained in Figure 3, for instance, could be used early in this test. Furthermore, to test the user's logic thinking abilities, we propose the use of a test such as the Test of Logical Thinking by K. Tobin and W. Capie [33]. These tests should be used for both pre-test and pro-test assessments, and their results should be compared.

Chapter 5

Game Analysis: Hexologic

Hexologic is a free web-based game also available on iOS, Android, Steam, and on the Nintendo Shop. This game is based on *Sudoku,* and each level consists of a grid of hexagonal cells, composed by separate rows, columns, and diagonal lines. Each line is expected to achieve a specific numeric value by summing all its parcels, and to fulfil this requirement, the user should place a value from one to three on each hexagonal cell. The values from all the cells in each line must sum up to the required total of that line. To place a value on a given cell, the user must simply click on it. Each click will increment the value of the cell by one, and when it reaches the maximum value of three, it is reset to an empty cell.

The game consists of 45 labelled levels, divided into three regions. It further contains 3 extra hidden levels per zone, summing up to a total of 54 levels. The user must pay attention to the levels menu to further unravel these 9 extra levels. The player has the option to play the game in the normal mode or in the hard mode. There are a few differences between the two modes, namely: the levels in the hard mode share the same overall shape as the levels in the easy mode but are structured differently such that the values for the sums at each line differ, and there might be an increase of line sums on the most difficult level. Furthermore, the hard mode features no feedback from the game on whether the user is filling in the gaps in the matrix correctly.

1.
2.
3.


Figure 5: Introductory *Hexologic* levels. The sections above represent the tutorial level, level 16 and level 31, respectively.

Regarding the game's visual aspect, the background is divided into three scenes, representing each game phase. The first is an underwater scenario, the second is a tropical jungle with a waterfall, and the third is an oasis. The game background uses a vivid and varied colour palette and has a dynamic appearance, provided by various slow-moving animations, such as corals, plants, fog, and clouds gently moving, water bubbles rising, and the flow of a waterfall. The game's music and sound effects are tranquilizing and immerse the player in a pleasant underwater ambience. These audio-visual features create a relaxing atmosphere for *Hexologic*. Adding to this soothing atmosphere, the game also contains smooth transitions, given that the grid in each level is pleasantly loaded one hexagon at a time. We can further observe from Figure 5 that the game has a very simple and minimalist User Interface, consisting of only one button that, when clicked, reveals four other collapsible buttons with the actions to refresh the level, mute the sound, resume play or return to the levels menu.

Hexologic is very intuitive and simple to understand; the player must only complete a grid by filling each of its cells with a value from one to three, provided that some lines must result in a specific value. Interacting with this game is also very simple, as there is no need for any mechanical gameplaying skill – the player must only click on the cell they intend to increment. Nevertheless, the experience of playing this logic puzzle becomes more difficult at each level. The players can, hence, enjoy a more complex *Sudoku* experience in a digital and atmospheric environment.

Whenever a new concept is introduced in *Hexologic*, we can observe that this concept appears isolated – its introductory level contains only this new mechanic – and thus the difficulty drops at each mechanic introduction, allowing the user to familiarize themselves with the new mechanic before advancing onto more intricate levels. Only after approximately 5 levels since the new mechanic insertion does the difficulty level equate the difficulty level prior to the new mechanic. Moreover, the additional mechanics are introduced at the beginning of each new game phase, namely at levels 16, where static value cells first appear, and 31, with the surge of groups of cells with the same value. These mechanics allow more variety as well as complexity in the game.

The game's key mechanic involves filling in every hexagonal cell in a line, so it acquires a final summed value. The second mechanic, introduced at level 16, adds new static cells to the board, and these retain pre-defined values that the user cannot affect. Finally, the third mechanic, which first appears at level 31, introduces groups of cells – whenever the player changes one cell of the group, all cells will be updated to have the same value. These three mechanics are displayed in Figure 5, in sections 1, 2 and 3, respectively.

