Chapter 12

Mobile Learning:
Benefits of Augmented Reality in Geometry Teaching

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ABSTRACT

As a consequence of the technological advances and the widespread use of mobile devices to access information and communication in the last decades, mobile learning has become a spontaneous learning model, providing a more flexible and collaborative technology-based learning. Thus, mobile technologies can create new opportunities for enhancing the pupils' learning experiences. This paper presents the development of a game to assist teaching and learning, aiming to help students acquire knowledge in the field of geometry. The game was intended to develop the following competences in primary school learners (8-10 years): a better visualization of geometric objects on a plane and in space; understanding of the properties of geometric solids; and familiarization with the vocabulary of geometry. Findings show that by using the game, students have improved around 35% the hits of correct responses to the classification and differentiation between edge, vertex and face in 3D solids.

Keywords: Education technology, Mobile devices, M-learning, Game-based learning (GBL), Extraneous Cognitive Load, Design Thinking, Concept Design, Augmented Reality, Geometry.

INTROD UCTION

Mobile platforms are now part of young people's life. Their pervasiveness makes them an ideal vehicle for the development of educational content both for classroom activities and informally. The possibility of learning anywhere and at any time is one of the most remarkable features of mobile learning. The past years have seen a great increase in mobile learning, alongside a larger offer of contents and technological possibilities and a greater interest among people in buying and using mobile platforms. Mobile technologies are becoming more embedded, ubiquitous and networked, with enhanced capabilities for rich social interactions, context awareness and internet connectivity. Such technologies could have a great impact on learning (Naismith, Lonsdale, Vavoula, & Sharples, 2004). As a research field, mobile learning is relatively new. According to Catenazzi & Sommaruga (2013, p. 9), 'the first initiatives date back to the last decades of the 1900s, but the wide diffusion of mobile learning took place starting from 2000 as a result of the large availability of mobile technologies'.

Mayer (2005) describes the cognitive theory of multimedia learning as several cognitive processes that include the selection of relevant visual and verbal materials, organization of these visual and verbal mental

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representations in coherent structures in working memory (short-term memory), and integrating the representations among themselves and with prior knowledge. The author also refers to the importance of design to prime these different cognitive processes in order to create multimedia instructional messages, in other words, to communicate containing images and words intended to foster learning (Mayer, 2005). Furthermore, the *Cognitive Load Theory* complements this process model by describing three types of cognitive load: intrinsic cognitive load, which describes the natural complexity of the information, germane cognitive load, which describes the amount of mental effort in the acquisition of knowledge by the learner in comprehending the materials, and extraneous cognitive load, which describes processing demands of information that is not directly related to the learning task, but to the manner in which instruction materials are designed. (Sweller, 2010). Therefore, in this cognitive perspective, the design of educational materials has effects on the cognitive process.

Pupils' motivation is probably one of the most important factors for teachers in the enhancement of the learning process (Williams & Williams, 2011). Motivation is an inner state which stimulates pupils to engage in a certain task (Lei, 2010). In this context, by promoting entertainment and voluntary performance, games are related to a cognitive process of intrinsic motivation (Dichev, Dicheva, Angelova, & Agre, 2014). Given the current technological possibilities and the popularity of games, the interest in games in a learning context has been on the rise (Bie & Lipman, 2012; Razak, Connolly, Baxter, Hainey, & Wilson, 2012; Hamari, Koivisto, & Sarsa, 2014; Schlagenhaufer & Amberg, 2015; Cheng, 2017). Sales, user statistics and public opinion polls are all evidence that computer games have become a dominant entertainment. Tobias and Fletcher (2011) state that, for the same reason, it is hardly surprising that teachers and trainers in different sectors consider the use of games in the teaching and learning process. Games and cognition are deeply intertwined and, with the advent of computer games, new scientific interests in this relationship have emerged (Gamberini, Barresi, Majer, & Scarpetta, 2008).

Primary-school learners experience difficulty in developing and consolidating their spatial sense, namely the visualization and the understanding of the properties of geometric figures on a plane and in space. They also present difficulties in acquiring the vocabulary associated to geometrical concepts such as face, edge, vertex, plane, prism, pyramid, cylinder, cone, sphere, among others.

In educational practice, physical objects are commonly used to establish a socially shared meaning. 'Physical objects support collaboration both by their appearance, the physical affordances they have, their use as semantic representations, their spatial relationships, and their ability to help focus attention' (Billinghurst, 2002, p. 3). The development of a game to be used in the teaching of primary-school geometry, whose main purpose was to develop learners' spatial sense, with emphasis on visualization could be of major importance to improve these pupils' competences, in addition, the union of the game with augmented reality could bring same advantages. Augmented reality (AR) offers functionalities which improve immersion, interaction and imagination, experiences connected to the constructivist principles of learning. Moreover, AR offers an intimate relationship between virtual and physical objects in real time.

This paper presents an AR game for primary-school learners (8-10 years old), aimed to facilitate the appropriation and the interpretation of geometric solids and 3D objects. The main objective of the game was to help students develop a better visualization ability; a better understanding of the properties of geometric solids in space; and familiarization with the vocabulary of geometry. The technology in this project was used to "augment" the visual field of the user with the information necessary in the performance of the tasks. The camera detected position (AR) markers which then generated virtual 3D objects, where the student was taken to learn the concepts of edge, vertex and face. The game allowed the teacher and the learner to engage in experimental operations in real time and at the same time. Learners adopted a natural interactive method and enjoyed the experience in a real environment, without resorting to the mouse or the keyboard. The teaching context was assumed to be favourable to the experimentation with new teaching/learning models given the low cost of AR technology as well as the presence of necessary infrastructure within schools.

The next section will present the state of the art. Then, the steps and the process of the conceptual design involved in the development of the game will be described. Afterwards, the evaluation of the prototype and further research avenues will be presented. Finally, the last section contains a discussion and proposals for future work.

STATE OF THE ART

Connections between play and education for both adults and children have already existed for a long time. According to A. Krentz (Krentz, 1998), 'etymologically in Greek the terms "paideia" the word for education/culture, "paida" the word for play/pastime/sport and "paides" the word for children, have the same root, and the three terms often show up in the same context' (Krentz, 1998, p. 5). Although the relationship between the words *play* and *children* may suggest that play is more connected with children's activities instead of adults', the term extends to activities we might not consider as laborious, serious, or solemn. The term *play*, in the context of the ancient Greek texts, is built on the opposite of the term *work*, which in the mainly agrarian context of Greek life had connotations of agricultural labour (D'Angour, 2013).

