Development of Game-Like Simulations for Procedural Knowledge in Healthcare Education

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Abstract—We present EGDA, an educational game development approach focused on the teaching of procedural knowledge using a cost-effective approach. EGDA proposes four tasks: analysis, design, implementation, and quality assurance that are subdivided in a total of 12 subtasks. One of the benefits of EGDA is that anyone can apply it to develop a game since it keeps development as simple as possible and uses tools for modeling and implementation that do not require a highly technical profile. EGDA has been applied to the creation of seven educational games in healthcare, and has been iteratively refined after each experience. EGDA is evaluated on two aspects. First, the effort and cost needed for creating these games is estimated and compared to current industry standards. Second, impact on knowledge acquisition and a student acceptance are discussed. Results suggest that EGDA can make game development more affordable, which is critical for increased adoption and scalability of game-based learning (GBL), while assuring a high educational value of the resulting games.

Index Terms—Computer-assisted instruction, games, gaming, health, software engineering process

1 Introduction

Research in game-based learning (GBL) continues to rise firmly and steadily, producing evidence on the potential of GBL [1] like significant improvements of academic performance and student motivation [2], [3]. As a consequence, the interest in using games in education is quickly increasing among different organizations [4]. However, there are still open issues regarding the use of educational games, their high development costs being one of the most relevant [5]. This limits wider adoption [6] and makes of GBL difficult to scale [7].

GBL can be implemented using different approaches and underlying supporting technologies. For example, there are examples of using IMS Learning Design to create gamified online courses [8], [9]. However, for the scope of this paper we will refer to GBL as the educational approach that uses digital computer games, implemented using purely gaming technology.

In this paper we propose EGDA: an educational game development approach. EGDA is optimized for creating digital games for learning procedural knowledge, which is required in most of science, technology, engineering and health disciplines, among others. Digital games and simulations have been proven effective tools to support learning in healthcare education [10], which is the main application field of EGDA. One of the novelties is that EGDA proposes a combination of two different tools to create the game: WEEV, a modelling tool to help game and domain experts design the game, plus eAdventure, a game authoring tool to assemble game prototypes. This facilitates involving domain experts in the design process, since game experts can make designs with the WEEV tool that are easy to revise and which can be seamlessly translated into running eAdventure games, which reduces the cost.

We first provide context about GBL in Section 2. In Sections 3 and 4 we present EGDA. In Section 5 we provide an evaluation of EGDA. Finally, in Section 6 we summarize the lessons learned and outline future research.

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2 Context

Despite the increasing acceptance of GBL, it is still widely considered by most teachers as a promising approach rather than a real alternative. In the last decade GBL has become very popular among educational researchers and innovators, appearing frequently in specialized reports as an interesting instructional paradigm because of its potential benefits [4], [11], and building upon success stories in different case studies and pilots [12], [13], [14]. For example, GBL has appeared in the last three editions of the *Horizon Report* series published by the New Media Consortium as a technology that could be adopted in the midterm [6], [15], [16]. But as time goes on, it seems that we are as far from massive adoption as we were years ago. Actually, many of the barriers and limiting factors identified over the last few years have not been fully addressed yet [17], [18].

One of the reasons preventing the adoption of GBL is that educational game development is hard to scale [7]. Successful approaches are usually fine-tuned for a particular subject, target audience, educational setting and teaching style. These limitations hinder their application in other settings if any of these variables change. In addition, educational game development requires involving domain experts, who have limited time and usually no external incentives (such as being part of a research project) to participate in game design.

This limitation is tightly related to the overall expensiveness of games. The high development cost constrains the number of educational games the industry is able to produce, being unable to fulfil current demands of educational games. There is a need to bridge this gap with game development formulas that allow cost reductions. According to [5]: "*Among the most critical development challenges is the need for tools that make it easy to create learning games and simulations quickly, and at low cost*". The challenge lays on how to cut down the cost without constraining the educational value, building upon prior successes [19]. One of the approaches is to bring game development closer to the educator, allowing educational communities to fulfil their own needs for game-based content with a higher level of autonomy [20].

In this work we focus on specific challenges and solutions for teaching procedural knowledge in healthcare environments. Procedural knowledge can be defined as the knowledge that is applied in developing a procedure or a sequence of actions to achieve a goal [21]. This type of knowledge is highly valuable in many professions, especially in disciplines like health, science or engineering, where complex and risky procedures are applied in a daily basis. This is one of the reasons why serious games are increasingly being used in these fields [2], [22].

For many of the procedures related to healthcare or manufacturing there are moral, cost or material constraints that require access to specialized equipment and controlled laboratories where errors can entail severe consequences. This limits the rehearsal possibilities of the students, and sometimes forces an error-reduced instructional approach that can impair learning. In contrast, video games allow learning by trial-and-error [23] in a risk-free environment [24], while keeping a high level of realism. Students make their own decisions and evaluate the consequences, experiencing a situation from multiple perspectives prior to applying the acquired knowledge in the real environment [25]. These are some of the reasons why educational games are considered effective tools for learning complex procedures [26].

3 Overview of EGDA

Over the last few years, we have created different games for teaching procedural knowledge in healthcare. We have used the results and the lessons learned in those experiences to formalize EGDA, a process that covers all the tasks from game design to implementation and evaluation. It is built around four basic principles, which are briefly described in the next subsections.

3.1 Procedure-Centric Approach

Our belief is that an intuitive understanding of the procedure rationale (as opposed to simply memorizing the sequence of steps) promotes situated learning [27], [28], which helps the students to remember and properly follow the procedures. EGDA uses this idea to facilitate the learning of a specific procedure, also emphasizing the potential negative impact on the quality and precision of the outcomes when specific steps of the procedure are ignored. Therefore EGDA is driven by the formalization of the procedure, which constitutes the backbone of the game. More elements are incrementally integrated until an accurate simulation environment is obtained, including gameplay features and teaching strategies. This ensures that the learning content (i.e., the procedure) is embodied within the game design and not merely juxtaposed, an aspect that is essential for any educational game that targets more than pure rote memorization [29].

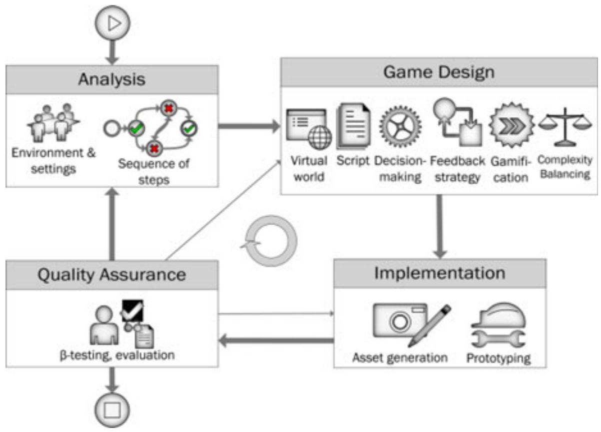

Fig. 1. Tasks and subtasks involved in EGDA.

