Abstract
In this paper, we describe the conception and the difficulties behind the implementation of the three-dimensional and educational math game 3DM6 with features that make it engaging and suitable for different audiences.

The 3DM6 game scope encompasses a school population attending three distinct levels of education that go from the 1st year of the 1st cycle to the 6th year of the 2nd cycle of the Portuguese Basic Education. Its fundamental purpose is to sharpen the curiosity of the players, integrating knowledge of various natures with special emphasis on mathematical knowledge. It includes both the general concept of a traditional board game and the main idea of a quiz, comprising features that differentiate it from a general game, among which are the learning opportunities resulting of the three-dimensional dynamics of the board where the game unfolds.

The option by the design of a game in a 3D format took into account the barely inexistence of this type of game both in the commercial circuit and in the research field on serious games. Besides, and above all, this characteristic may bring a source of new learning opportunities acting also as a motivating agent making players feel more interested and engaged.

There are several studies pointing to a possible relationship between games, including board games, and the development of spatial processing. However, little is known about the influence of 3D board games in the development of this type of capability or in any other math capability.

At this stage of the 3DM6 game development, we have designed and implemented the physical structure of the game along with three distinct sets of card decks, taking into account the target audience and the goals to be achieved. Within this context, during the design phase, the incorporation of features to help players to acquire mathematical knowledge and/or to reinforce the learning of some specific academic contents were, as expected, taken into account.

The math contents present in the game respects the curricular national programs of the Portuguese Basic Education and the proposed challenges have in consideration, essentially, the awakening or the development of the following capabilities: mental calculus, math reasoning, critical thinking and problem solving. The other contents are, basically, ludic and of historical and cultural nature.

Keywords: Serious Game, Non-Formal Learning, Playful Learning.

1 INTRODUCTION
Despite all the new instructional approaches that teachers continually seek, many are the students who see school as ineffective and boring. It is by no means surprising that, in schools, lack of motivation and involvement is being seen as a major problem [1].

Games are privileged environments of motivation and commitment. It is then more than natural that some researchers have devoted some of their effort to study ways to import their main features to build tools to support learning (serious games), improving not only student knowledge but also the development of fundamental mathematical skills such as problem solving, mathematical reasoning and mathematical communication.

As referred in [1, 2], games are safe environments for children to express themselves providing rule-based boundaries which help shape their expressions in what concerns to necessary skills and social practices. Games are sources of motivation, appealing to several different mechanisms so people feel engaged without, usually, any kind of reward besides the possibility to win and the joy enabled by playing. In fact, according to [3], several educators sustain that allowing students to learn by playing is, in fact, a "definitive and effective improvement in the quality of education". This is essentially due to the fact that learning-based games stimulate learning desire by requiring truly involvement from the players by its challenging and competitive characteristics [3, 4].
Serious games are environments conceived for a purpose other than entertaining and represent a very important instructional research field when it comes to children. The act of playing and gaming is essential to children's physical and cognitive development. As stated in [2, 5], games are also an interesting tool to help children in controlling their urges, frustration and anxiety, and in checking reality, comprehending the relations between action and outcome, self-discipline, self-control, and, in general, enhancing socialisation. They are also characterized by the ability to simulate children's world, and so increase their will to participate and be engaged through playing [3]. Serious games are a form of experimentation with relatively unthreatening means and with a low expense.

Game-based learning represents a new method to consolidate formal concepts. Concerning mathematics learning, they offer new possibilities to problem solving with a special emphasis in data interpretation and in the development of mathematical logical reasoning [4]. Besides the development of the intellectual, games can also play an important role in the person's social and affective sides since they are privileged environment for experimentation, perception and imagination of the users [4].

However, most current serious games do not fit an explicit learning theory. In a majority of serious games does not exist an explicit quantification of the difficulty degree of their formal contents, neither a distinction among academic levels. As stated in [6], these characteristics are crucial for the development of a curricular trajectory.

Spatial reasoning, the ability to function with visual-spatial information, is considered to be a fundamental key in what concerns to mathematics, representing a big role in other disciplines, such as sciences, technology and engineering, and also in music, visual arts, physical education and geography [3, 7].

Algebra, and, Geometry and Measure are mathematical areas linked to spatial thinking, concerning both relationships and representation. In fact, standard mathematical tasks require the blending of spatial skills, with a strict link between spatial skills and the development of numerical comprehension [7]. It has been shown that persons with a better spatial reasoning usually have a better performance in mathematics [7, 8].