In Plato's *Republic*, the connection between play and education is central. Krentz (1998) states that in order to understand Plato's philosophical message it is necessary to pay close attention to the 'connection between education/culture (paideia), and the pedagogical approach (paidagogia) to teaching and learning that are to be carried out in the community. The central aim of pedagogy (paidagogia) is to encourage learning as a form of play (paidia), which is the most persuasive and effective approach to learning for free citizens in a society which honours philosophers' (Krentz, 1998, p. 6). According to Jane McGonigal, the ancient Greek Herodotus reported the use of game-playing in society by a king to distract his citizens from a famine (McGonigal, 2011). More recently, in the early Soviet era, game elements were used by the Soviet Union leaders as a substitute for monetary incentives for performing at work (Dicheva, Dichev, Agre, & Angelova, 2015).

One of the early and best-known projects in the field which combines games and AR in an education context is Construct3D (Hannes, 2004). Construct3D is a major project that resulted in a geometric construction tool especially designed for the teaching of mathematics and geometry in secondary and tertiary education. It allows the visualization of three-dimensional (3D) objects which so far had to be calculated and constructed by means of traditional methods. AR is used as a way of improving interfaces for a future generation, allowing students to work directly in a 3D space. Despite the advantage of free hand movements, in this project the use of a Head Mounted Display (HMD) was a necessary tool, and the possibility of mobility in other spaces was not accessible. In the opinion of Akçayir and Akçayir (2017), one of the principal reasons why AR technology is so widely used at present is that it no longer requires expensive hardware and sophisticated equipment, such as HMD. The authors state that 'the technology now can be used with computers or mobile devices. Thus, using AR technology is not as difficult as it was in the past. It is used today in every level of schooling, from K-12 to the University level' (Akçayır & Akçayır, 2017, p. 1).

A study by Lin et al. (2015) who integrated AR into teaching activities to assist K-12 students in learning solid geometry revealed, among other findings, that AR-assisted teaching has a favourable effect on students with low academic achievement. Perceptions indicated a low feeling of task load experienced by most users and, after AR-assisted teaching, student performances from the experimental groups improved, although the experimental and control groups did not differ significantly from each other.

In a previous study by these authors, the findings were that teaching geometry by means of information technology enhances students' comprehension of abstract mathematical concepts. They present as a possible reason that image-based teaching can help students to focus their attention (Lin et al., 2015). In addition to this, previous studies also confirmed that the use of three-dimensional dynamic multimedia in teaching geometry may encourage the curiosity of students, support their active learning and increase their achievement in geometry (Erbas & Yenmez, 2011).

In the last four years the number of AR studies in the field of education has increased (Cheng, 2017) and one the most reported advantage is that it promotes enhanced learning achievements (Akçayır & Akçayır, 2017). In science learning, studies have shown that students often hold robust misconceptions about several scientific ideas and that digital simulations and dynamic visualization tools have helped to increase the learning outcomes by providing scaffolding to understand different aspects of the contents (Yoon, Anderson, Lin, & Elinich, 2017). According to the authors, AR has the potential to augment users' interactions, engagement, and experiences and has revealed numerous affordances for science learning, including 'supporting students' scientific spatial ability, by (a) allowing them to manipulate and learn content in three-dimensional perspectives; (b) engaging them in scientific inquiry by encouraging them to make observations, ask questions, collaborate with others, and investigate and interpret data; and (c) enhancing their conceptual understanding by enabling them to visualize invisible or abstract concepts or events' (Yoon et al., 2017, p. 158). In a project that investigated optimal uses of AR in science museums, Yoon et al. (2017) found that students who interact with an exhibit using AR are better able to understand the science concepts than students in a non-AR condition. Furthermore, an experimental study by Lin et al. (2013), which intended to validate the correlation between spatial ability and mathematics performance, revealed that spatial ability and mathematics scores are highly correlated.

Moreover, with the increasing demand for Science, Technology, Engineering, and Mathematics (STEM) professionals in a worldwide innovation and global economics, STEM disciplines are viewed as a means of developing citizens' scientific literacy. Despite this panorama, Hsu et al. (2017) state that readiness and motivation on the part of students to pursue STEM majors and careers seem to be decreasing. Through a study developed with high school students in which they had learning experiences with AR lessons, the authors reported students' feedback that they felt inspired to deepen their knowledge, understood the importance of a transdisciplinary work for the innovation and creativity needed in futures places, and felt motivated to choose STEM-related majors at university (Hsu, Lin, & Yang, 2017). In other words, in addition to all the advantages mentioned by different authors about the use of AR in the context of teaching, the use of this technology also seems to have the capacity to motivate students both to feel more interest in deepening their knowledge about the contexts in question as well as in the field of technologies where AR is inserted. According to Squire and Jan (2007) 'science education needs to prepare students for a future world in which multiple representations are the norm and adults are required to "think like scientists" (…) and AR games offer an opportunity to create a "post-progressive" pedagogy in which students are not only immersed in authentic scientific inquiry, but also required to perform in adult scientific discourses' (Squire & Jan, 2007, p. 5).

Despite the various advantages, technical limitations associated with AR can also be found in the literature. According to Akçayır and Akçayır (2017), without a well-designed interface and guidance for the students, AR technology can be too complicated for them to use. The authors also found that the various devices that deliver AR applications may cause additional technical problems as well that bulky AR technologies such as HMDs are not easy to handle, therefore AR technologies should be developed to be smaller, lighter, more portable, and fast enough to display graphics.

DESIGN PROCESS

With the complexity of design problems increasing dramatically in the last decades, the need to use a method has become more important in the development of a design project. Although we can find design process tendencies in very different places and in different tasks, they all end up having in common the inclusion of the end user (Foo & Mårtensson, 2016). Therefore, there are several methods to achieve goals in design projects bearing in mind end users, deadlines etc.

Design thinking is a process of addressing problems in the development of a product, which can facilitate innovation and open up alternatives, not only lead to artefact creation. According to Liedtka (2013), when the individual elements of design thinking are combined and viewed together as a system from the beginning to the end aimed at solving problems, it emerges as a clearly distinctive way of thinking. The concept offers a unique integration framework that brings together both the creative and the analytical reasoning modes. Moreover, it is accompanied by a process and a set of tools and techniques (Liedtka, 2013). Brown (2008) reinforces the idea that design thinking must be present from the very beginning in order to be part of the creation process and increase the possibility to generate more ideas. Through this process, the author claims that the development is faster than by any other means (Brown, 2008).

In addition to technological considerations, the process should consider human behaviour, its needs and preferences. A human-centred project, especially when it includes observation-based research, will reflect more precisely people's needs.

The first step in any process should be understanding what project is being developed and why. In this stage, a mode of participatory design known as *Bodystorming* was adopted. *Bodystorming* emerged in the 1950s (Osborn, 1963) and is often considered a way to generate ideas and a form of start prototyping in context (Oulasvirta, Kurvinen, & Kankainen, 2003; Oppegaard & Still, 2013; Foo & Mårtensson, 2016;). According to Maguire (2001a), the awareness of context issues grew in the mid-1980s, promoted by the work of Whiteside and his colleagues who 'found that although many products performed well in their laboratory experiments, they did not work when transferred to the real world. They put this down to the fact that the research often overlooked something crucial to the context in which the product would be used' (Maguire, 2001a, p. 454). Thus, design sessions were carried out in the natural context, in a classroom, instead of being lab-based.