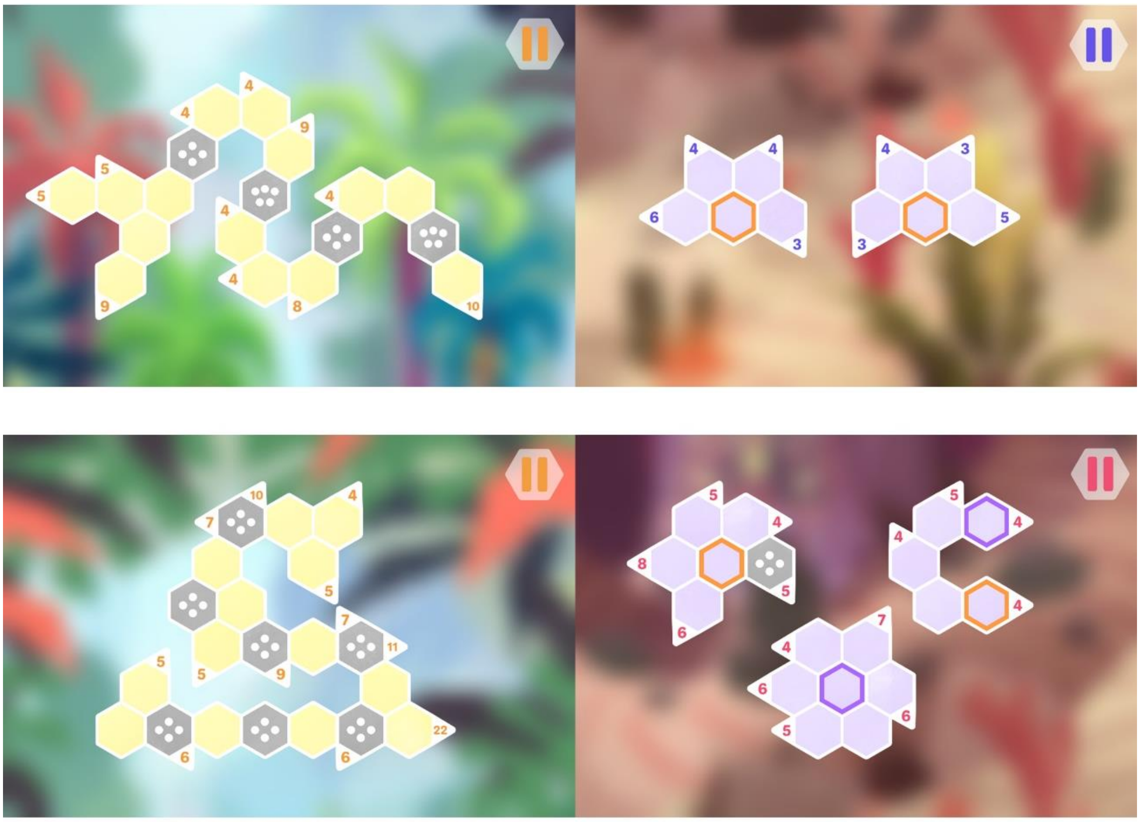

Figure 6: Comparison between easy mode levels 26 and 36 (above) and 29 and 39 (below) from *Hexologic*.

By analysing the complexity of the gameplay throughout the levels in this game, we can further indicate that the difficulty rises appropriately, and that the complexity decay at introductory levels is adequate. Nevertheless, levels 40 to 44 allowed for various correct combinations at multiple cells, thus making these levels somewhat simpler than the previous ones, even though there was a new mechanic at play. For instance, by comparing levels 29 and 39 in the easy mode, it can be noted that, although both levels contain one obvious first move, the move on level 39 further reveals the completion of eight other different cells, considering each group as one cell only. The same automatic revealing of new cells also happens in level 29, however, only four cells are revealed, and the moves to do so are not as obvious as in the latter level. This happens because level 39 is divided into separate regions, facilitating the visualization of the board cells as a whole, even though this level has more empty ungrouped cells than the previous stated level (level 29 contains 13 unique empty cells, whereas level 39 has only 15 of these cells). As a result of having different regions in each level, the cells will consequently share less edges, hence producing fewer intertwining results, and thus making it simpler to discern and comprehend each level. For instance, when comparing levels 26 to 36 (in Figure 6), both from the easy mode, it can be noticed that:

