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This paper aims to highlight the problem-solving nature of video games by examining problem-solving techniques in the context of the educational game Zoombinis. Using screen-capturing software, the gameplay of an 8-year-old participant was recorded and analysed in relation to his strategies towards solving the implicit Mudwall problem in the game, from a global-local perspective. Findings indicate the development of techniques —'stepping-stone' and 'probable-exclusion'— that through Polya's problem-solving steps, the game's design and participant's experimentation, can be used to solve the Mudwall puzzle, illustrating such game's potentiality as a problem-solving environment.

Keywords: Problem-solving, video games, techniques, global-local problem.

Introduction

Compared to other media, video games offer interactivity to the player. As this unique attribute is constantly explored and worked upon by game designers, educational researchers examine the role video games can play to learning. Playing video games, for example, can create highly motivational and engaging environments for players (Van Eck, 2015). Devlin (2011) and Monaghan (2016) view video games as ideal means of presenting and learning mathematics, which, through their design, can potentially represent mathematics by overcoming the symbolisms used in paper. Literature has focused on ways video games could influence mathematical learning, either be played during students' spare time (Lowrie, 2005) or be included in traditional classrooms (Moore-Russo et al., 2015) or other classroom settings (Calder & Campbell, 2016). However, even when researchers are optimistic about the future, they are still reserved on what has been realized so far by video games (Ke, 2008). Video games have been studied in many mathematics education research studies mainly as motivational and engaging educational environments (Kebritchi et al., 2010; Chang et al., 2015). Nevertheless, few studies focus on how mathematical content is presented in these games. The study (Thoma, 2017), part of which is presented in this paper, examined the educational game Zoombinis as a mathematical problem-solving environment for young children. Zoombinis has been viewed as engaging, challenging and motivational by previous studies (Yelland, 2002; Moss, 2004). The aim of this study was to examine how the problems are presented in Zoombinis, how young players interact with the game, and how they form techniques to deal with said problems. In this paper, we focus on the techniques developed by one participant in a specific puzzle of the game, called Mudball Wall (Mudwall thereafter). After presenting the theoretical framework of the study, a description of the game—and then the Mudwall puzzle—will be offered showcasing the key features that make it a problem-solving environment. Next, the analysis is presented using excerpts of the participant's playthrough highlighting his techniques, followed by a discussion with concluding remarks.

Theoretical framework

Downs and Mamona-Downs (2007) propose two perspectives on mathematical problem: the *local* and *global*. The authors argue that every problem's structure implies a global system of principles and assumptions that are related to this and other similar problems. However, the structure of a certain problem remains highly local and specific. Problem-solving approaches and arguments can develop at a local level, that in turn might be generalised from a global perspective, namely a meta-level of similar problems. According to Downs & Mamona-Downs (2007) the "switch" (p.2271) between the two perspectives might happen in two ways: by viewing problem-solving as an amalgamation of both global and local perspectives, or by examining strategies emerging from a local perspective, that become important in the global. One construction that could emerge through the interrelationship of the local-global could be a *technique*. In this paper, the term technique is used based on the definition offered in Mamona-Downs and Downs (2004):

> A technique, as does a method, conveys a mathematical argument that can be extended over a variety of tasks. Our convention is that a technique splits the argument into pre-determined stages, each of which addresses a specifically formulated aim. For a method such explicit structuring is not stressed. (p. 236)

While techniques can be linked with a specific mathematical theory, some techniques can be formed as "products of problem-solving activities" and "successfully completed solutions" (p. 237). After formed, techniques can be used as problem-solving tools. This way one technique could deal with many problems, as well as objects, that share similar attributes, very often without the problem-solver being aware of this technique. Additionally, Mamona-Downs and Downs (2004) view each solution as a construction, which can guide a problem-solver towards understanding the technique as a response to past problem-solving experiences. Finally, techniques could be viewed as existing between heuristics and algorithms (Mamona-Downs & Papadopoulos, 2017).