3.2 Collaboration between Experts

Educational game design is inherently a multidisciplinary process. For this reason, EGDA aims to facilitate the incorporation of domain and game experts, as well as reducing the number of professional profiles needed to create a game. In addition, many educational game development initiatives treat domain experts and educators as external consultants, while we advocate for bringing the process closer to these experts. This also results in higher involvement of the specialists who have the knowledge and, eventually, a higher educational value. Therefore, EGDA requires close collaboration of two profiles: *domain experts* and *game experts*. Domain experts provide their tacit and explicit knowledge about the procedure while game experts contribute to the process with their expertise in game development. Game experts also help domain experts in eliciting their knowledge, which may be difficult to formalize.

3.3 Agile Development with Authoring Tools

EGDA proposes an iterative agile development cycle (Fig. 1) grounded in sound game design principles and methodologies [30], [31] to achieve high educational value with low production cost. The main tasks involved are (1) analysis; (2) game design; (3) implementation; and (4) quality assurance. Each task is also compounded by different subtasks, described in more detail in Section 4.

The main outcome of the **analysis** task is the formalization of the procedure, including an explicit description of all the steps, as well as possible incorrect actions. The formalized procedure is the input for the **design** task, which produces a complete game description document with all the game mechanics, objects, characters, puzzles, etc. that will be used. The **implementation** task utilizes this document to produce working prototypes with one or more easy-to-use high level authoring tools to speed up the process. Game authoring tools are essential in EGDA, as they reduce custom development costs and allow greater domain expert involvement. To facilitate game design, the affordances and expressive resources provided by the tools must be known before the process starts. Finally, the **quality assurance** task produces information to improve the game which is used in all of the other three tasks. The cycle should be repeated until the desired quality is obtained (three to six times in our experience, depending on the complexity of the game). In the first iterations most of the effort is dedicated to analysis and design. In intermediate iterations the focus is on implementation. Quality assurance is always present in different forms, although gets more important towards the end.

3.4 Low-Cost Game Model

EGDA is designed to produce games that are similar to the 2D *point-and-click* conversational adventures that were very popular in the 1990s, such as the *Myst* © saga. In these games, the virtual world is decomposed in multiple pictures (termed *scenes*) that are linked to set a navigational environment (the *game world*). We use virtual worlds to simulate the physical setting where healthcare procedures are performed by capturing 2D photos of the settings to be later populated with the objects needed to complete the procedure.

This type of environment supports reflection and decision making [32], and the approach reduces the development costs, as state-of-the-art graphics (e.g., highly defined 3D models, cinematics, etc.) are not used. In the simplest scenario, only a digital camera and access to the equipment are needed. At the same time, realism is preserved as students see their own work place. Moreover, the simplicity of these games facilitates deployment and use, since the technical requisites are kept to a minimum. On the one hand, the games can be used as standalone desktop applications, which are easier to download, install and run. On the other hand, the games can be directly delivered through the internet, without the need to perform local installations. This is an advantage for educators, who can use games in a versatile manner to better fit their instructional approach. These games are also easier to understand by students who are not savvy game players and may thus feel confused with advanced Game-Based Learning products.

4 Detailed Description of Tasks in EGDA

The next subsections provide details of all subtasks in EGDA outlined in the previous section (Fig. 1). Instead of outlining EGDA (as Section 3), this section provides insight on the tasks that the procedure proposes in a reproducible manner so other researchers can apply it.

4.1 Analysis

As part of the analysis phase, the procedure must be formalized between game and domain experts. This collaborative process is essential to achieve a good educational game design, and it is also one of the most challenging and time consuming [33] because of the disparate vocabularies and culture of game designers and domain experts, who may have completely different backgrounds [34].

Therefore a formalization strategy should be agreed upon, allowing both types of participants to acquire part of the expertise and vocabulary of their counter-parts. Game experts would acquire *domain knowledge* (in this case, procedures and their rationale and pitfalls), while domain experts learn the *affordances* of educational gaming and the chosen implementation platform (the specific game authoring tool and game engine). As a result, a common vocabulary for describing domain knowledge and game changes, understandable by all participants, is obtained. Depending on the complexity of the procedure and the characteristics of the participants, the common vocabulary can be explicitly represented using a formal notation or a visual representation that is used to support communication (e.g., using diagrams, flow charts or even a Domain Specific Visual Language (DSVL)) [35]. It is worth noting that the process of agreeing on (and perhaps formalizing) a common vocabulary is not trivial, and the vocabulary will, with all likelihood, need to be improved and refined in successive iterations. During this process, informal meetings among participants should be arranged to exchange and revise documents. In a typical meeting, domain experts would demonstrate how procedures are performed (if possible, in the physical setting), show videos or any other materials that illustrate the domain knowledge, and provide other background material to the game experts. Game experts would showcase relevant game examples to help the domain experts understand the range of expressive resources that can be used to transform the procedure into a game, and propose particular uses to illustrate parts of the target procedures.

In some cases, procedures are fully described and formally specified, but that is not always the case, especially if the organization does not implement a consistent knowledge management plan. It is common to encounter organizations where specific procedures are only known and applied by a few specialists within the organization, with an insufficiently detailed or inexistent formalization. Moreover, sometimes this knowledge or part of it is tacit [36], as it is usually acquired through experience. Hence it is difficult for the specialists to elicit the knowledge. From a knowledge management perspective, producing an explicit formalization of the procedure is an interesting by-product of the game development process that benefits the whole institution, as it facilitates sharing the know-how between personnel, reduces the time needed to train new personnel, and protects valuable knowledge assets from being lost, by making them less dependent on the availability of specific domain experts [37]. Additionally, the process of formalization frequently results in parts of the procedure itself being refined and improved, as flaws or incomplete parts are identified [38].

The knowledge formalization process must contemplate different aspects, from the scenarios where the procedure is applied to the definition of the outcomes of potentially wrong actions. The main output of this task is a document with the formalized procedure, ready to be used as input for the design of the game. We have distributed these aspects in two different tasks: describing the environment and settings and formalizing the steps of the procedure, which are addressed in more detail in two different subsections.

4.1.1 Describing the Environment and Settings

The initial step of this subtask is to obtain a high-level specification of the physical setting (e.g., a laboratory, an operating room, etc.). The definition of the scenario typically describes the purpose of possible objects (e.g., a microscope in a laboratory exercise) as well as the people or other agents that interact during the execution of the procedure.