1. Level 26 has 14 empty unique cells, while level 36 only has 9.
2. Level 26 has only one region, whereas level 36 has two.
3. Level 26 requires 11 sum results (there are 11 different lines at play), whereas level 36 only requires 8.
4. Level 36 has two individual cells that are shared by three different sum results, whereas level 26's maximum share value on a single cell is solely two but occurs at eleven cells. In comparison, level 36 only has four double-used cells.
5. Zooming out of the cell level, level 36 has two instances of four interconnected lines, whereas level 26 has one instance of the same occurrence.

The features listed above imply that level 26 is more complex than level 36, as only the listed features 4 and 5 create a more complex gameplay in level 36 rather than level 26, and the difference between both levels at the feature numbered as 4 is minimal.

Nevertheless, the game has a hard version for each level. A comparison between the easy and hard versions of level 45 can be seen in Figure 7. By comparing these two versions of the same level, we can easily determine the aspects which the developers deemed as more complex, namely: using larger numbers for the line sums and lesser values for the static cell numbers, and flipping the board both vertically and horizontally to make it harder to visualize the starting point to solve the grid.

Figure 7: Comparison between easy and hard modes for level 45 in *Hexologic*.

Similarly to *Sudoku* [34], *Hexologic* can display positive effects on the user's cognitive abilities and improve their generic problem-solving skills. It can also potentially improve their fluid intelligence, specifically when it comes to matrix reasoning and visual perception abilities, as they must mentally abstract themselves from the grid itself and deconstruct it in its various lines, considering the cells as parts of a whole; only then can they analyse the level's starting point and plan how to complete the grid's gaps. We propose that the player should be able to fulfil the following learning objectives through *Hexologic*:

1. Deconstruct a grid into cell-containing lines (visualizing the grid as lines with multiple values, lower cognitive process of comprehension).
2. Understand the abstraction that connects every line in a grid (higher cognitive critical thinking process of analysis).
3. Improve generic problem-solving skills (higher cognitive process of application).

One plausible evaluation methodology for *Hexologic* would be to assess the user's ability to filling in the gaps and thus complete various matrixes of numbers, by means of a numeric reasoning test. Another useful test for evaluating the player's reasoning and problem-solving skills is the Test of Logical Thinking by K. Tobin and W. Capie [33], similarly to the research by Y. Baek et al. [34] regarding the effects of playing *Sudoku* on logical thinking abilities.

Chapter 6

Game Analysis: Rullo

Rullo is a free web game based on *Sudoku* and *Kakuro*. The player is faced with a matrix of numbers at each level, and to progress onto the next level, they decide which numbers to rule out of the matrix so as to obtain a specified value by summing each column and row separately. The user must simply click on a cell to rule its value out of the matrix. By clicking on a disabled cell, the user enables it again.

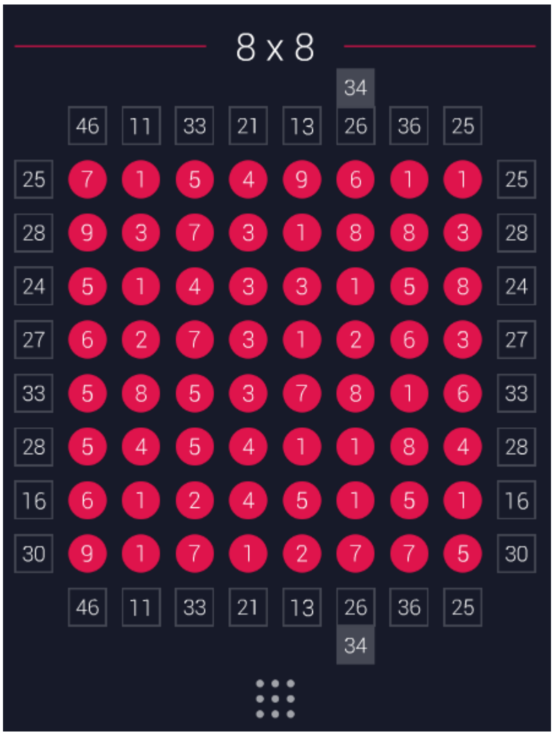

Figure 8: Example of a level in *Rullo* based on an 8x8 matrix with each cell number ranging from 1 to 9.