Video games as problem solving environments

Video games generally have an overarching theme, story or goal that create a setting for the player-problem solver. This is what we consider as the global perspective of the problem (*global problem* thereafter). The global problem is not always explicit, but rather it is experienced through solving problems from a local perspective that players face at each puzzle (*local problem* thereafter). Most of these local problems in games hint or build towards a solution of a global problem, either explicitly, shared with the players, or hidden from them until they make the connection themselves. We see video game problem-solving endeavour, having similarities to Polya's basic steps of problem solving (1973, pp. xvi-xvii): trying to understand the problem; making connections between available data to devise a plan; carrying out said plan; and reflecting on actions. Since video games are interactive media and usually offer real-time feedback the player may be guided by the game's design towards the steps mentioned. Additionally, variations of the same problem can guide the development of certain techniques. However, for the above to happen a player must have experience and a clear understanding of the games rules. Thus, the understanding for this paper is that techniques can be formed only once an initial exploration phase has past, when the player has some awareness of the actions they are allowed to perform and has formed an idea or expectations on what results said actions might yield. Therefore, experimentation is important in these early stages and is usually the first step of a developing technique. In its mathematical essence regardless the problem, experimentation has the following elements:

> "Locate the variables, the key-elements of the problem. Keep all except one constant, and start experimenting with this one to understand its role towards the solution of/solving the problem. Afterwards, keep this one constant and experiment using another one. Do the same for each element of the problem until you can understand the role each one plays towards solving the problem." (translated from Greek, Mamona-Downs and Papadopoulos, 2017, p. 81)

Based on the above, a game can be defined as a collection of global problems, that through experimentation and consecutive playthroughs of local problems, can lead players into reflecting on their actions, and developing techniques that lead them to a solution.

The participant and data collected

The participants of the study were four children aged 6 to 8 years old. A requirement for the study was participants had never played the game before. This way, the exploration and the formation of problem-solving techniques could be captured from their first stage of development. Data were collected by the first author through video captured from participants' gameplay, recording their on-screen actions, exclamations, inquiries, ideas as well as conversations between them and the researcher who is the first author of the paper. To enrich audio data, participants were advised to express their thoughts and actions verbally as has been done in similar studies (Ke, 2008). Additionally, suggestive and encouraging prompts were used by the researcher in an effort to produce more data, while creating a comfortable and game-friendly environment for the participants. The 8-year-old participant presented in this paper, with pseudonym Damian, played the game in four hourly sessions, in different days in a week.

For each participant, the screen recordings were categorized to short segments of playthroughs, namely successful or unsuccessful attempts of the same game puzzle. Then, the data were analysed according to participants' actions to go through the puzzle (experimentation); approaches to understand what works or not (local problem); being able to see the underpinning rules (global problem); being able to transfer what they have learned in one playthrough to the next one (shift from the local to the global); development of techniques. The total amount of time allocated in each stage and the gameplay session were also taken into account.

Zoombinis[1]: the game and the global-local problems

Zoombinis are creatures that try to find a new home. Guided by the player in groups of 16, they visit and must go through a total of 12 puzzles before reaching their goal. Each Zoombini has four attributes: hair, eyes, nose and feet, and these are often the variables used in each game puzzles (three Zoombinis can be seen in Figure 2). Each puzzle has a penalty system that stops Zoombinis

[1] https://external-wiki.terc.edu/display/ZOOM/The+Game

from progressing, thus forcing the player to backtrack, collect any Zoombinis left behind, and try the puzzle again. This way, players are encouraged to work towards more efficient and effective solutions, improving them through continuous playthroughs of local problems. Based on the above, we define local problems of a puzzle the individual attempts of this puzzle. The puzzle has an underpinning rule that is controlled by variables that are not known to the player, which we call global problem. However, in each of player's attempts the values of these variables change randomly as we explain in the context of Mudwall in the next section. That means the player begins a new attempt with new values of the variables, which justify a new local problem. However, the global problem remains the same and the solver has to unpack it, often working unknowingly towards its solution. While a local problem might be solved by chance, this solution will not work the next time the player visits the puzzle, due to the randomization mentioned before. In order to be effective problem solvers, players need to find techniques for the global problem that corresponds to this puzzle that will allow them to solve every local problem they will encounter at this puzzle. Considering the specific penalty of each puzzle, the global problem is the search for an optimal solution with minimum and ideally zero Zoombinis left behind after the problem is solved.