The setting should be modelled and described identifying not only all the elements specifically involved in the procedure, but also those not involved but accessible in the physical setting and which may cause distraction or interfere during the process. For example, in a laboratory there may be equipment available that is not required for a particular procedure (the student must know what materials are going to be used). These elements may later be used as potential distracters to enhance the game experience. The experience of the domain experts is critical, as they know how students usually interact with the environment and they can point out elements that usually create confusion among students to be used as "red herrings" during the game.

As a result of this subtask, a detailed description of the environment, the elements and materials used, potential distracters and participants is obtained.

4.1.2 Capturing and Formalizing the Sequence of Steps

The sequence of steps is first described in full detail. This subtask is usually more complicated than describing the environment and settings, and it requires several iterations following a top-down approach where the basic steps are formalized and, in subsequent iterations, split into multiple substeps. Both correct and incorrect actions and decisions are captured. All the steps in the process have a purpose, and different mishaps, either minor or major, may happen if a specific step is not followed, or is followed incorrectly or in an inappropriate moment.

Differentiating between correct and incorrect actions is important. The main difference is that the knowledge that domain experts have of what is the right way to execute a procedure is usually *explicit*, although it may not be previously formalized. In contrast, knowledge related to inaccuracies or wrong actions tends to be *tacit* and it is even more unusual to have it formalized before the game development process starts. This difference is partly a consequence of how procedures are learnt. The right way to do it is learnt first, either through instruction or through observation of other domain experts. Common mistakes and their consequences are learnt progressively through experience until mastery is achieved. Besides, wrong actions are sometimes *operational*, being related to the environment or settings rather than the procedure itself. For example, if students practice a procedure with other peers and must share resources (e.g., a machine), the kind of issues that arise is different from students learning in isolation. For that reason, first iterations should focus on capturing the "right" steps and later iterations will add knowledge related to "wrong" steps.

This subtask requires the most interaction between game experts and domain experts, due to the inherent difficulty of making the experts' *tacit* knowledge *explicit*. To support

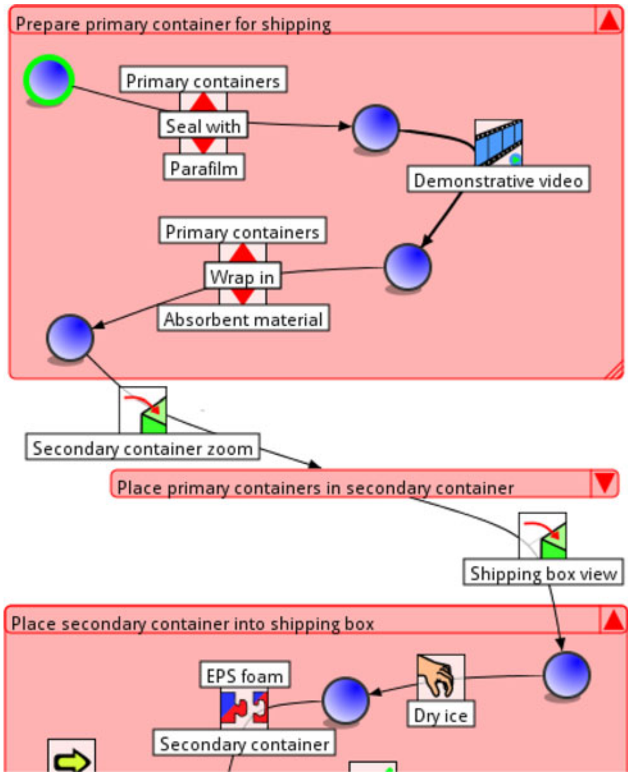

Fig. 2. Diagram excerpt produced with the WEEV modeling tool during the formalization and game design phases of the *HazMat* game. It shows the steps to ship hazardous materials (e.g., virus sample) in the WEEV Domain-Specific Visual Language.

this process we have developed a Domain Specific Visual Language [39]. This visual representation of the procedure facilitates its understanding as the flow can be easily followed (Fig. 2). Another advantage of the DSVL is the support for the aforementioned top-down formalization of the procedure. The WEEV tool [40] is a reference implementation of this DSVL, and allows the resulting design to be used to produce a game skeleton that can be edited further with the eAdventure tool. Although WEEV is particularly well-suited to formalization support, its use is optional, and does not preclude that of alternative visual instruments such as graphs or flowcharts which may contribute to the subtask's outcome: an agreed upon formalization of the expert's knowledge, understandable by all participants.

4.2 Game Design

Transforming the procedure into a game design requires a change of the language and terms used to formalize the procedure. Even though the vocabulary used to describe the environment, elements and steps of the procedure must be neutral and platform-independent, it must also be compatible with the affordances and requirements of the game authoring tool used to implement the game. In this sense, certain aspects of the game platform's technology and its expressive affordances must be known by all participants before the game development process starts, to avoid designs that include non-implementable characteristics.

The game design can be subdivided into five subtasks, described in detail in the following subsections. The first subtasks are the creation of a *virtual world*, the writing of a

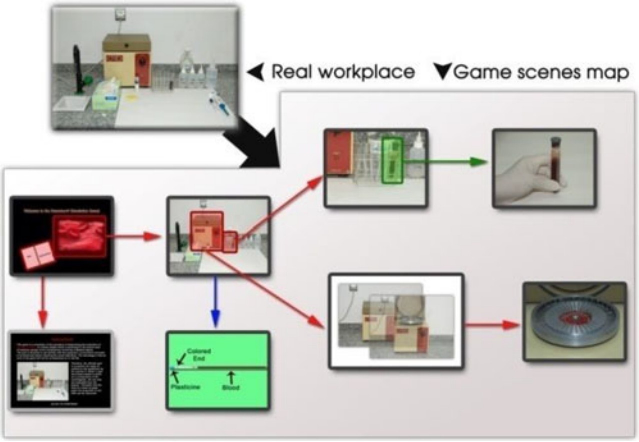

Fig. 3. Example of translation of the real environment into game scenes for a procedure where a blood microsample is centrifuged to measure the proportion of red cells.

game script, and the design of the *decision-making* structure. Together, these first subtasks result in the basic skeleton of a working simulation. The fourth subtask addresses the *feedback strategy*. Finally, the last subtask involves *gamification*, a process where additional game elements are introduced with the goal of increasing player engagement.

The main output of the game design task is a document with sufficient information to start the implementation of different prototypes.