When playing *Rullo*, the user is faced with a different numeric matrix at each level. This table-like structure contains an equal number of rows and columns (except if the user is playing the endless mode), and each table cell stores a number. The game board further indicates a value for each row and column. This value represents the number that should be obtained by summing all the cells in the given row or column. To obtain that result, the user should be aware of their current total value at the given line and calculate the difference between the current total value and the desired value, so as to understand how many and which specific cells they must remove from the board. If the difference is 8, for instance, as can be noted in the sixth column of the grid presented on Figure 8, where the current summed value of the column is 34 and the desired value is 26, the player must choose to either rule out a cell with the value of 8 (either the cell at row 2 or the cell at row 5), or a combination of available cells that sum up to the value of 8, such as 7 + 1, 6 + 2, or 6 + 1 + 1; if opting to rule out a combination of cells, the player should further identify which specific cell they are to rule out, given that there are three cells with the value of 1 in this column, for instance. To assure that they are making the correct choice when it comes to ruling out a cell, the player should constantly compare the value of the cell they have removed to the difference between the current and desired line sums of the other line that cell belongs to.

Rullo is very simple to interact with, and yet quite complex, as there are many actions in this game available to the user at the distance of a click. To disable a matrix cell, the player must simply click on an available cell; to enable it, they should click on it again. Moreover, to see the current numeric value of a row or column, the user must only click on the square that contains the goal for that specific row or column; upon doing so, a small box will appear on top of the goal displaying the current value that the line's cells sum up to. The same action of clicking the goal for each line can also create a different result if that specific line already withholds the correct summed value; in that case, the row/column will become locked and highlighted. The player can take this feature into account when they are sure of the choices they have made in a specific row or column.

The game's visual appearance is very simple, and every shape is sharply defined. Besides, the music and sound effects are very soothing. Each screen in the game, including every level and the menu screens, is loaded with soft transition animations, further emphasising this relaxation feeling. Moreover, the User Interface in *Rullo* is also very simple and non-intrusive, consisting of only one collapsible matrix-looking button that reveals three buttons: a mute button, a home button, and a button to reload the level.

Interacting with *Rullo* is straightforward – the user is only required to click on the screen – and as the game also has very simple rules, it is thus very intuitive; nevertheless, its gameplay is difficult, and solving each level can consume quite a few minutes. Even though there are never new mechanics at play – no mechanic is added through the gameplay, and hence the same unique mechanic is used throughout all levels – the experience of playing this logic puzzle is varied and provides the player with a choice of difficulty levels, given that there are different game modes and grid formats from which the user can choose from. For instance, the player can choose to play the classic mode or the endless mode. The classic mode allows the user to opt on a preferred grid format (5x5, 6x6, 7x7 or 8x8) and to choose the interval of numbers to appear on the grid; they can choose to see cell numbers ranging from 2 to 4, 1 to 9 or 1 to 19. On the other hand, the endless mode presents the player with varied boards of different dimensions (they are no longer mandatorily square-shaped matrixes) and displays an identification of the current level the user is solving.

Even though *Rullo* does not have a typical level selector screen, it still allows the user to play the game in an orderly manner – following a sequence of levels – by playing in the endless mode. This mode keeps track of the user's current level and takes them back to where they left off. The classic mode keeps track of the number of times the user has won in each of the 12 different level types; nonetheless, whenever the player opens one of these, a random level will be loaded (even if the user had not completed the previous level they were presented with).