In the case of the project/application described in this paper, since one of the authors taught in this field, it was possible to carry out these sessions in two classes and understand the problems in a learning and teaching context. He observed that a substantial part of pupils revealed difficulty in understanding the third dimension of geometric solids, namely depth. One of the found difficulties was related to the explanatory process since two-dimensional drawings on the blackboard were used to represent three-dimensional objects. During these sessions, in randomly chosen classes, the pupils were asked about their use of smartphones, if they used to play games and what kind of games they used to play, as well questions related with geometric solids and the third dimension. The observation of the pupils' discussion and activities provided meanings and interpretations which were introduced in the interaction design process of the game.

The next step was the definition of objectives, the identification of expected behaviours and the description of players. The game "vertice" (see Fig. 1) aimed to facilitate learning about and interpreting geometric solids and 3D objects; namely, to enable learners to develop their capacity for visualization, their understanding of the properties of geometric solids in space and their familiarization with the vocabulary of geometry. At the same time, fun was expected to be an essential component of the experience. The expected behaviour was that the player (learner) would play the game and continue to play it via a user-centred, highly engaging interface.

In this context, the name for the game and the first sketches (Fig. 1) emerged. Several studies 'implied that different aesthetic designs can induce emotions and that these emotions affect users' performance and cognitive process' and, moreover, the users positive perceptions suggested 'that positive emotions were produced by the different design of multimedia elements such as visual design principles, design layout, colour, and sound'(Um & Plass, 2012, p. 7).

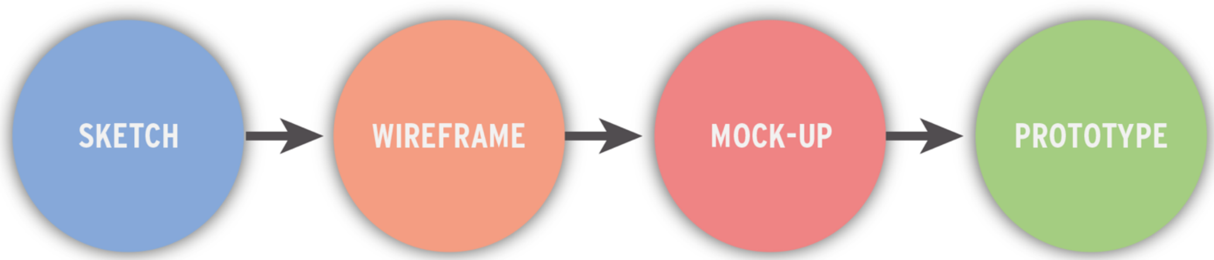

Figure 1. Conceptual design, different phases of the process

Sketch

The design process ordinarily starts with a conceptual idea of the envisaged product when its design parameters are still vague and incomplete. During the working process, the final product can be represented concretely in the form of drawings or computer models (Bayer et al., 2015). Prototyping is about the visual representations of complex systems and interaction models that meet high levels of design and usability. Although we can find several definitions of prototype in software engineering and human-computer interaction (Alperowitz, Weintraud, Kofler, & Bruegge, 2017), most practitioners will agree on the general meaning of a dynamic prototype as a working model under construction. Despite the importance of drawing to complete this process successfully, prototyping is not about improving the ability to draw, but about the intellectual and physical freedom to express ideas easily and spontaneously. Different forms of prototyping can help narrow the search for a solution in different phases of the process and these were also employed in the reported project (Fig. 2).

In early stages of designing the user interface of applications, sketching and wireframing are useful as a communication medium to explore, express, detect usability issues and communicate the design intentions (James & Brad, 2001; Murugappan, Piya, Yang, & Ramani, 2017; Sanchez Ramon, Garcia Molina, Sachez Cuadrado, & Vanderdonckt, 2013). This flexibility is particularly important to sketch rough design ideas quickly, to test designs by interacting with them and to fill in the design details as it becomes necessary to make choices. Sketching is basically a freehand drawing that gives a low-fidelity representation of the application. It is also considered a fast way to generate an idea for brainstorming. Several kinds of tools are used as part of the design process for expressive design representations (Coyette, Kieffer, & Vanderdonckt, 2007). Since conceptual sketching is characterized by ambiguity and the need to create several design variations quickly, these tools must support flexibility. According to James and Brad (2001) sketching with a pen is a mode of informal and perceptual interaction that has been shown to be especially valuable for creative design tasks. 'For designers, the ability to rapidly sketch objects with uncertain types, sizes, shapes, and positions is important to the creative process. This uncertainty, or ambiguity, encourages the designer to explore more ideas without being burdened by concern for inappropriate details such as colours, fonts, and precise alignment' (James & Brad, 2001, p. 57).

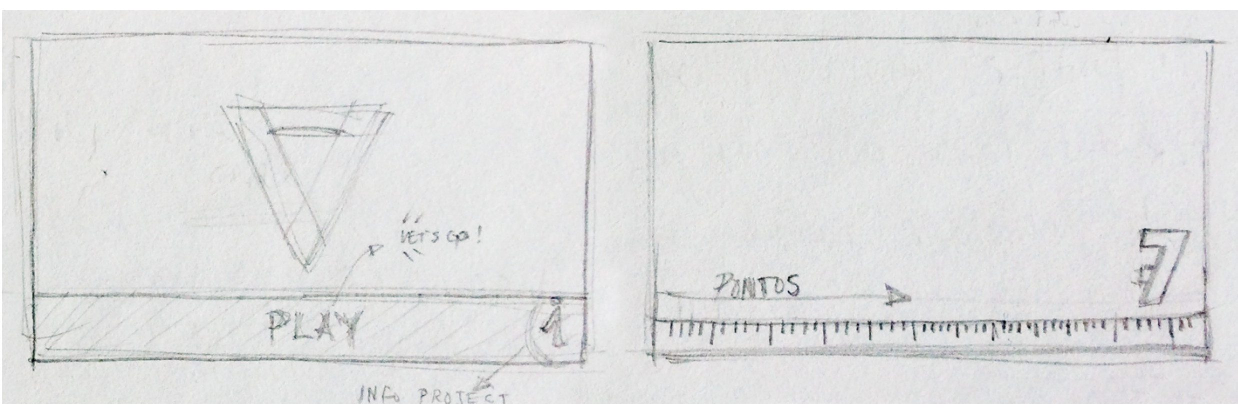

Figure 2. Sketching phase

Wireframe

As the design process evolves, the used representations move towards a higher level of detail and fidelity. Although a wireframe is still considered a low fidelity representation, wireframing tools are used to refine the concepts that come out of sketching and they frequently offer some facilities to generate mock-ups and prototypes (Sanchez Ramon et al., 2013). Without the distraction of graphic design, wireframes show layout, content and functionalities and sizes are almost pixel perfect. Wireframes can be also hand-drawn. In this phase, the representations of every important piece of the product are focused on basic structural issues and usually they have the appearance of a set of boxes.