4.2.1 Designing the Virtual World

The high-level description of the environment is translated into game elements. In the case of a 2D game, this involves the design of a series of interconnected game scenes. The 2D scenes in this map, and the way that they are linked together, will constitute the student's navigation environment. In the EGDA game model, each screen is composed by a single picture and provides a specific view of a part of the environment, materials or participants of the procedure. Multiple views of a specific part can be used to allow students explore the situation from different perspectives or angles, or to provide more details if necessary. Fig. 3 provides an example of how a typical laboratory workstation in a School of Medicine was decomposed into multiple game scenes for a training game. Notice how some scenes are essentially close-up views of others, providing additional details on instruments; while other scenes contain abstract representations of machine controls or descriptions of the procedure. The game environment model can be produced also with the WEEV tool or using any other graph representation.

4.2.2 From Procedure to Game Script

In this subtask, the description of the procedure is iteratively extended until it can be used to specify the flow of the game. Through this process, a game script is eventually obtained. But a script is not only a sequence of steps; it is necessary to enhance it to provide the student with an experience that fosters immersion.

When the game starts, students need to be *situated*. The lack of appropriate contextualization can seriously damage the gameplay experience, making the students feel lost, and diminishing the educational yield of playing the game. First, the students need to have a clear understanding of the main goal of the game (i.e., how to succeed) and the general rules (what you should and should not do in order to succeed). Clear rules and goals are elements present in all good video games [32], [41]. Second, students need to know what the initial conditions of the game are. For example, if the player adopts a specific role in the game (e.g., a medicine student who attends a clinical surgery intervention for the first time) this has to be clearly specified. Students also need to know any initial conditions regarding the in-game materials, settings or instruments that affect how the procedure must be executed (e.g., a pre-screening of the patient is available and a coronary problem has been identified). This can be addressed in a cost-effective manner by the use of cut-scenes, which are non-interactive, expositive scenes where the player is consuming content rather than playing. Cut-scenes can be videoclips or slides.

The game script can be created by an aggregation of smaller subprocedures that are applied in different situations. The concept of aggregation is interesting because it facilitates maintenance of the game by making it more modular and therefore subject to piecewise improvement. Modularity also facilitates extending the game to cover new situations or parts of the procedure. During gameplay, the student will be confronted with different situations or problems that must be solved. Each of these situations can be focused on a different part of the procedure. For example, consider a game for conducting medical sample analysis: the game can set the player in the lab, ready to analyze samples. From time to time the player receives requests from doctors to carry out different types of laboratory analysis on incoming samples. Each test would require the application of a different procedure. This design strategy can also be randomized: having to deal with exceptional situations allows students to rehearse procedures that are used only under rare circumstances or experience abnormal situations, enhancing replayability and immersion.

4.2.3 Decision-Making Support

In the context of a procedure simulation game, effective decision-making support by the game mechanics is one of the most important requisites. Providing an adequate sense of agency and control is a critical component for any game [42]. When making decisions to advance in the procedure (and therefore in the game), students analyze the information that is available at the moment, reflect on the best available option (with an amount of implied risk assessment) and then execute it in the game. The pattern is repeated recurrently throughout the whole game. The game must: (1) guide the user in discovering available information related to the decision and the different available options; and (2) provide the student with a straightforward way to execute those actions in the game.

There are many ways to provide alternatives in games and support decision-making, with varying degrees of in-game subtleness and development costs. An effective cost-balanced approach is to combine highly exploratory scenes with others where options are presented more explicitly. The simplest way to present options is the use of multiple-choice questions presented in text, although options can also be presented visually using animations (at a slightly greater production cost).

The game must also provide mechanisms to execute decisions. Interactions available in the EGDA game model are inspired from the conversational adventure genre, including unary and binary actions. Unary actions are performed on a single element (e.g., *grab* a *key*) while binary require two elements (e.g., *use* a *key* in a *lock*). Interactions can be *point-and-click* as well as *drag-and-drop*.

4.2.4 Feedback

The way that feedback is naturally conveyed in video games is a powerful enhancer of the learning process [43], and therefore feedback delivery should be carefully designed and planned. Most video games combine several sources of feedback to serve different purposes. From a usability perspective, feedback is needed to indicate that a desired user interaction was actually executed. Feedback should also support and facilitate reflection on the events that occurred in the game, and especially highlight the effects on procedures of wrong decisions. This type of feedback has been shown to contribute strongly to learning [44]. Feedback also contributes to create a continuous perception of progress, an inherent feature of good games which prevents frustration and encourages the player to go on, among other benefits [45].

The goal of this subtask is the adoption of a general feedback strategy. This strategy should be consistent throughout the game, and coherent with the chosen game mechanics. For instance, frequent and time-consuming feedback cutscenes break the sense of immersion in a time-constrained simulation. In most cases, feedback should be simple (limited to simple audio or visual clues), short and non-intrusive in order to avoid breaking the pace of the game.

Feedback should be more explicit and extensive in parts of the procedure that are especially complex or where precision must be maximised. Debriefing screens providing reasoned explanations of the internal processes taking place should be included from time to time. This helps students reflect on the underlying concepts in more depth, and transfer the acquired knowledge to real world situations. Various types of materials can be used for this purpose. While cutscenes with large pieces of text may be useful, they should be used carefully and only when necessary. A short video showcasing a particular aspect of a procedure can be more useful and engaging.

When dealing with feedback for incorrect actions, the timing can be adjusted to reflect the consequences of valid and invalid manipulations, both in the procedure itself and in its possible by-products. Feedback can be provided immediately, but deferred feedback may have significant advantages when the consequences of incorrect manipulations are not immediately observable. For example, the consequences of a mistake during the preparation of a blood sample might not be evident until it is analyzed, several steps later. This is a common aspect of complex procedures and it is important to ensure that the game reflects these situations, making students "pay a price" for mistakes (e.g., having to start over) and helping them avoid the same mistake next time. Negative consequences of mistakes can be overly exaggerated to increase the impact on the student.

When the game is completed, the student can be presented with deferred feedback for self-assessment purposes, including a list of all mistakes and incorrect actions performed. This information can be used to identify potential weaknesses in the game, tweak the formalization of the procedure and reinforce learning without requiring teacher intervention [46].

4.2.5 Gamification of the Design

Once the procedure has been accurately captured and virtualized, *gamification* techniques can be applied to increase student engagement and motivation [41]. *Gamification*, which is a very active research topic, is usually described as the application of game mechanics and elements in non-gaming contexts [47], for example to improve customer fidelity for an online purchasing company. In EGDA *Gamification* is inspired by current research but applied in a different manner, as it concerns the application of game elements to a simulation environment to make it more engaging.