The Mudwall puzzle

In the Mudwall puzzle, the Zoombinis are faced with a tiled wall that obstruct their journey. The player tries to get the Zoombinis to go over the wall using a mudball launcher machine. This machine fires mudballs onto the 5×5 tiled wall and the player needs to hit the marked tiles that have dots in them (a double-dotted marked tile can be seen in Figure 2). The number of dots on each marked tile corresponds to how many Zoombinis will go over the wall successfully. The machine has buttons of five colours (blue, red, yellow, purple and green) and five shapes (square, triangle, star, circle and rhombus). In each playthrough the 5×5 matrix (named A for the purposes of this paper) is a permutation of five shapes on one axis, and a permutation of five colours on the other axis, which is not known to the player. Each cell of this matrix corresponds to a unique combination of shape and colour. Additionally, there is a hidden permutation of the two axes as well, as the colours or the shapes can either be on the horizontal axis or the vertical one. These random permutations allow for: $5! \times 5! \times 2! = 28800$ possible different 5×5 matrices. Furthermore, on each such matrix, marked tiles are distributed randomly. The number of marked tiles can be from one to eight, based on the number of Zoombinis the participant has at the beginning of this puzzle. We consider the local problem of the Mudwall as: "Are you able to find the coordinates (i.e. shape and colour combination) of all the marked tiles, on this specific wall?". The player does not have an unlimited amount of mud due to the penalty system of the game. Essentially, the player's aim is to use the least possible amount of mudballs to the player to locate the coordinates of the marked tiles. We consider the underpinning global problem: "Can you find the coordinates of the marked tiles, in each possible wall (out of the 28800 that might appear), by firing the least amount of mudballs every time?". In the following section, we describe Damian's playthroughs of the Mudwall puzzle and illustrate the development of his problem-solving techniques.

Analysis of Damian's Mudwall puzzle playthroughs

Damian visited the Mudwall puzzle six times, spending 2 to 4 minutes in each playthrough, for a total of 15 minutes. It is important to highlight that due to the linear progression of the game described above, Damian was engaged with other puzzles in Zoombinis between playthroughs of the Mudwall. Thus, a considerable amount of time has passed between each of the events described below, ranging from ten-minute gaps up to days. In his playthroughs he was mostly quiet and engaged, and only spoke about any of his strategies when he was sure of their results. In the following pages, matrices (Figures 1 and 3) created by the first author as part of the analysis demonstrate Damian's sequence of actions. Additionally, a screenshot (Figure 2) of the overall playthrough is offered where a step-by-step summary is not necessary.

At his first encounter with the Mudwall puzzle Damian is mostly exploring and experimenting, trying to understand how to interact with the puzzle. He located and used the available buttons of shapes and colours but he was not able to identify the goal of the problem and subsequently solve it. This experimentation phase was expected, as the Zoombinis video game constantly enforces an exploratory attitude through gameplay and narration, where players have to identify the variables, the goal and finally the solution of the problems they come across. Before ending his first playthrough, without having successfully launched any of the Zoombinis over the wall, he noticed that he run out of mud, which marks his first realisation of the penalty system of this puzzle.