Mock-up

Although sketches and wireframes as low-fidelity models are very helpful in the early stages of the design process and offer a clear set of advantages compared to high-fidelity prototyping (Coyette et al., 2007), they are insufficient in validating ideas and concepts. Thus, mock-ups help to define and refine the requirements by providing certain functionalities and contribute to new features in later phases of the project. They are very useful to define the overall interaction of the user with the application (Alperowitz et al., 2017) and to test. They are much easier, cheaper and quicker to make than a functional prototype in which studies and experiments are often more complex and less clean (Schmidt & Albrecht, 2017). Thus, this step is important for getting to the prototype phase. There are several kinds of tools to create mock-ups regarding the form, precision, interactivity and feasibility (e.g. Axure, Balsamiq, Sketch for interactive mock-ups; Illustrator, Photoshop and paper for a different interaction approach) and some services offer the possibility to execute the mock-up on a mobile platform (Alperowitz et al., 2017). Figure 3 shows part of the mock-up of two mobile screens with some interaction information for the developed application, produced with vector graphics software.

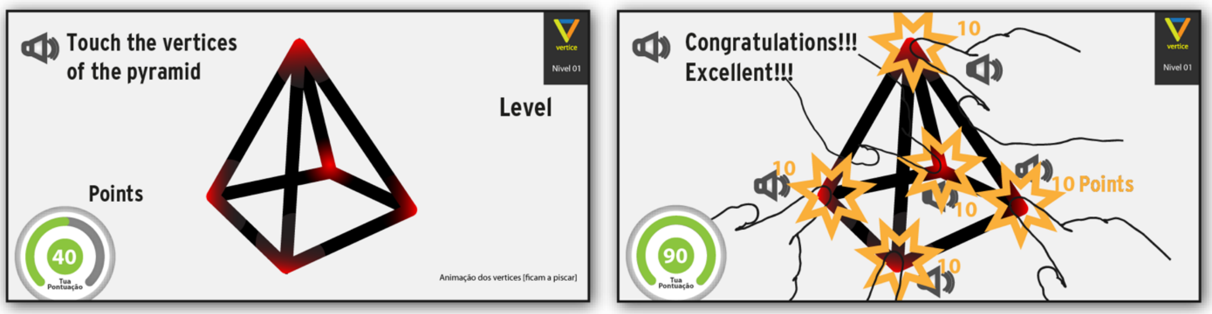

Figure 3. An example of a part of a mock-up of two mobile screens with some interaction information, produced with the Illustrator software

Since engagement was expected to be an essential component of the experience for the pupils interacting with the AR application, some game elements and game mechanics were incorporated: engagement cycles to familiarize the learner with the game environment, and progression cycles which represent the different levels of difficulty and competences. Regarding the engagement cycles, an initial, very simple scenario was created, consisting of only one area of a plane which presented the player with only one vertex. For a better engagement with this cycle and to minimize the rejection by the player, the area which he/she was expected to touch was highlighted by means of a red flashing light, as shown in Fig. 4 left. At the same time, the player heard an instruction: "Touch the vertex". After players' interaction with the vertex, feedback on their action was immediate, rendering them capable of interpreting their choice against the objective. A score was attributed and an encouragement was heard: "Very well, congratulations!". This step was repeated with the introduction of new objects. The continuous iteration of this cycle – action-feedback-interpretation – aimed to help learners to develop their cognitive abilities gradually and to get used to the interface.

The end of these three engagement cycles also marked the end of the first level which introduced the concept of *vertex*. The second level maintained the same approach, but this new progression cycle introduced the concept of *edge*. Again, players were presented with three engagement cycles which increased progressively in their degree of difficulty. The third level brought the last of these engagement cycles, meant to allow learners to experience the game and at the same time acquire knowledge on basic concepts. This third level was another progression cycle which transferred knowledge on the concept of *face* by means of the same approach which assisted the player through the signalling of the area which he/she was expected to indicate. After these first cycles, the signalling was eliminated and new objects were presented, the first ones always with very simple structures, followed by increasingly complex structures.

Prototype

Finally, to test and to demonstrate the feasibility of the functionality of the product while it is still possible to take risks, the use of prototypes provides several benefits and a basis for discussion in order to explore the product requirements (Schmidt & Albrecht, 2017). Hence prototypes allow to explore how the technology works and what it feels like to use it. Tools to produce high-fidelity models must enable building a user interface that looks complete and equipped with a wide range of editing functions for all graphic user interface (GUI) and heads-up displays (HUD) that should be usable.

In an initial stage, pre-production, the first components to be developed were the graphical user interfaces (GUIs). The initial panels, the score indicators, the level in which the player finds him/herself, the buttons and their behaviours, and the data introduction toolbars were built in vector graphics format. Next, these were exported to a .png format for a potential use of the images with transparency features and without a background. It was then necessary to draw the 3D objects, which were created in Blender ("Blender," 2017) given its ease of usage and its free availability. All the drawings, already with the division of objects according to the interaction needs for the vertex, edge and face elements, were exported to the Autodesk FBX format (.fbx). The design of the recognition pattern (marker) represented the next step. A drawing was developed in A4 size, with some images of geometric figures and with the image which represented the game icon. Care was taken to draw an image which contained the necessary information, but which, at the same time, contemplated economical printing in greyscale. The marker was prepared using the Vuforia developer portal ("Vuforia," 2017). The instructions on the expected actions as well as the feedback phrases to confirm or question the player's choices were recorded, for which Audacity 2.0.4 ("Audacity," 2017) was used. More detailed information can be found in Leitão, Rodrigues and Marcos (2014, p. 69).