Since it is up for the player to choose their preferred parameters to play the game, the difficulty of the game is also in their control – choosing a larger grid and number interval for each cell will result in a more intricate gameplay. However, since *Rullo* is a game of logic and patience, every matrix will already be difficult by default. Given that *Rullo* is based on *Sudoku*, it is expected to produce similar results to the ones obtained by Y. Baek et al. [34], such as improving the player's problem-solving and cognitive skills. *Rullo* can also potentially cause positive effects on the player's fluid intelligence, as it can improve their matrix reasoning and visual perception abilities. The player must be able to visualize every cell of the board as the partial result of a line and column, and to rationalize with each cell of the matrix simultaneously in order to obtain the correct summed result for each row and column. We propose the following learning objectives for the learning activity of playing *Rullo*:

1. Identifying rows and columns (lower cognitive process of knowledge).
2. Understand the abstraction that connects every cell in a matrix (higher cognitive critical thinking process of analysis).
3. Improve generic problem-solving skills (higher cognitive process of application).

To evaluate the player's learning outcomes from this game activity, we propose assessing reasoning and problem-solving skills through K. Tobin and W. Capie's Test of Logical Thinking [33].

Chapter 7

Game Analysis: Dynetzzle

Dynetzzle is a free web-based game also available on Steam. It is based on the features of a standard six-sided dice, such as its eleven nets and the summed value of its opposite faces. At each level, the player will be faced with the unfolded geometry of one or various cubes. To progress onto the next level, they must fill in the gaps on the cube so that each face contains unique number, and that the sum of every pair of opposite faces in the cube is seven. To place a value on a cube face, the user must simply click on it. Each click will increment the numeric value in the face by one, and when it reaches the maximum value of six, the face becomes empty.

The game's free web version is very short, consisting of 10 levels, and it can further be observed in Figure 9 that the game has a very simple User Interface, consisting of a mute button, a button to return to the levels menu, and a text-based indication of the current level the user is playing. Besides, there is an introductory screen to the game, which briefly explains how to play the game based on the concepts of nets and face values summing to a total seven. The game's visual appearance is very simple, consisting of basic shapes and colours, and, unlike the previously analysed games, the sound in *Dynetezzle* is slightly fast-paced, and contains louder beats. Nevertheless, the sound quality is slightly grainy, and as this noise is audible, it can negatively affect the user's experience while playing the game.