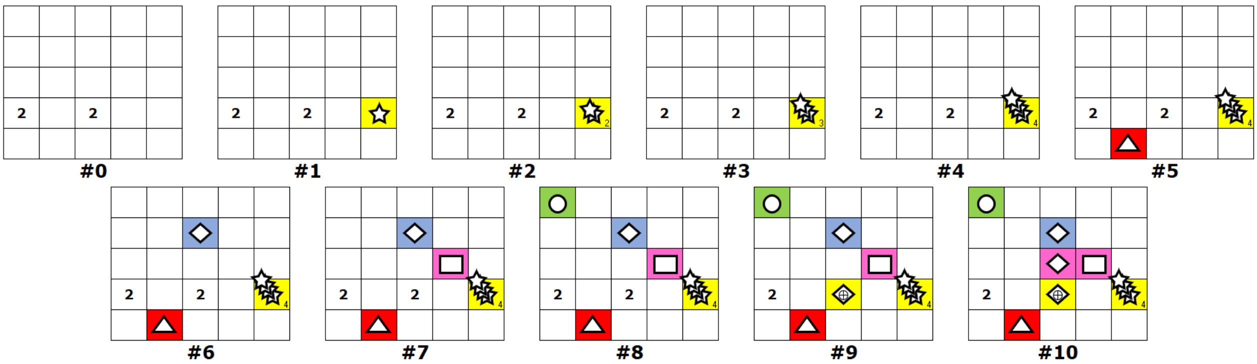

Figure 1: Damian's second playthrough, where he hit his first marked tile #9, the yellow-rhombus marked with a '+' sign in its center

On his second playthrough, Damian shot four times consecutively the same yellow-star mudball (Figure 1, #1 to #4). During his shots, his cursor movements indicated how he was trying to hit adjacent tiles to yellow-star, by point-and-clicking on the tiles themselves, then firing the mudball. After his fourth shot, he stops trying to direct his mudballs this way, and explores different combinations of shape and colour. In his last two shots (Figure 1, #10) a pattern can be seen, the process of keeping one variable unchanged. This will be explored by Damian on his next playthrough. Finally, he managed to hit one marked tile $A_{4,3}$ (Figure 1, #9). After conversing with the researcher, he became aware that this is his aim on the Mudwall puzzle, to aim for the marked tiles.

In the third playthrough (Figure 2), Damian focused on keeping the colour constant and changing the shape. Once the column with the yellow shapes was completed, he tried to complete the blue column until his mud finished. During this playthrough, Damian identified the relationship of colour and shape to columns and rows of the tilled wall.

Figure 2: Damian's third playthrough, one Zoombini has made it over the wall successfully

In his fourth playthrough (Figure 3) Damian found the coordinates of all the marked tiles, getting all his Zoombinis over the wall. This is his first totally successful playthrough, and from this point onwards he was able to develop techniques which he then uses on his last recorded playthroughs. We present this playthrough in detail, aiming to illustrate the techniques Damian developed. His first shot (#1) is a yellow-circle and the second (#2) a red-square (Figure 3). He changed both variables keeping neither colour nor shape constant. The current information does not allow him to relate the shapes and colours to the rows and columns of the matrix. With his third shot (#3) of a red-triangle, Damian keeps one variable constant (colour) and changes the second (shape). This creates a connection between the two mudballs: both share one variable, in this case the red colour (Figure 3, #2 and #3). These two mudballs now reveal that the matrix has colours in the columns and therefore shapes in the rows as illustrated below (Figure 3, #3-known data). We can see the approach of keeping one variable unchanged as systematic experimentation, which we name the *stepping-stone technique*.