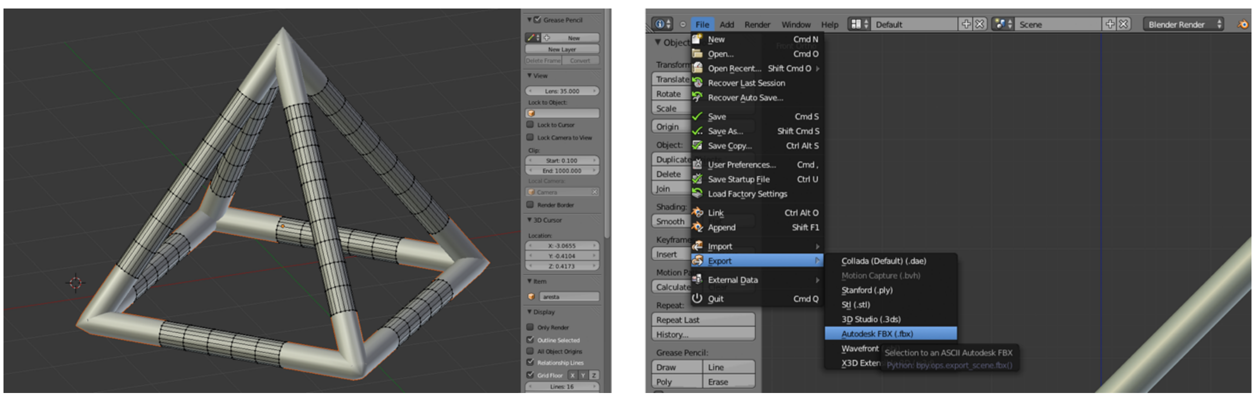

Figure 4. Construction of solid geometric figures and exportation from blender

In the second stage of the implementation, all the developed components referred to above were imported into Unity3D ("Unity 3D," 2017). The Unity scenes corresponded to the levels. Therefore, in the first scene, which was named "start" and which corresponded to level 0, the icon for the game was introduced, as well as the two buttons to start or to quit the game. This stage worked with the Main Camera, present by default in Unity, since there were no immersive stages yet. The game objects named GUI Textures served to introduce the images and then to position, rescale or turn them as desired. A folder called Resources was created to which all the designed GUI were imported in .png format in order to take advantage of the transparencies. The importance of the transparencies resided in the fact that sometimes the interfaces would superimpose themselves onto the images viewed by the camera. Similar steps were followed for the sound. Once the sound was selected, it was indicated into the Inspector panel that it should be heard on starting the game ('Play on Awake') and that it should stay in constant rotation ('Loop'). For the two buttons, it was first necessary to create two 3D Text game objects, and then to apply to each of them a script developed in Java in order to obtain the interaction.

In level 1, where the game effectively began, the marker was first integrated with the Vuforia extension. After making the registration in the application's online platform, it was necessary to create a database where the marker image was processed to immediately after download a file and import it into Unity 3D.

The Vuforia application offers two types of databases. The Devise Database, was chosen as being the most appropriate for the simplicity of the project. Inside Unity, the installation of the extension Vuforia for Android and iOS was necessary. After this step, it was necessary to delete the Main Camera which comes by default with Unity 3D and replace it with the AR Camera which Vuforia provides for RA applications. Afterwards, the marker (Image Target Prefab) had to be added to the stage and configured. The Image Target (images which Vuforia SDK can detect and follow) as well as the AR Camera are located in the folder Qualcomm Augmented reality/Prefabs. All that was needed was drag and drop inside Hierarchy, to introduce the marker which would determine the position of the objects.

In the Inspector panel, with the AR Camera selected, it was required to add the script 'Data Set Load Behaviour' and activate it. Similarly, with the image target selected, it was necessary, in the script 'Image Target Behaviour', to configure the Data Set component with the marker to be used and, automatically, in the stage view, it was possible to view the marker. It was also essential to create a light point for a better visualization. In this case, a directional light was applied in order to illuminate the whole scene. The stage was now set for the introduction of the 3D models. The important point here was to maintain the model subordinated to the Image Target and, afterwards, to position and scale it as desired in the scene itself.

At this level, two GUI Textures were introduced for the .png images, one corresponding to the information on the current level and another to the score background. A GUI Text was also added to the score background for the updating of the score points. In this case, since the information was not an image but a text, a semi-bold sans serif font was chosen for better legibility. The colour was chosen to create a good contrast with the background. It was important at this stage to subordinate these GUI to the AR Camera.

The animations were tackled next. In this application, they consisted of flashing which indicated the point of contact. Previously in the development of 3D models, care was taken to separate the contact points as different objects, which facilitated the animations and the action attributions. With only the vertex selected, in *animation* (in a process similar to other animation and video software) the colour was changed and its constant rotation (loop) was activated in a space of 30 frames. In this way, the flashing effect was obtained by means of a gradient towards red and then with a gradual return to its original colour. A Java script was also attributed, similar to the one attributed to the buttons in the initial stage, which this time indicated the passage to the next level and the attribution to the *val* GUI (GUI text) of the first points. Finally, the sound was added: the initial sound corresponded to the expected action and then the feedback to the performed action.

As initially envisaged, in a process of simplification of all the structures, all the levels were developed in the same way. It was only necessary to change the models in *Image Targets*, position, scale and turn them as desired, and reproduce the animations. Additionally, the Android Developer Tools had to be installed in order to allow the connectivity of the game with an Android device. For this purpose, it was necessary to indicate its localization in the Unity 3D options in *external tools*. The Unity Remote application allows the Android device to function as a remote controller of the Unity3D editor project. In this way, the development turns to be faster since one does not have to constantly compile and implement in the Android device every time the project needs to be visualized following further modifications (see Unity, 2017).

PROTOTYPE EVALUATION AND FURTHER RESEARCH AVENUES

The evaluation of the prototype was carried out in a public primary school in Portugal, which was receptive to the project since one of the authors had been teaching there for several years. The evaluation took place at the beginning of the 2013/2014 school year and involved two classes (53 pupils, 30 girls and 23 boys, aged 8-10). In the first class, with 27 pupils, the geometric concepts of vertex, edge and face were explained verbally and by means of drawings on the whiteboard (Class 1) – control class. In the second class (Class 2), with 26 pupils, in addition to a short, simplified explanation like that provided to Class 1, the game was presented to the children. It was also explained to them how the game worked with AR, similar to the process employed in more popular games (such as Invizimals of PlayStation Portable or more recently

Pokemon Go of Niantic, Inc.). The children were also told that they were going to hear instructions during the game and were shown the image that served as marker, towards which they had to direct the device.

Figure 5. Experimental group in interaction with the game

Children were given the opportunity to interact with the game. Initially, each pupil interacted with the game individually, but after a while more and more pupils gathered around the player: some who had not had their turn yet to satisfy their curiosity, and others, who had already played, to offer help. The game ran generally smoothly and pupils encountered little difficulty. Although the sound was not always at its best, which could prejudice the understanding of the action required, it did not affect the course of the game thanks to the visual signals present in the first levels, which were meant to create greater involvement with the game. The tendency to use the smartphone horizontally was noted in all children, probably related to their use of PlayStation Portable. More detailed information can be found in Leitão, Rodrigues and Marcos (2014).

After these sessions, the students in both classes were asked to complete a test according to the learning outcomes in order to get information on their learning. It consisted of several figures in black with the edge, or the vertex or the face highlighted. For each figure a form with a checkbox was presented, allowing the student to select one of the options – edge/vertex/face. The results for Class 1 were as follows: 33.3% pupils identified the edge, 55.6% pupils identified the vertex and 59.3% identified the face. In Class 2, they were the following: 84.6% pupils identified the edge, 88.5% the vertex and 88.5% the face. Overall, in Class 1 (control class) after the presentation and work done by the teacher, the students hit correctly 49.4% of the questions, and in Class 2 the students hit correctly 87.2% of the questions (Fig. 6).