Gamification strategies should be cost effective and avoid conflicts with the correct representation of the procedure and the environment. Players enjoy intrigue and curiosity, opportunities for challenge, strategy and problem solving [48], competition (self-directed or with peers) or humour [49], which can be implemented in a cost-effective manner. Very advanced technology or state-of-the-art 3D graphics are attractive and can contribute to create an immersive environment, but they are comparatively much more expensive. Fortunately, these features are not strictly necessary to engage students in a learning activity, and very simple strategies can yield amazing results. For example, the use of quantifiable heuristics to display students' progress and achievements in the form of a visible score can provide an effective form of challenge. These heuristics can be complemented with badges [50] or other visual elements that can display status or skills acquired by the student. Other potential sources of challenge include the total number of objectives fulfilled, the time required to complete each procedure, or the total number of mistakes.

Quantifiable heuristics are comparable and can be used to foster competition between peers and tap into the student's desire for self-improvement. When displayed prominently or when aggregated in a public ranking, heuristics can drive students to improve their results, increase replayability by encouraging students to explore all possible situations and endings, and reinforcing the learning process.

4.2.6 Complexity Balance

During game design, it is necessary to regularly revise the overall complexity to ensure that the game will be implementable with the available resources and within the expected time-frame. The complexity of designs increases progressively, as alternative paths and endings are added. Designs start with a simple representation of the main steps of the procedure, expanding as the procedure is defined in greater detail, and reaching full complexity as game elements are added in an incremental fashion. At a certain point it may be necessary to trim some paths or limit parts of the game, resulting in a smaller and potentially less engaging game-world. Finding a correct balance between breadth and depth (with consequences in educational value and user engagement) while keeping development costs in check is a critical component of any game development project.

4.3 Implementation

The implementation phase is compounded by two subtasks: *asset generation* and *prototyping*. It is driven by the use of a simple, high-level authoring tool, which simplifies the process of generating working prototypes of the game. However, the time required to capture the resources (images, photos, etc.) is still considerable. The implementation task receives as input the design document produced in the previous task, and its main outcome is a set of working prototypes to be used for different purposes.

4.3.1 Rapid Prototyping

Iterative prototyping is critical in game development [51]: it allows the use of a staged and stepwise evaluation and testing plan [52], and facilitates analysis and design tasks. On the one hand, it is easier for domain experts to find inaccuracies or overlooked aspects in the formalized procedure by reviewing a working (though incomplete) prototype rather than looking at designs or documents, as prototypes can provide explicit context which may have been overlooked in other formalizations. On the other hand, prototypes allow game experts to rapidly test game mechanics and identify major pitfalls in the design.

EGDA proposes the use of one or more authoring tools for rapid prototyping and game implementation. Game authoring tools have proliferated in the last years, making development more agile, less expensive and more accessible to people without solid programming skills. There are tools of every kind, ranging from complex semi-professional software (e.g., Unity) to simpler, high level authoring tools meant to be used in amateur productions or even by students, such as Game Maker [53] or Scratch [54]. The development of EGDA has always relied on eAdventure for implementation [55] and WEEV for modelling, open source free software packages focused on conversational adventures and simulations, although similar tools could be used (e.g. Adventure Maker or Storyline) to achieve comparable results.

Different prototypes can be created for different purposes (Fig. 4):

- *Mock-up prototypes* allows rapid evaluation of the accuracy of the formalized procedure.
- *Intermediate prototypes* mainly used to elicit comments on the game design for the next iterations.
- *Beta/Final prototypes* stable prototypes that are used for end-user evaluation.

4.3.2 Gathering the Art Resources

Game resources may include workplace pictures, animations or other visual assets, sounds, videos, etc. Gathering

Fig. 4. Different prototypes created for one of the games produced, which is set up in a visit to the operating theatre in hospital. Left: Mock-up prototype. Middle: Intermediate prototype. Right: Final version.

the final version of a game's resources is one of the most expensive parts of the process. On the one hand, generating "in-house" art resources is a very time-consuming task. On the other hand, hiring a professional artist can have a significant impact on the budget. In order to plan for the projected cost of resource acquisition, a list of all necessary resources has to be prepared and kept updated during game design and development. Mock-up prototypes can use placeholders while the design stabilizes and until better versions become available (Fig. 4). Intermediate prototypes can combine sketches and temporary art resources. Final prototypes should always include final versions of all art resources.

Careful planning of recording and resource capturing sessions allows for significant cost reduction and shortens the development cycle. The final version of the resources is only necessary once the design is stable and has been validated with mock-up and intermediate prototypes. All relevant equipment and materials should by then be identified, and the exact views and recordings thoroughly planned. The scheduling process may be not trivial if access to specialized, dangerous or expensive materials is needed. Additionally, a clear understanding of the technical formats expected by the game authoring tools is critical to ensure the production of high-quality resources.

4.4 Quality Assurance

As commonly argued in the literature, using games for education does not always entail an improvement of the learning process. Ak [56] identifies four aspects for which actions to ensure quality assurance must be taken. These aspects also appear in other game evaluation studies [57]:

- *Reliability*. The game should be stable and free of programming errors. While this is not so important in the beginning, it is crucial to ensure the reliability of the game once it is deployed.
- *Playful/Engaging experience.* The game should be appealing, motivating and engaging for the students it is targeted to.
- *Usability.* Interaction with the game should be pleasant and prevent frustration.
- *Educational value.* The game should be accurate and precise, and provide valuable insight about the procedure to the student.

Elaborating on these four aspects, we propose the evaluation questions shown in Table 1, based on those proposed by Youngblood that were especially designed for medical simulation and gaming [58]: To answer these questions we propose combining three types of evaluation sessions:

TABLE 1
Evaluation Questions for Quality Assurance, Based on Proposal by Youngblood (2006)

Question	Who answers?	Related to
Are there any bugs or unexpected behaviours in the game?	Beta-testers	Reliability
Does the game work in all the target platforms (e.g. Windows and Mac)?	Beta-testers	Reliability
Does the game simulate the procedure and environment faithfully?	Domain experts	Educational value
Is the content embedded in the game (e.g. reference materials, dialogues, text) accurate and appropriate for the target audience?	Domain experts	Educational value
Are game goals and rules clear for the novice user?	Students, Domain experts, Game experts	Playful/Engaging experience, Educational value
Is the game appealing for the target audience?	Students, Game experts	Playful/Engaging experience
Are the context and preconditions clear for the novice user?	Students, Domain expert, Game experts	Playful/Engaging experience, Educational value
Is it easy to learn to use the game?	Beta-testers, Students, Game experts	Usability
Is it easy to use the game?	Beta-testers, Students, Game experts	Usability
Are the learning goals covered?	Domain experts	Educational value
How well do the students achieve the learning goals?	Students	Educational value
Do the students learn anything else? (incorrect or correct knowledge)	Students	Educational value

- *User-centred evaluation*. This is the most important type of evaluation to ensure quality. Introducing formal evaluations throughout the whole design and development process will unnecessarily extend the production of the game and increase the cost. It is more efficient to conduct frequent informal, user-centred evaluations that could be arranged with colleagues and students in short sessions without requiring formal evaluation instruments, which allows identifying major pitfalls and design flaws more easily [59].
- *Beta-testing*. Members of the development team, colleagues, or students, can be recruited to perform beta-testing of the prototypes. Beta-testing evaluations differ from user-centred evaluations in that attention is only paid to the reliability and perhaps usability of the game. Beta-testers will explore the game, trying out all possible actions and options, seeking hidden bugs, technical errors or major usability flaws. No feedback about the educational value or playful experience is expected.
- *Formal evaluation*. In final iterations a more formal approach is encouraged, where research questions are formally formulated for quality assurance. Formal evaluation is the most time-consuming type of evaluation and therefore only one or two experiments towards the end of the process are recommended, oriented to evaluate the educational gain compared to traditional instruction.