The spatial performance can also be an important auxiliary tool to predict the performance of children in mathematics. Children with a better spatial visualization, differentiating multiple spatial forms or shapes, rotating or manipulating them in the imagination and combining them to form different shape, can easily develop arithmetic skills [8].

There are studies connecting spatial play with spatial skills or with number processing. In a study referred in [9] with a large group of 4 to 7 year-old children, it was found that those who frequently participated in block play, puzzles, and board games had higher spatial ability than those who participated more in other category of activities like drawing, playing with sound-producing toys, trucks, and riding bikes.

Mental rotation and spatial visualization are key features of spatial reasoning. Spatial visualization is considered to be the ability to mentally form complex figures from simple ones, concerning different movements and transformations. It is also related to the ability to extrapolate the three dimensional representation of an object by its 2D representations and to make a plane representation of a 3D object [3, 10]. Mental rotation is characterized by the capability of being able to mentally manipulate both two and three-dimensional objects [7, 8], both quickly and accurately in the mind [3]. One interesting fact of solving problems in 3D by mentally rotate objects is that this procedure includes both: reaction time and rotation angle measure. By lowering the first and augmenting the second, the degree of difficulty is improved [3]. Mental rotation is also considered to be fundamental in both mathematical learning and achievement [7, 8].

In spite of the few existing studies on 3D games and their impact on the development of mathematical abilities [9], several authors, for example [11], argue that educational games with an "explicit theoretical background" act effectively in the development of mathematical competencies, being that board games are of great potential in the development of number sense.

In line with these ideas, we have opted by design a 3D board game for children, the 3DM6 game, having in mind the development of mathematical abilities with emphasis on geometrical thinking and mathematical reasoning. Our option is essentially related with the following question: In what extend 3D board games can have a meaningful influence in the development of the above-mentioned mathematical abilities?
By being a 3D board, it is expect that children will fell more engaged and stimulated than when playing with a two-dimensional board game. However, we will embody the main dynamic interactions of the traditional 2D board games in the 3DM6 to turn the adaptation to the 3D board game as smooth as possible. Besides, making use of the engagement/competition environment, we expect that players may develop an increasingly better strategy to win the game. The strategies may require geometrical thinking and mathematical reasoning.

Finally, with this game, we also expect players to enhance their inductive and deductive reasoning supported by the positive and negative feedback of their actions when playing [12]. We hope that 3DM6 turn out to be a worthy aid tool for the development of players strategic thought, principally in actions involving spatial geometric thinking.

2 3DM6 DYNAMICS

2.1 Theoretical Framework

There are some essential steps to have in consideration in the development of serious games. In designing a serious game, the balance between the play component (fun and entertainment) and the instructional component (learning goals) is fundamental and must always be present. In fact, is in the attenuation of the natural tension between these two components that lies one of the biggest challenges for serious game designers.

Since 3DM6 is a board game, one cannot forget the common characteristics of classic board games such as the ones described in [13]: players should have a game identifier that they can move following basic rules; players should have only one unique way to follow, and the winner of the game is the first element to arrive to a final marker position.

However, because it is a serious game, there are other aspects to take into account. In addition to motivation, fun and entertainment, according to [14] it is also necessary to incorporate the possibility of choosing the learning content, its quantity and order, from a wide range of learning contents.

In the teacher’s point of view, the game must not only offer the possibility to employ different learning contents, but also to combine different levels of difficulty under the same topic, and of course, being able to turn tedious topics, in the student perspective, into exciting ones. Finally the game should also be “self-explanatory” [14], which is line with the common spirit of board game where rules must be simple and in a small quantity [13].

During our research, we have struggled with a lack of theoretical framework in what concerns to board games related to serious games. We have used an adaptation of some digital game mechanics for the design and development of the 3DM6 game, such as the ones enumerated in [14] and [15].

Basic game mechanics related also to board games are: clear goals, epic meaning, challenges, transparency of results, loss aversion and progression [14]. Considering learning as a final goal of the game it is also important considering the following mechanics, present in [15]: 3D, story, pathway, exploration, goals, achievements, social, participation, competition, chance, surprise, anticipation, rules, location based, completion, movement, and manipulation.

2.2 Dynamics

3DM6 is a three-dimensional board game composed by cubic blocks of distinct sizes, in which the player’s identifiers move around. In each game move, several different possibilities of progression occur, which represents a higher level of difficulty when compared to a traditional two-dimensional board game. The 3DM6 game is composed by: a full three-dimensional board, one personalized game dice, four different game identifiers, and some specific pieces with a particular meaning (explained latter) and three personalized card decks.