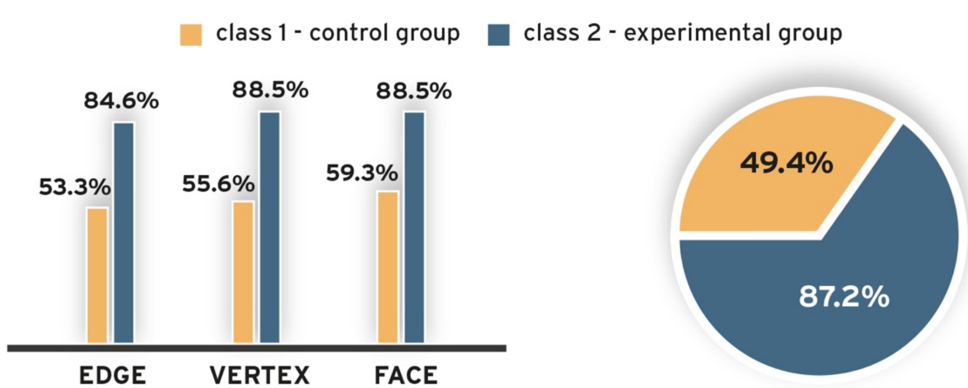

Figure 6. Left: Percentages of correct answers by evaluated item. Right: overall percentage of correct answers

As noticed, there was a great difference in the learning of the concepts between the pupils in Class 1 and Class 2. One of the reasons could result from the pupils' level of concentration during the explanation of the concepts, without the game, in Class 1. Explanation is a traditional method for knowledge transmission, implying a passive attitude and little engagement for the pupils. Additionally, in Class 2, the game served to repeat various times the concepts through interaction and experimentation, which contributed to the consolidation of knowledge.

The small sample size employed in the study represented one limitation. Carrying out the experiment in a larger number of classes and schools would be important to get a better 'validation' of how much the game can improve learning. In this case, the experiment led to an increase of almost 35% of correct answers when playing the game when compared with traditional teaching. In the future, the game can also be extended to other geometrical concepts such as plane, prism, pyramid, cylinder, cone, sphere, etc. Another limitation was not to have done a prior test in order to assess the children's knowledge of geometric concepts before the explanation or the interaction with the game. This meant that it was not possible to determine whether the learning occurred only during the class in which the concepts of vertex, face and edge were presented to them (by one method or the other), or whether the children already had some previous knowledge. A third area which would have deserved more exploration was the children's degree of contact and interaction with technology and whether this had any influence on the results of the learning through the game. A plausible hypothesis would be that children already familiar with technology (computers, smartphones, tablets, etc.) find it easier to interact with the game and, consequently, derive greater benefit from it. Similarly, future work could also include a study to establish the relationship between learning outcomes and the children's degree of familiarity with new technologies (types, usage frequency, level of difficulty, purposes etc.). This would allow better precision in the evaluation of the game's efficiency in the attainment of learning outcomes.

CONCLUSION

Game-based learning (Muñoz, Lunney, Mc Kevitt, Noguez, & Neri, 2013; Razak et al., 2012) takes children to immersive environments where they learn to use an impressive range of tools and complex machines. Many hours are dedicated to the memorization of scenarios, during which they develop sophisticated tactics to reach their objectives and win the game. In many cases, games are developed in collaboration with children all over the world in an exchange of solutions. Eventually games can contribute to emotional and social development, including different forms of cooperation and competition. Moreover, they allow children to discover why rules are important and which ones work best. While playing, children direct their attention to details in order to have the best possible performance in the game. In fact, these experiences help children to develop more mature thinking and problem-solving abilities (Yatim & Masuch, 2007). However, creating engaging game applications can be very difficult. As stated by Maguire (2001b), 'human-centred system development is a collaborative process which benefits from the active involvement of various parties, each of whom have insights and expertise to share. It is therefore important that the development team be made up of experts with technical skills and those with a "stake" in the proposed software' (Maguire, 2001b, p. 589). Furthermore, is not a simple step to bring together a team.

The elaboration of the game "vertice" aimed to provide pupils with a learning tool which would facilitate knowledge acquisition according to constructivist principles. Constructivism advocates that learners should, through own experience (Huang, Rauch, & Liaw, 2010) build new knowledge upon the knowledge they already possess, a process which allows each learner to have their own idiosyncratic version of a specific piece of knowledge. In this way, knowledge is actively constructed by the learner, and not passively absorbed from books or verbal explanations. The game "vertice" validated once again the statements of several authors, that by playing games students learn to act, their curiosity is stimulated, they acquire initiative and self-confidence and they develop better language skills, reasoning and concentration (Przybylski, Rigby, & Ryan, 2010). The improvement of cognitive capacities as well as knowledge acquisition are facilitated by exploration, action and experimentation. When associated to social interaction, these methods, in fact, encourage more that just individual knowledge acquisition, but a collective construction of knowledge and a negotiation of meanings (Silva & Silveira, 2012). The learning process becomes more pleasant, different from a traditional class which implies passive knowledge reception. Such methods promote active learning by means of active problem-solving (Boyle, Connolly, & Hainey, 2011). According to Prensky (2005), when playing, individuals interact with the game environment and receive immediate feedback on their actions, thus being able to interpret their choices in accordance with their objectives. The continuous repetition of this cycle (action-feedback-interaction) allows players to develop their cognitive capacities gradually. The teachers and learners (as also shown in our experiment) have recognized that games can help the development of strategic thinking, planning, communication, numeracy, negotiation skills, group decision-making and information processing (Kirriemuir & McFarlane, 2004).

Augmented reality is a growing field that can be explored for different applications adapted to every knowledge area, presenting a great potential in education with the development of educational games. As already mentioned, the game presented here demonstrated a capacity to awaken curiosity, motivation and initiative among the children due to its engaging and interactive nature. Thanks to its novelty, the use of AR stirred great interest on the part of the children during the game. From a pedagogical point of view, it helped them attain the competences that the game aimed to develop: ability of visualization, the understanding of the properties of geometric solids and familiarization with the vocabulary of geometry. The pupils' receptivity to the game was, as expected, very positive, since they came across curricular content in a different and entertaining manner. The 3D model, especially given its powerful capacity of representation, proved to be an efficient means to convey the concept of three-dimensionality, compared to the bi-dimensional drawings on the whiteboard.

Design thinking was the problem-solving approach adopted in the development of the game. It implied constant attention to the target audience, i.e., children/pupils. It was also an approach which sought to achieve a balance between the objectives (improvement of pupils' visualization abilities, their understanding of the properties of geometric solids in space, familiarization with the vocabulary of geometry) and the image and presentation, bearing in mind popular games in this age group. As a result, the interfaces, which represent the information and the instructions for the pupil/user, were designed as secondary elements in order to simplify usability and to interfere as little as possible with the camera vision. Another constant concern was user-centeredness, meant to facilitate pupils' learning and interaction with the game, while not limiting their performance. The use of gamification techniques (Deterding, Dixon, Khaled, & Nacke, 2011) – whereby games and game elements were used in an educational context – facilitated the process of behaviour definition, which influenced interaction and motivation. In addition to a scoring system that increased pupils' motivation, the game dynamics allowed integrating educational content with the game narrative.