The outcome is a set of proposed modifications to any of the sub-products of the other tasks (analysis and design documents or prototypes).

5 EGDA in Practice: Case Studies

In this section we describe the case studies where EGDA has been applied (Section 5.1). Through these experiences, we have been able to evaluate the effectiveness of EGDA from the perspective of development costs and return on investment (Section 5.2). Based on previous publications and also new data collected, we discuss in Sections 5.3 and 5.4 two parameters that we measured to evaluate the quality of two of the games produced: the effectiveness of the games as learning tools (Section 5.3) and the student acceptance and perceived usefulness (Section 5.4). Although other games were also evaluated, data collected does not support a quantitative analysis and have therefore been omitted from this section.

5.1 Overview

The seven games produced with EGDA have been developed in collaboration with different organizations related to health and medicine instruction, like the Massachusetts General Hospital (MGH, Boston, US), the School of Medicine of the Complutense University of Madrid (Spain), the Spanish National Transplant Organization (ONT), or the Miguel Servet Hospital (Aragon, Spain).

Three of these games have been already deployed to end users while four more are currently undergoing further evaluation cycles (see Table 2 and Fig. 5).

These games have been used to improve learning processes and clinical practice when the application of complex procedures is an essential part of the professional activity. The games increase the rehearsal opportunities for students in situations where access to equipment or resources was limited. They have also been used to reduce the stress of students and trainees.

5.2 Development Costs and Return on Investment

In this section the efficacy of EGDA is discussed by estimating the cost of the games developed, which is compared to current industry standards. This task poses two challenges. First, game development cost is complex, almost impossible to calculate with precision. Therefore we will only try to make a rough estimate of the order of magnitude of the game development cost based on the work hours spent. Second, difficult to compare the cost with other games, partly because in few cases the overall cost of a game project is reported, and partly because the inherent singularity of each title makes a fair comparison almost impossible. We have just gathered together some of the data we were able

TABLE 2
Summary of Games Developed

Institution(s) and Target audience	Topic and Motivation	Status
CVC		
Mass General Hospital, Boston Resident physicians	98-steps CVC protocol Increase rehearsal opportunities, reduce trainee/student anxiety & stress	Prototype [60]
HazMat		
Mass General Hospital, Boston (MGH) Hospital staff	Hazardous materials packaging & shipment Reduce training costs, simplify certification process	Deployed since 2009
Operating theatre		
Complutense School of Medicine, Madrid Medicine students (surgery)	Introduction to the surgery room Reduce trainee/student anxiety & stress	Under evaluation (ETA 2013) [61]
Checklist		
San Carlos Hospital, Madrid; Mass General Hospital (MGH) Clinical surgery staff (nurse, surgeon, anaesthesiologist)	Application and use of the safety checklist in clinical surgery Improve current usage of the checklist	Under development (ETA Q3 2013)
Donations		
Spanish National Transplant Organization Healthcare personnel related to the transplantation processes	Management of the supra-hospital transplant coordination (donor evaluation and organ allocation) Improve training of new personnel	Under evaluation [38]
HCT		
Complutense School of Medicine, Madrid 2nd year medicine students	Measurement of the level of Hematocrit in a blood sample Increase rehearsal opportunities	Deployed and evaluated since 2009
First Aid		
Miguel Servet Hospital; Schools of the region of Aragon, Spain 14-year-old high school students	Instruction in basic cardiopulmonary resuscitation techniques Produce alternative instruction content for cases when experts are not available	Evaluated in 2011 [62]

to find on game development costs and will compare the order of magnitude to our games.

A coarse estimation of the work hours dedicated to game development is provided in Table 3, ranging from 66 hours for the simplest game to 410 hours for the most complex. The resulting total is then compared with the estimated completion time of each game, which is a rough measure of the complexity of the games. However, this yields an estimated development cost for each minute of gameplay that can be used to understand the return on investment. To develop one minute of gameplay around 10 hours of work are needed.

The total estimated development cost, in US dollar, is obtained by multiplying hours invested by an estimated hourly wage of $50 per hour.

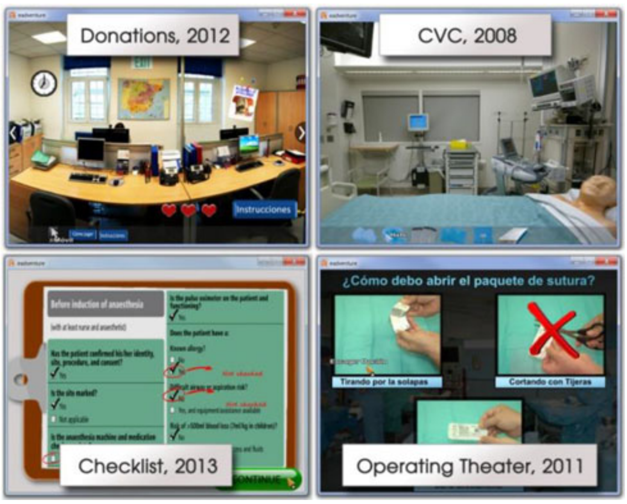

Fig. 5. Screenshots of four games developed according to the EGDA.

TABLE 3
Estimation of Hours Invested for Creating the Games

Game	PT	PH	PH/PT	Cost ($)	$/PT
	Avg. play time in min	Total labor hours	Labor hours per min of game play	Total estimated cost $=PH x $/h	Estimated Cost per min of game play
CVC	30.00	410	13.67	$20,500	$683
HazMat	20.00	140	7.00	$7,000	$350
Operating theatre	21.30	141	6.62	$7,050	$331
Checklist	48.00	225	4.69	$11,250	$234
Donations	40.00	180	4.50	$9,000	$225
HCT	8.00	66	8.25	$3,300	$413
First Aid	20.00	122	6.10	$6,100	$305
Order of magnitude		10^3	10^1	10^4	10^2-10^3
* Estimated cost per hour: 50 $/h					

This number is used to estimate the development cost in dollars and cost per minute of gameplay.