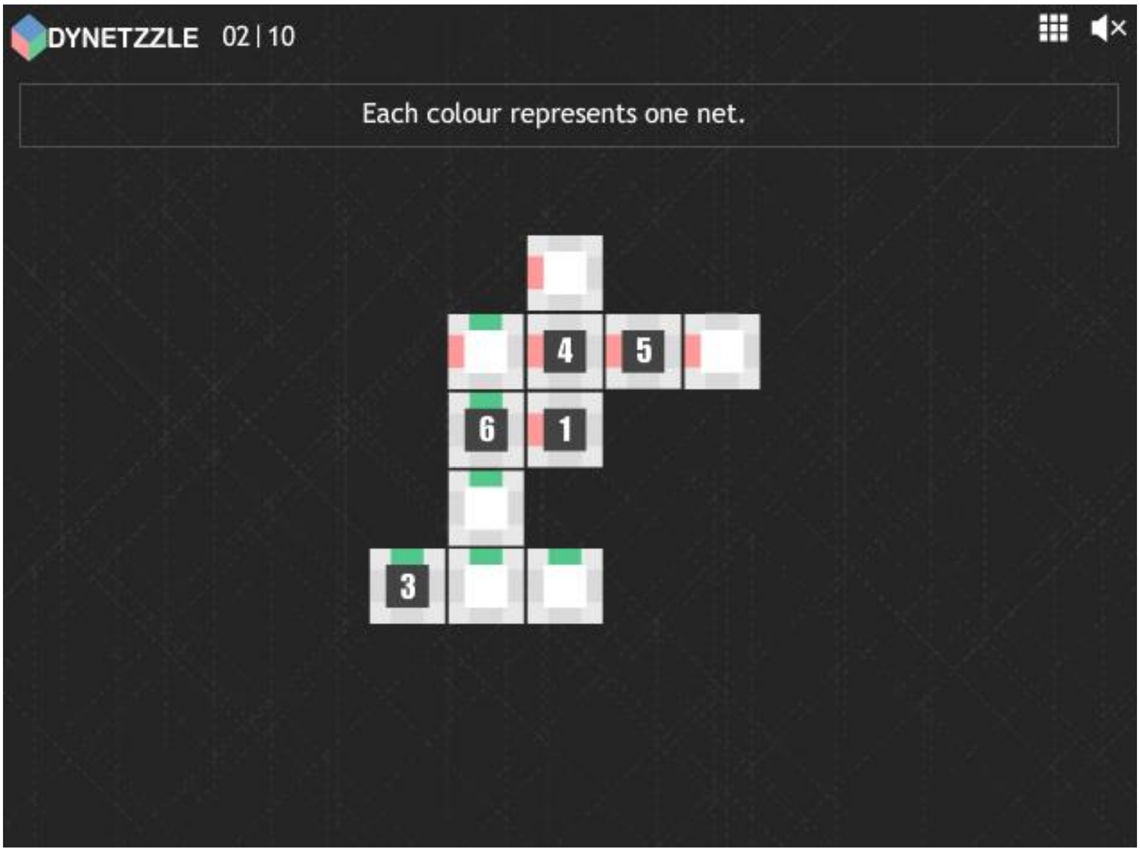

Figure 9: Demonstration of level 1 in *Dynetzzle*.

Dynetzzle is a complex game, and its difficulty increases quite quickly. This happens through the addition of both more cubes and an enhanced variety of cube net types at each level. Besides, the number of intersecting faces between different cubes also increments rapidly with the game's progression. It can further be stated that the difficulty level keeps increasing even when a new concept is introduced in the game, such as the display of multiple cubes, represented by different colours, or the use of different net types.

There is a total of eleven two-dimensional representations of a cube; each representation is called a net, and all eleven cube nets are represented in Figure 10. *Dynetzzle* mixes various cubes represented through different nets in the same level, so as to provide players with intricate challenges.

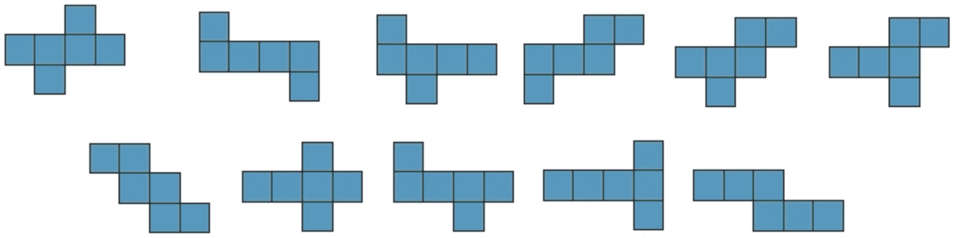

Figure 10: Demonstration of all the 11 existing cube nets.

The game's key mechanic involves filling in every face of the cube, so that the summed value of every opposite face is seven. The second mechanic, introduced at level 2, adds multiple cubes to each level, identified by different colours; instead of manipulating one cube, the player must now manage various cubes, that can be intersected. Lastly, the third mechanic, which first appears at level 3, introduces the use of various types of cube nets. All of these features add both variety and difficulty to the gameplay, as they complicate the player's visualization of the cubes in a 3D space.

Although the game is quite challenging, as it becomes increasingly difficult to piece all the cubes together in a three-dimensional space, there is always an obvious entry point to start solving each level. It is clear that every two cells in the same line of the same cube will be opposites; hence, the player only has to find one of these instances in the game to start solving it. In Figure 9, for instance, since the cell on the top of the pink cube is two cells above a cell with the number 1, it is evident that this empty cell must retain number 6 so as to sum up to the desired amount of 7. The same occurs in the cells below, that must retain 2 and 3, from left to right.