A further development of the application could envisage responsive design which allows content to adapt to screens of different sizes. The introduction of additional levels could also be an aspect worth exploring, to include for instance more complex geometric solids and other types of difficulty (such as movement and time). The sound, too, presents potential for further development, not only to improve its quality, but also by employing a voice more suitable to the target group, by creating new soundtracks to accompany the storyboard and by diversifying the interaction prompts and responses. Additionally, the introduction of leaderboards would not only enable players to measure their progress, but also to compare it with that of other players. And, finally, game analytics would be an easy means of tracking the players' behaviour. Through the collection and analysis of data, it would be possible to obtain feedback to improve design, quality, and to identify errors and correct them.

The presented paper and application reinforces that which has already been referred to by other authors (e.g. Kaufmann, 2004), namely that learning by means of games can significantly benefit learning outcomes and the development of more mature thinking. The results suggest that the game-based learning with AR has a positive effect on pupils' content knowledge. The capacities of new technologies, the miniaturization of devices, the universal access, the handy analysis of digital data, the ease of diffusion and update, the bandwidth and, not least, the financial accessibility of means and resources, ensure good conditions for the use of this type of games in teaching.

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REFERENCES

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1–11. http://doi.org/10.1016/j.edurev.2016.11.002

Alperowitz, L., Weintraud, A. M., Kofler, S. C., & Bruegge, B. (2017). Continuous prototyping: Unified application delivery from early design to code. *CEUR Workshop Proceedings*, *1806*, 36–43.

Audacity. (2017). Retrieved June 15, 2017, from http://www.audacityteam.org

Bayer, J., Bukhari, S. S., Langenhan, C., Liwicki, M., Althoff, K.-D., Petzold, F., & Dengel, A. (2015). Migrating the Classical Pen-and-Paper based Conceptual Sketching of Architecture Plans Towards Computer Tools - Prototype Design and Evaluation. *The Eleventh IAPR International Workshop on Graphics Recognition. IAPR International Workshop on Graphics Recognition (GREC-2015), 11th, Located at 13th International Conference on Document Analysis and Recognition (ICDAR), August 22-23, Nancy, France*. Retrieved from http://www.dfki.de/web/forschung/publikationen/renameFileForDownload?filename=bare_conf.pdf&file_id=uploads_2934

Bie, M. H. de, & Lipman, L. J. A. (2012). The use of digital games and simulators in veterinary education: an overview with examples. *Journal of Veterinary Medical Education*, *39*(1), 13–20. http://doi.org/10.3138/jvme.0511.055R

Billinghurst, M. (2002). Augmented Reality and Education. *New Horizons for Learning*, (figure 1), 21(3) 195-209. http://doi.org/10.4018/jgcms.2011010108

Blender. (2017). Retrieved June 15, 2017, from https://www.blender.org

Boyle, E., Connolly, T. M., & Hainey, T. (2011). The role of psychology in understanding the impact of computer games. *Entertainment Computing*, *2*(2), 69–74. http://doi.org/10.1016/j.entcom.2010.12.002

Brown, T. (2008). Design thinking. *Harvard Business Review*, *86*(6), 84–92, 141. http://doi.org/10.5437/08956308X5503003

Catenazzi, N., & Sommaruga, L. (2013). Mobile Learning and Augmented Reality: New Learning Opportunities. *Social Media: Challenges and Opportunities*, 9–13.

Cheng, K.-H. (2017). Exploring Parents ' Conceptions of Augmented Reality Learning and Approaches to Learning by Augmented Reality With Their Children. *Journal of Educational Computing Research*, (1), 1–24. http://doi.org/10.1177/0735633116686082

Coyette, A., Kieffer, S., & Vanderdonckt, J. (2007). Multi-fidelity Prototyping of User Interfaces, 150–164.

D'Angour, A. (2013). Plato and Play: Taking Education Seriously in Ancient Greece. *American Journal of Play*, *5*(3), 293–307.

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: defining gamification. In *Proceedings of the 15th International Academic MindTrek Conference on Envisioning Future Media Environments - MindTrek '11* (pp. 9–15). http://doi.org/10.1145/2181037.2181040

Dichev, C., Dicheva, D., Angelova, G., & Agre, G. (2014). From Gamification to Gameful Design and Gameful Experience in Learning. *Cybernetics and Information Technologies*, *14*(4), 80–100. http://doi.org/10.1515/cait-2014-0007

Dicheva, D., Dichev, C., Agre, G., & Angelova, G. (2015). Gamification in Education : A Systematic Mapping Study Gamification in Education : A Systematic Mapping Study. *Educational Technology & Society*, *18*(June), 75–88.

Erbas, A. K., & Yenmez, A. A. (2011). The effect of inquiry-based explorations in a dynamic geometry environment on sixth grade students' achievements in polygons. *Computers and Education*, *57*(4), 2462–2475. http://doi.org/10.1016/j.compedu.2011.07.002

Foo, H., & Mårtensson, O. (2016). *Designing for engagement using gamification in mobile applications*.

Gamberini, L., Barresi, G., Majer, A., & Scarpetta, F. (2008). A game a day keeps the doctor away: a short review of