In all cases development was carried out by teachers and home staff of the institutions where the games were going to be used, including computer scientists and medicine instructors. There was no need to hire external staff, which is an argument to support that EGDA makes game development more affordable for teachers and other low-tech profiles.

On average, each minute of game play has had a cost of order 2 or 3 (greater than $100 and lower than $1,000). Approximately the total cost of the games has an order of magnitude of 4, ranging from $3,000 to $20,000.

These numbers may seem too high for educational materials, but they are actually very low compared to standard development costs for games, even those tagged as 'serious' or educational. For example, consider *Immune Attack*, one of the best educational games developed in the recent past [63]. The development of *Immune Attack* was funded by a $999,865 NSF grant [64], and it took approximately 4 years to develop. Considering an estimated length of 120 minutes, the estimated cost per minute of game is around $8,000. *Science Pirates* is another great educational game whose evaluation results and development cost are known [65]. It was funded by a $450,000 USDA's (US Department of Agriculture) National Institute of Food and Agriculture grant [66]. It takes around 2 hours to complete the game, resulting in around $3,000 per min. And these costs are relatively low compared to AAA games being developed at the moment, with budgets on par with Hollywood films, ranging from $3 to $100 million [67]. While it is very difficult to compute specific average gameplay lengths for commercial games as a whole, any game requiring over 30 hours to complete is generally considered "a long game" (a 20 hour game with a development cost of $3M costs $2,500 per minute). Compared to these costs, EGDA games are at least one order of magnitude cheaper to produce.

It is true that the comparison above is not truly fair since EGDA games do not use 3D technology as *Immune Attack* or *Science Pirates*, which is more expensive than 2D. In 2008 the eLearning Guild carried out a survey among its members (eLearning professionals and developers) to understand current trends on serious games and simulations development (called Immersive Learning Simulations in the report, which did not distinguish between them) [68], which was completed by 1,100 of its members. The games and simulations considered in this report are similar to EGDA games, being 2D content of similar duration developed in Flash or with other high level authoring tools equivalent to eAdventure. From data provided on the report ([68, p. 13, Fig. 10]),the average development cost can be estimated around $200,000 on average and $58,000 on median. EGDA games are still far from these numbers.

5.3 Educational Impact

The effectiveness of the *First Aid* and *HCT* games as learning tools has been analysed in two randomized trials where the use of the game is compared to the classic instructional approach. In both cases the knowledge acquired is measured before and after the intervention (i.e., the application of the selected instructional approach) and results from control and experimental groups are compared. In the case of the HCT game also results in the final test are compared to the previous year to analyse educational gain.

Fig. 6. Screenshot of the First Aid game. Student is presented with alternatives to support decision making. Note: The game was originally developed in Spanish and translated to English after validation.

In Section 5.3.1 we briefly discuss evidence collected from the evaluation of the First Aid game, which has already been published in the Journal of the Spanish Society of Emergency Medicine [62]. The results from the HCT game are divided in two sections: Section 5.3.2, where we summarize findings published in the International Journal of Medical Informatics (IJMI), and Section 5.3.3, where we enhance the discussion with new, unpublished data.

5.3.1 First Aid Game: Educational Gain from Unattended Gameplay

The *First Aid* game (Fig. 6) was developed to teach cardiopulmonary resuscitation (CPR) manoeuvres to high school students in the Spanish region of Aragon. Traditionally, two doctors expert in emergency medicine and CPR training provide this kind of instruction. However, the number of experts that can dedicate time to student instruction is limited, so not all the students in the region can receive training every year. Having a game available will help to provide similar instruction to all students in the region. The game could be used also in any Spanish or English speaking country, as it is now publicly available for download in both languages.

344 students were divided into control and experimental groups (CG and EG) [62]. Both groups were instructed in CPR for 50 minutes. The CG devoted these 50 minutes to attend a practical session driven by the two experts in emergency medicine, while the EG played the game without further tutoring. Pre and post tests were conducted to measure knowledge acquisition. Students in EG improved from an average score of 5.41 to 7.48 while CG improved from 4.95 to 8.56. The improvements were considered statistically significant in both groups after a paired Student's t-test ($p < 0.001$ in both cases). While improvements of students in the CG were higher, being the difference statistically significant ($p < 0.001$ unpaired Student's t-test), the game was also effective as a learning tool and represents an inexpensive and reusable solution, as opposed to the practical sessions with experts.

Fig. 7. Screenshot of the HCT game.

5.3.2 HCT Game: Impact on Student Performance

The HCT game (Fig. 7) was developed for a Physiology course in the School of Medicine at the Complutense University of Madrid to instruct students in the application of the Hematocrit (HCT) blood test. This test calculates the level of red cells (Hematocrit) in blood with a classical laboratory test approach based on the centrifugation of a blood microsample, which separates the plasma and cellular components in two layers. It is freely available for download, in English and Spanish.

The HCT Blood test is practiced a few weeks after the academic year begins, during the second session of the course. The HCT practical session also covers the Haemoglobin (HB) test which is not covered by the game. During the year a total of 14 practical sessions are conducted. For several reasons, like the high number of students—around 400—and sessions, this course has complex logistics. Therefore the time and resources for rehearsing the procedures in the actual laboratory are limited. In the case of the HCT test this is especially cumbersome as resources for practicing are only available at the beginning of the course, nine months before the final practical exam. There are also ethical issues, as blood samples are obtained from laboratory rats that must be sacrificed.

Results from a preliminary evaluation of the HCT game are available on previous publications [69]. Sixty-six students were randomly selected for the Experimental Group, who played the HCT game in a controlled environment for 30 minutes two weeks before the laboratory session where they practiced the HCT test. Students in the Control Group did not have any contact with the game, and proceeded to the laboratory sessions as usual in all previous editions of the course. After completing the game, the results of the HCT test were compared for both groups. Measures reported by students in the experimental group presented a higher reliability, considered as the deviation of the value obtained from the HCT correct value (3.10 versus 26.94, SD; variances significantly different after a Mann–Whitney U-test, $p < 0.001$). These findings suggested that students in the experimental group were able to learn the procedure by playing the game, and they were also able to transfer knowledge acquired to the real world as their measurements of the Hematocrit were more accurate in EG than in CG.