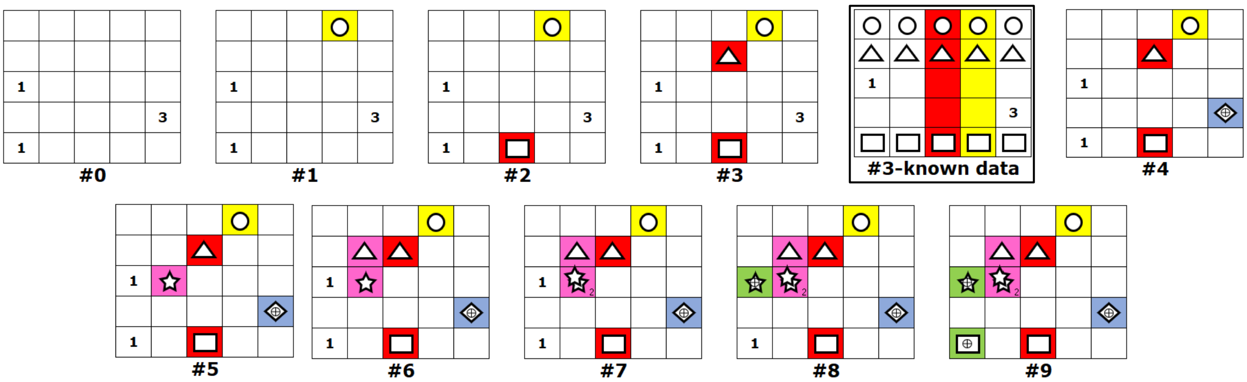

Figure 3: Damian's fourth playthrough and his first fully successful one

Our interpretation is that Damian used the stepping-stone technique with the aim of landing on a marked tile. However, as the colours are in the columns he did not manage to land on the marked tile $A_{5,1}$ and lands instead on tile $A_{2,3}$. By observing that the colours are arrayed on the columns, he can deduce that shapes are on rows. With the new information gained, Damian now focuses to hit either the tile $A_{3,1}$ or $A_{4,5}$ which are marked. He knows that the first row will be circles, the second triangles and the fifth squares. Thus, he eliminates all shapes except rhombus and star, as well as the colours red and yellow, as they belong on the third and fourth column respectively (Figure 3, #3-known data). Finally, he chooses the colour blue, and the shape of a rhombus, both choices for which he has no information yet. His fourth mudball is blue-rhombus that lands on $A_{4,5}$ with success. We see this elimination of available options as another type of systematic experimentation, which we call *probable-exclusion technique*.

For his fifth (#5) mudball, Damian uses again the probable-exclusion technique and fires a pink-star (Figure 3). This time his shot lands on $A_{3,2}$. He finally finds both tiles $A_{3,1}$ and $A_{5,1}$ using both the probable-exclusion and stepping-stone techniques.

On his fifth and sixth playthroughs Damian employs the strategies shown in his fourth playthrough. He begins by keeping one of the two variables constant in his first two mudballs. From that point he uses interchangeably the stepping-stone and the probable-exclusion techniques, aiming for marked tiles whenever he gains some new information. Both his last playthroughs were successful as he managed to get all his Zoombinis through with mud to spare.

Discussion and conclusion

The aim of this paper was to examine the development of problem solving techniques in the context of the educational video game Zoombinis. We analysed Damian's experimentation approaches in relation to solving the local and global problem of the Mudwall puzzle, a problem he had no experience with. During his first local problem, he explored Mudwall by locating the variables, both colour and shape; as well as the penalty system of the mud decreasing after each shot. In his second local problem, he explored the machine's controls showing awareness of its function and managed to hit a marked tile thus experiencing a successful result, indicating his global problem goal. On his third local problem, he worked with only two colours, minimizing the variety of his choices, but establishing the connection between colour-shape to row-column. Finally, in his fourth playthrough he used the two techniques of stepping-stone and probable-exclusion, that combined lead him to his first successful solution in terms of the game. It is at this stage that Damian can be considered as having simultaneously solved the global problem of finding all the marked tiles without his mud running out. Thus, we identified strategies that go beyond random trial and improvement.

However, not every participant of the original study was as successful as Damian with the Mudwall puzzle. For the limited time of less than five hours of gameplay, all participants showed examples of experimentation, formed techniques and adapted them, some successfully reaching a global solution in the various in-game problems. It was also interesting how similar patterns emerged from the different participants' data, leading to the suggestion that due to carefully crafted game's design, players can be smoothly guided to a specific form of problem solving approaches.

This paper examined the video game Zoombinis as an environment used to learn problem-solving techniques. In their study Mamona-Downs and Downs (2004) highlight some issues regarding teaching techniques, such as students not wanting to use a technique after they had been taught it, and the difficulty to identify the underlying technique through the mathematical tasks which were provided for that reason. In my view, in the context of the video game, the first issue potentially could be resolved as students are the ones discovering and adapting the technique themselves.

Problem-solvers implicitly guided by a global problem, they have the agency to interact and experiment in a story-driven and challenging environment and thus find the need for a more efficient solution. Along the way, techniques and other constructions formed from this process, would be something players developed on their own and something that is efficient at providing a solution.

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