computer games in mental healthcare. *Journal of CyberTherapy & Rehabilitation Summer 2008*, *1*(2), 127–145.
Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? - A literature review of empirical studies on gamification. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 3025–3034. http://doi.org/10.1109/HICSS.2014.377
Hannes, K. (2004). *Geometry Education with Augmented Reality*. Retrieved from http://gretchen.ims.tuwien.ac.at/media/documents/publications/kaufmann_diss.pdf
Hsu, Y.-S., Lin, Y.-H., & Yang, B. (2017). Impact of augmented reality lessons on students' STEM interest. *Research and Practice in Technology Enhanced Learning*, *12*(1), 2. http://doi.org/10.1186/s41039-016-0039-z
Huang, H.-M., Rauch, U., & Liaw, S.-S. (2010). Investigating learners' attitudes toward virtual reality learning environments: Based on a constructivist approach. *Computers & Education*, *55*(3), 1171–1182. http://doi.org/10.1016/j.compedu.2010.05.014
James, A., & Brad, A. (2001). Sketching Interfaces : Toward More Human Interface Design, 56–64.
Kirriemuir, J., & McFarlane, A. (2004). Literature Review in Games and learning. *Futurelab Series*, (8), 39. Retrieved from https://telearn.archives-ouvertes.fr/hal-00190453%0Ahttp://telearn.archives-ouvertes.fr/hal-00190453/
Krentz, A. (1998). Play and Education in Plato's Republic. *Twentieth World Congress of Philosophy*, (2). Retrieved from https://www.bu.edu/wcp/Papers/Educ/EducKren.htm
Lei, S. A. (2010). Intrinsic and Extrinsic Motivation : Evaluating Benefits and Drawbacks from College Instructors ' Perspectives, *37*(2), 153–160. Retrieved from http://web.a.ebscohost.com/ehost/pdfviewer/pdfviewer?sid=1b4f8e6a-7ae0-444d-9d6c-b0e343f3df1f%40sessionmgr4003&vid=0&hid=4106
Leitão, R., Rodrigues, J. M. F., & Marcos, A. F. (2014). Game-Based Learning: Augmented Reality in the Teaching of Geometric Solids. *International Journal of Art, Culture and Design Technologies*, *4*(1), 63–75. http://doi.org/10.4018/ijacdt.2014010105
Liedtka, J. (2013). Design Thinking : What it is and why it works. *Design at Darden Working Paper Series*. Retrieved from http://batten.squarespace.com/storage/books-journals-articles/DesignThinking_WhatitIs_Liedtka.pdf
Lin, H.-C. K., Chen, M.-C., & Chang, C.-K. (2015). Assessing the effectiveness of learning solid geometry by using an augmented reality-assisted learning system. *Interactive Learning Environments*, *23*(6), 799–810. http://doi.org/10.1080/10494820.2013.817435
Maguire, M. (2001a). Context of Use within usability activities. *International Journal of Human-Computer Studies*, *55*(4), 453–483. http://doi.org/10.1006/ijhc.2001.0486
Maguire, M. (2001b). Methods to support human-centred design. *International Journal of Human-Computer Studies*, *55*(4), 587–634. http://doi.org/10.1006/ijhc.2001.0503
Mayer, R. E. (2005). Cognitive Theory of Multimedia Learning. In *The Cambridge handbook of multimedia learning* (pp. 31–48). Cambridge university press.
McGonigal, J. (2011). *Reality is broken: Why games make us better and how they can change the world*. (Penguin, Ed.).
Muñoz, K., Lunney, T., Mc Kevitt, P., Noguez, J., & Neri, L. (2013). An Emotional Student Model for Game-Based Learning. In *Technologies for Inclusive Education: Beyond Traditional Integration Approaches*. http://doi.org/10.4018/978-1-4666-2530-3.ch009
Murugappan, S., Piya, C., Yang, M. C., & Ramani, K. (2017). FEAsy : A Sketch-Based Tool for Finite Element Analysis. *Journal of Computing and Information Science in Engineering*, *17*. http://doi.org/10.1115/1.4034387
Naismith, L., Lonsdale, P., Vavoula, G., & Sharples, M. (2004). Literature Review in Mobile Technologies and Learning Literature Review in Mobile Technologies and Learning. Slough: FutureLab. Retrieved from http://www.futurelab.org.uk/resources/documents/lit_reviews/Mobile_Review.pdf
Oppegaard, B., & Still, B. (2013). Bodystorming with Hawkins's block: Toward a new methodology for mobile media design. *Mobile Media & Communication*, *1*(3), 356–372. http://doi.org/10.1177/2050157913496421
Osborn, A. F. (1963). *Applied imagination : principles and procedures of creative problem-solving.* (3rd ed., r). New York : Scribner's.
Oulasvirta, A., Kurvinen, E., & Kankainen, T. (2003). Understanding contexts by being there: Case studies in bodystorming. *Personal and Ubiquitous Computing*, *7*(2), 125–134. http://doi.org/10.1007/s00779-003-0238-7
Prensky, M. (2005). " Engage Me or Enrage Me": What Today's Learners Demand. *Educause Review*, (October),

60–64. Retrieved from http://cff.wiki.elanco.net/file/view/Engage+Me+or+Enrage+Me.pdf/84842561/Engage+Me+or+Enrage+Me.pdf
Przybylski, A. K., Rigby, C. S., & Ryan, R. M. (2010). A motivational model of video game engagement. *Review of General Psychology*, *14*(2), 154–166. http://doi.org/10.1037/a0019440
Razak, A. A., Connolly, T., Baxter, G., Hainey, T., & Wilson, A. (2012). The use of Games-Based Learning at Primary Education Level Within the Curriculum for Excellence: A Combined Result of two Regional Teacher Surveys. In *Proceedings of the 6th European Conference on Games Based Learning* (p. 52).
Sanchez Ramon, O., Garcia Molina, J., Sachez Cuadrado, J., & Vanderdonckt, J. (2013). GUI Generation from Wireframes. In *Actas del XIV Congreso Internacional de Interacción Persona-Ordenador*. Madrid, España. Retrieved from http://hdl.handle.net/2078/153911
Schlagenhaufer, C., & Amberg, M. (2015). A Descriptive Literature Review and Classification Framework for Gamification in Information Systems. *ECIS 2015 Completed Research*, 0–15. http://doi.org/10.18151/7217466
Schmidt, A., & Albrecht. (2017). Understanding and researching through making-A Plea for Functional Prototypes. *Interactions*, *24*(3), 78–81. http://doi.org/10.1145/3058498
Silva, D., & Silveira, I. (2012). Jogos Educacionais com Realidade Aumentada: Desafios de Integração e Possibilidades na Construção de Objetos de Aprendizagem. In *Conferencias LACLO 3.1*. São Paulo.
Squire, K. D., & Jan, M. (2007). Mad city mystery: Developing scientific argumentation skills with a place-based augmented reality game on handheld computers. *Journal of Science Education and Technology*, *16*(1), 5–29. http://doi.org/10.1007/s10956-006-9037-z
Sweller, J. (2010). Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational Psychology Review*, *22*(2), 123–138. http://doi.org/10.1007/s10648-010-9128-5
Tobias, S., & Fletcher, J. D. (2011). *Computer games and instruction*. Charlotte: Information Age Publishing.
Um, E., & Plass, J. L. (2012). Emotional design in multimedia learning. *Journal of Educational Psychology*, *104*(2), 485–498. http://doi.org/10.1037/a0026609
Unity 3D. (2017). Retrieved June 15, 2017, from https://unity3d.com
Vuforia. (2017). Retrieved June 15, 2017, from https://www.vuforia.com
Williams, K., & Williams, C. (2011). Five key ingredients for improving student motivation. *Research in Higher Education Journal*, 1–23. Retrieved from http://www.jupapadoc.startlogic.com/manuscripts/11834.pdf
Yatim, M. H. M., & Masuch, M. (2007). *Educating children through game making activity*. Retrieved from http://www.learnit.org.gu.se/digitalAssets/862/862887_yatim_masuch.pdf
Yoon, S., Anderson, E., Lin, J., & Elinich, K. (2017). How Augmented Reality Enables Conceptual Understanding of Challenging Science Content How Augmented Reality Enables Conceptual Understanding of Challenging Science Content, *20*(January), 156–168.