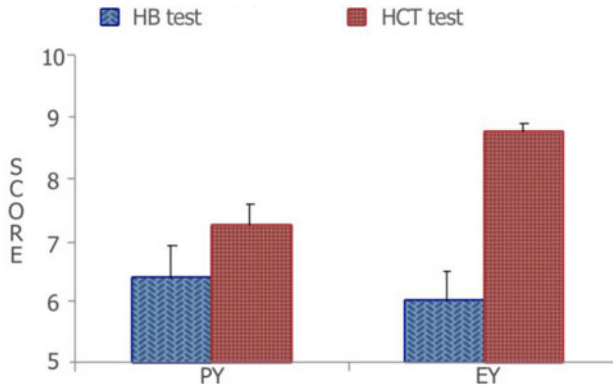

Fig. 8. Comparative of the score obtained by the students in the HB and HCT tests in the experimental year (EY) and the previous year (PY). Results of the HCT test improved significantly while the HB remained almost unchanged.

5.3.3 HCT Game: Educational Gain

After that experiment, the HCT game was made available through the e-learning system of the Complutense University of Madrid three weeks before the final exam of the module (seven months after the practical session) for all the students (making it available to the EG only could have been an unfair disadvantage for students in the CG taking the same exam).

To further measure the impact on the learning outcomes, student performance in the final exam was compared to the previous year, when the game was not available. In the final test students are requested to perform the procedures instructed in one of the 14 practical sessions of the course, randomly chosen. If the second session is selected, students must perform the HCT and HB tests. Results from both tests were also compared.

Both tests (HCT and HB) have similar complexity. As a result, student performance is usually similar in both procedures. For example, in the previous year to the experiment (PY), the average score obtained by the students was 7.2 for the HCT test and 6.4 for the HB test, being this difference not statistically significant ($p = 0.12$ after a paired Student's t-test) (Fig. 8).

However, in the experimental year (EY) the average score obtained was 8.8 for the HCT test and 6.0 for the HB test, being this difference statistically significant ($p < 0.0001$ after a paired Student's t-test). Comparing results across years, the HCT score increased from 7.2 to 8.8, being the difference statistically significant ($p = 0.0002$ after an unpaired Student's t-test), while the HB score decreased slightly from 6.4 to 6.0, being this difference not statistically significant ($p = 0.32$). These data suggest that the score of the HCT increased significantly, while the HB scored remained invariant, and thus the game seems to have had a significant impact in improving students' performance.

5.4 Student Acceptance and Perceived Usefulness

For both the First Aid and HCT games the student perceived usefulness of the games was measured through subjective questionnaires but also by tracking voluntary access to the content (after the trials they were able to play the games for self-studying and practicing without teacher guidance). In this section we discuss results obtained, which have not been published elsewhere.

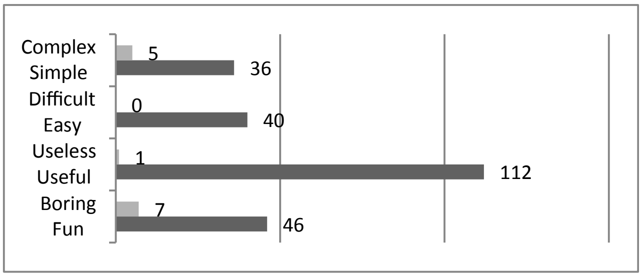

Fig. 9. Students' opinions collected about the First Aid game.

5.4.1 First Aid Game

Students in the control group were surveyed on their impressions about the First Aid game. They were presented with a tag cloud with the following adjectives to describe the game: "fun", "boring", "useful", "useless", "easy", "difficult", "simple", and "complex". There were no restrictions on the number of tags that could be marked. Although this way of evaluation may be deceptive, results shown in Fig. 9 suggest a high acceptance and perceived usefulness from the students, as most of them marked the option "useful" (112 out of 187 students) and only one the option "useless".

5.4.2 HCT Game

Students in the EG were asked to fill in a questionnaire about the perceived usefulness of the game just the first play. Results were mostly positive. Most of the students reported that using the game was a positive experience (81 percent) and agreed that the simulation had helped them to identify and use the equipment in the lab (65 percent) and to complete the practical exercise more easily (61 percent).

During the three weeks that the game was available to all students, they had no pressure or incentives to use the game, nor did instructors motivate students to use the game in any way. The number of accesses to the game were measured and compared to other materials.

From the 406 students enrolled in the course, 177 (43.6 percent of the students) accessed the game at least once. The average access time to the game (6:45 minutes) was the second highest among all the contents available to the students. Only one static document had a higher time/access ratio (10:01 minutes), but its reading was compulsory as opposite to the HCT game.

In addition, the game was one of the most accessed contents (497 times). Only seven pages had more accesses than the HCT simulation game (from a total of 38 pages), but they were published for a considerably longer period of time (four to seven months) and their use was compulsory.

Given that the use of the game was completely voluntary these data suggest that in general students found the game useful to practice for the final exam.

6 Conclusions and Future Work

Ongoing research on Game-Based Learning demonstrates that it can be a very useful educational paradigm. While good examples of educational games populate the literature [19], the approaches used are still hard to scale [7], in part because of their high development costs [5].

In this work we have formalized our educational game development approach for teaching procedural knowledge in healthcare environments, with special focus on reducing the development costs.

EGDA is a *procedure-centric* process. First, the procedure and the knowledge associated to it are formalized. The formalized procedure acts as the central communication point for the stakeholders involved along the whole process, including domain experts (e.g., medicine instructors) and game experts. Second, the procedure is used to build an accurate simulation environment. Finally gaming elements are added to achieve a GBL environment.

EGDA and its products have been evaluated, focusing on three aspects: efficiency (in terms of development costs), learning effectiveness and student acceptance. Regarding the evaluation of the EGDA itself, the average production cost per minute of game developed is far below current industry standards. This suggests that EGDA can help to achieve a significant reduction of the production costs of the games, which has been identified as an important requirement for educational games to go mainstream [6] without compromising the educational value.

This retention of the educational value was evaluated and it is supported by previously published experimental data, as well as new evidence. In summary, findings suggests that these games improve students' performance and knowledge retention, and also transfer the knowledge acquired in the game to the application of procedures in real settings. The students also perceived the games as useful learning tools. These conclusions are drawn from data collected for two of the seven games developed, as in those cases a quantitative evaluation was conducted. Although qualitative data collected through formative and informal evaluations of the other games are consistent with these findings, further research would be required to confirm the validity of the results.

Several limitations should be addressed with future research. EGDA is tailored to a very particular domain and it is unclear how it could be used in different settings. Moreover it does not contemplate strong interaction mechanisms between peers. While it is possible to simulate interaction via multiple-choice conversations, all the responses and outcomes must be implemented in advance, and the real player is a single student, a severe limitation of the software of choice (eAdventure) which does not support multi-user games. Future research should look into how EGDA could be used to teach procedures where the collaboration of different colleagues is essential, but this would require using different software. It would also be interesting to explore how more complex technologies, like 3D graphical engines or haptic devices could be integrated into the EGDA approach without resulting in a significant cost increment.

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