The story underlying the 3DM6 game is the space exploration. Everything enrols in the search of a new planet. In this game players will be in search of planet 3DM6, however, they do not know how this planet looks like. The game starts in an 3D environment composed by one big cubic block. There will be game identifiers positioned in specific positions, in the lower layer of the cube. The winning position is signalized in the cube’s top face. To win the game the player needs to move his/her piece in a 3D matrix to reach the winning position.
The number of steps that each player advances is given by the number presented in the game dice. Being a personalized dice, the player can move according to this number (1, 2 or 3). However, in each play they can only move in one direction, a direction chosen among 4 possible ones. In other words, the player cannot change direction in a play move.

Each game recesses has one, among four specific colours. Three of the colours, the yellow, magenta and blue cyan, represent one of the three distinct type of cards presented in the game. When a player “falls” in one recesses of a determined colour, he needs to answer to the corresponding challenge present in one of the cards with the same colour. If the player fails nothing happens, if he wins, he has the possibility to take one of the additional game pieces, whose role will be explained latter, and can set it in one of the game’s re-entrances. These pieces can either have recesses or not. The goal is to place these game pieces strategically, in order to turn the game more profitable for the player and more ruinous for the others. Each one of these game pieces has associated colours. In the case of pieces with recesses, any player falling in one of them must answer to a new challenge, picking a card of the card deck with the corresponding colour. The colour white means that there is no question to be answered. The player’s final goal is to finish the game in first. The game ends when one the players reach the final position. If one player becomes blocked in all directions, not being able to move, he loses the game.

In 3DM6 game, the movements of the game identifier have a higher degree of freedom. In fact, in this game and in each play move, players can choose between 1 to a maximum of 4 different possible paths to follow, corresponding to the four orthogonal directions, up, down, right, and left, being that, with these movements they may leave one of the faces of the cube to visit a new one.

3 3DM6 CONCEPTION

3.1 Card Decks Challenges

In the 3DM6 game, three target audiences were taken in consideration to design the three card decks challenges. One of the target audience comprises children attending the 1st and 2nd years of the 1st cycle of the Portuguese Base Education; other is targeting children attending the 3rd and 4th years of the same cycle, and another, children attending the 5th and 6th years of the Portuguese Basic Education.

In this first version, three decks of cards were built, one for each target population, taking into account the math curricula of the Basic Portuguese Education. Despite the fact that pedagogical and scientific appropriateness underlying the challenges presented in the card decks is not under the scope of this paper, it is essential to emphasize that each card decks concentrates simultaneously two of the target school years. This option had in mind the goal of having children of different ages playing simultaneously, without losing interest in easy challenges or for issues by dealing with unknown or inappropriate topics.

All card decks have their challenges grouped into three difficulty levels, each one of which represented by the colours on the back of the card. The number of cards of each level to be present in the game may be adaptable to the players’ learning path. Each card has a symbol representing one of the special pieces that must be moved if they correctly answer the question.

3.2 3D Printing

For the physical construction of the board, the game identifiers, and the game special pieces, we opted for the 3D printing manufacturing, as it is the nowadays modus operandi for 3D prototyping [16], besides being a low-cost procedure.

According to [17], 3D printing is a growing technique in the development of new applications that can take particular advantages not only for printing 3D objects, but also from all the environment of the virtual construction of a the 3D prototype. When compared to screen based programs, 3D printing has the advantage of creating a three-dimensional physical object, which can be touched and observed [17]. A study described in [8] shows that the rotation ability of ten-year-old boys is stimulated with the visualization of 3D printed objects. In fact, when used in the education system, 3D printing enables teachers and educators to develop and practice new learning methods with the possibility to experiment, failure, and creating and test new methods [17], by all the diversity the 3D printing represents. Therefore, by developing both the board, the game identifiers and the special game pieces.
with 3D printing technology, we intend to take 3D printing objects to classroom in order to accustom both children and teachers with this way of knowledge building.

### 3.3 3D Board Game Implementation

For 3D prototype modulation, we use the Fusion 360 program, which is an integrated CAD, CAM and CAE software from Autodesk. This program was chosen not only because it is a free program for students, but also for the reason that facilitates precision modelling.

When considering the impression of the prototype, we opted for 3D printers of the University of Aveiro since the team project group is from this university. However, one of the problems associated with the use of the 3D printers is the fact that we didn’t have permanent access to them.

In order to develop the various components of the game it was necessary to employ two almost identical 3D printers, BEEINSCHOOL and BEETHEFIRST. None of these printers has filament refrigeration after the extrusion. Therefore, usually printed objects’ material is denser in the lower part of the body, than on the upper part. This means, that the resulting object becomes slightly deformed than the expected object, which is an aspect to have in account during objects’ digital modulation. There are 3D printers with this functionality; however, they are not available in this stage of the project. Other important characteristic of the used 3D printers is that they have an error of 0.4 mm, which, considering the dimensions of the objects is sufficient for the pieces do not fit perfectly.