As this game revolves around the visual representation of cubes as two-dimensional objects, it can plausibly have positive effects on the user's fluid intelligence, specifically when it comes to spatial relations and visual perception abilities. The player must be able to employ their dynamic spatial reasoning to mentally assemble the 3D cube through its two-dimensional projection. Thus, the user must be able to comprehend the concept of nets as a visual cube planification, understand that the value of opposite faces in a dice must be seven, understand that each cube will have only one occurrence of each number, and identify opposite faces in a cube through the visualization of a net, as well as any errors that might occur, such as the repetition of a number in a net, or the incorrect pairing of two faces as opposites. For this reason, we propose the following learning objectives for *Dynetzzle*:

1. Understanding the concept of cube nets (lower cognitive process of comprehension).
2. Applying the concept of nets to visualize different cubes (higher cognitive process of application)
3. Differentiating opposite faces in a net (higher cognitive critical thinking process of analysis).
4. Improving generic problem-solving skills (higher cognitive process of application).

As a test to assess the potential learning outcomes to proceed from the learning activity of playing *Dynetzzle*, we propose the use of spatial reasoning cognitive tests, namely the ones that test the ability to unfold 3D geometry, as both pre-tests and pro-tests, as these tests provide a specific evaluation of the cognitive skills of paper unfolding and spatial reasoning. To test the pupil's ability to identify and evaluate errors in a cube, the tests should further contain examples of incorrect opposite pairing and allow the user to manually fix the pairing. A test such as the Test of Logical Thinking by K. Tobin and W. Capie [33], should be further used to assess the user's general logic reasoning.

Chapter 8

Conclusion

While conducting this analysis, we have stated that it is quite complex to define specific learning objectives for each of these games, because, while some of them are quite directly involved with mathematical principles, such as the Four-Colour Conjecture, or 3D geometry, such as *Dynetzzle*, the others are more related to generic cognition, in a sense that they are using matrixes and numbers as structures where the user must identify numeric groups and manage their value. Hence, whilst we can define very specific learning objectives for *Dynetzzle* and *Four Color Theorem*, the learning outcomes for *Hexologic* and *Rullo* are much broader.

According to J. Biggs and C. Tang, problem solving skills can reasonably be seen as generic and standalone, and “generic metacognitive problem-solving strategies could be seen as an enabling outcome for lifelong learning” [35, p. 115]. Hence, playing these short games for entertainment purposes can cause the incidental learning of cognitive aspects, such as fluid intelligence (namely through paper folding, spatial relations, matrix reasoning and Shipley abstraction), general memory and learning, and broad visual perception, which in turn can enhance the player’s ability to learn new concepts, given that “Individuals with higher cognitive abilities have higher educational attainment” [36, p. 1140]. According to N. Falkner, R. Sooriamurthi and Z. Michalewicz, “the ultimate goal of puzzle-based learning is to lay a foundation for students to be effective problem solvers in the real world” [27, p. 187]. *Four Color Theorem* can further incite players to learn more about the Four-Colour Conjecture through tangential learning. According to S. Turkay and S. Adinolf, “Players learn by becoming interested in an in-game topic, and expand their knowledge on this topic by studying outside resources without obligatory reinforcement” [37, p. 3348]. Furthermore, game-based learning activities are incredibly valuable when it comes to motivating students and increasing their willingness to take risks and learn through failure, and since highly motivated students are better learners, games can further enhance students' general learning abilities in this sense [2] [21] [23] [24] [26] [27] [34] [38].

Even though the proposed learning objectives for each of the four games were not used by the game developers, we can still discuss their value, for these games are not educational, but are still logic-driven puzzle games, and research shows that puzzles can be a valuable tool for learning, especially when it comes to STEM-based learning [24] [26] [27] [34]. Moreover, a study by E. N. Castellar et al. [39] revealed that an educational math game produced positive results in cognitive abilities and arithmetic performance enhancement when compared to paper exercises.

Furthermore, some commercially successful and purely entertainment-centred puzzle games, such as *Portal 2 (2011)* [40], have been studied for their ability to produce learning outcomes. In fact, V. J. Schute, M. Ventura and F. Ke [40] have determined that playing *Portal 2* can be more beneficial than using the *Lumosity* platform when it comes to select cognitive enhancements, such as spatial abilities.