Other negative point is the fact that we do not have full access to the printers, in the sense that it was not possible to change its printing parameters, which difficult the impression of several objects in different 3D printers.

The calibration of the 3D printers was manually done; however, we hadn’t the possibility to do so, and also the upload of the file STL par Gcode was made by the printing technician. Because of that, we couldn’t control neither the fill density nor the precision of printing.

The filament used was plastic PLA. This choice was made not only taking in account the cost of this material, but also by the fact that it is less toxic and easier to work with.

Another particularity to have in account when considering 3D printing prototyping is the amount of time that it take to print the objects. Depending on the characteristics of the piece, when considering its density and definition, principally, it can take several hours to print a relatively small piece. Which means that all the process to obtain just one final piece, with just negligible defects, can take several days.

Despite the good quality of the 3D printers used, it was necessary to print various prototypes, because the printed object had always defects when compared to the modulated object. Being so, it was necessary to print the object, then analyse its defects and understand what would be necessary to change in the digital modulation in order to fix the inaccuracies obtained. All this back-forward process was accomplished for the various 3DM6 game objects: board game, game identifiers and game obstacles.

#### 3.3.1 Board Game

The board game is the biggest object that was necessary to print, with 20 cm of edge length. Since the dimensions of the 3D printer’s table are bigger than the dimensions of the board object, it was not necessary to subdivide this piece in order to print it.

The board game has the format of a cube with a totality of 125 re-entrances (recesses), 25 in each face, where both game identifiers and game obstacles will fit in. Since these recesses exist both on the top face of the cube, and on the lateral faces, then the holes need to be strictly compatible with the fittings of the game identifiers and the game obstacles. If this does not happen, the pieces will consistently fall, and the game will lack dynamics, causing children to lose interest.

Being the object printed according to one specific vertical axe, all the holes will become deformed when the filament solidifies. When it is being printed, the filament is almost in a liquid state, then it will fall and, on the top face of the cube, the material will be denser close to the bottom of the hole, and on the side faces of the cube, the material will fall, and the hole will be deformed.
The first prototype of the 3MD6 is still a rather rudimentary prototype but will serve for testing with end users.

3.3.2 Game Dice

3DM6’s game dice is a personalized dice with equal opposite faces, having only the numbers 1, 2 and 3 represented. It was also prototyped to be 3D printed. In the dice modelling was necessary to have in account specific characteristics of the excepted functionality of this element.

The game dice has two main features to have in consideration. Firstly, it is a game piece that is constantly being used and secondly its use is composed by throwing and rotating it. Being so, it necessarily needs to be a rigid and strong piece, in order to not break during its normal use, and it also needs to be a rotatable piece, which means that it needs to be designed in order to do so.

Considering the fact that it is really hard, by 3D printing, to have the filament uniformly distributed through all the object, it was not possible to do, until the moment, a fair game dice, with equal probability associated to all faces. By so, this fact represents a future challenge, whose solution could eventually pass by choosing an alternative method to get the personalized dice.

3.3.3 Game Identifiers

The game will have a total of four game identifiers, one for each player. When modelling the game identifiers was necessary to have in account that these pieces need to be steady in a given position of the three-dimensional board, not only in the lateral faces, but also in the downward faces added to the game by some of the specific pieces described next.

![Figure 1 - 3DM6 board digital model prototype.](image)

![Figure 2 – Prototypes of cubes’ special pieces.](image)
3.3.4 Specific Pieces

The game has two different types of game obstacles: the cubes, allowing the players to use it as a complement of the board, since they have recesses equal to the ones present in the board (Figure 2), and obstacles, that completely blocks player’s way. Both obstacles increase the difficulty of the game, inducing the use of different strategies either to advance in the game or to put in a more advantageous position compared to his/her opponents.

The obstacles are a set of 8 different solids: cone, cylinder, triangular prism, quadrangular pyramid, tetrahedron, octahedron, dodecahedron, icosahedron. This add up the goal to familiarize children with some classical solids.

4 CONCLUSIONS AND FUTURE WORK

Here, we have described various aspects behind the design and conception of a 3D serious educational board game with special emphasis in the development of spatial and mathematical reasoning. Once we have the game prototype ready, we will proceed to the evaluation phase, analysing the reaction of the 3 target game audiences in relation to the ludic, scientific and pedagogical components, completing the cycle described by [18].

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