8.1 Future Work

Given that the learning objectives for *Four Color Theorem*, *Hexologic*, *Rullo* and *Dynetzzle* have already been defined, the future work involves creating a participant profile and recruiting research participants in order to test the validity of the games as learning activities. The previously defined pre-tests and pro-tests should be employed on each game to measure their unique outcomes.

Our research has also been mainly focused on general problem-solving skills and math-related abilities, such as number reasoning. Nonetheless, there is a great potential in other types of games, such as word games for vocabulary development, and science-scoped strategy games that can plausibly enhance chemistry and biology knowledge. One game example for the incidental learning of biology concepts is *Plague Inc. (2012).*

Regarding general cognitive skills, first-person shooter games can also be exceptionally valuable tools for improving spatial perception and reasoning.

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Appendix

Table A.1: Extended list of results upon searching for logic puzzle games with the "math" tag on Kongregate.

Name	Relevant Tags (Besides Puzzle and Math)	Rating	Number of plays	Year	Motive for discarding
Hexologic	Mouse Only, Relaxing, Minimalism	4.26	237,470	2018	N.A.
Medieval Angel: My Uprising (Part 2)	Adventure, Detective, Funny	4.12	62,642	2018	Wrongfully tagged as “puzzle”
Rullo	Brain, Mouse Only, Minimalism, Educational	4.03	425,682	2016	N.A.
Liquid Measure 2 Dark Fluid Level Pack	Brain, Mouse Only	4.00	665,585	2011	Outdated flash game
Classic Hashi Light Vol 1	Brain, Mouse Only, Maze	3.98	329,620	2011	Classic game adaptation
Mix Sudoku Light Vol.1	Sudoku, Puzzle, Brain, Mouse Only	3.98	273,990	2010	Classic game adaptation
10	Block, Mouse Only, Brain	3.94	627,657	2013	Chain-sum game
Minim	Mouse Only, Brain, 3D	3.94	226,397	2009	Outdated flash game
Dynetzzle	Mouse Only, Brain, Minimalism	3.91	265,796	2014	N.A.
Mix Sudoku Light Vol 2	Sudoku, Puzzle, Brain	3.87	205,067	2011	Classic game adaptation
Mamono Sweeper	Brain, Mouse Only	3.87	89,083	2010	Outdated flash game
Puzlogic Plus	Mouse Only, Sudoku, Relaxing	3.84	123,023	2019	Sufficient game sample
9	Mouse Only, Brain, Educational	3.82	339,558	2014	Chain-sum game

2048+	Brain	3.80	304,515	2014	Classic game adaptation
Refraction	Educational, Space, Brain, Science Fiction, Multiplication	3.77	560,596	2010	Outdated flash game
Hashi Light Vol 2	Mouse Only, Maze	3.76	95,338	2011	Classic game adaptation
DropSum v2	-	3.73	422,754	2009	Chain-sum game
10 is Again	Mouse Only, Brain, Block	3.73	341,735	2013	Chain-sum game
2048 Flash	Keyboard Only, Relaxing, Brain, Minimalism	3.71	736,509	2014	Classic game adaptation
Kakuro Light Vol 1	Brain, Mouse Only	3.68	38,744	2011	Classic game adaptation
Classic Nurikabe Light Vol 1	Mouse Only	3.63	37,301	2011	Classic game adaptation
DropSum v1.3	-	3.62	170,999	2008	Chain-sum game
Skyscrapers Light Vol 1	Brain, Sudoku	3.61	61,482	2013	Classic game adaptation
2048	-	3.59	16,158	2014	Classic game adaptation
CalcuDoku Light Vol 1	Sudoku, Brain, Educational, Mouse Only	3.59	119,745	2012	Classic game adaptation
Nambers Level Pack	Brain, Minimalism, Mouse Only	3.58	164,052	2016	Chain-sum game
Nambers	Mouse Only, Brain	3.57	14,246	2015	Chain-sum game
Hitori Light Vol 1	Brain	3.56	26,209	2012	Classic game adaptation
Finite Moves	Brain, Mouse Only, Educational	3.52	42,373	2015	Not directly related to math