On the Design of Digital Game-Based Learning Environments for Education of the General Public on Focused Scientific Topics with an Application to Underwater Acoustics

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Abstract. Game-based learning environments for educating the general public on focused scientific topics rely upon voluntary engagement of participants usually in presence of competitive attractions, multiple sources of distraction and time constraints. In addition certain educational topics present an inherent complexity that necessitates the implementation of games with sophisticated interfaces and steep learning curves that may discourage players to engage. In this work we analyze the challenges and propose a new model for the design of efficient multistage game-based learning environments based on the general scheme "attract > engage > educate > evaluate". An existing game-based learning environment for introduction to underwater acoustics is presented as a very close design example of the proposed model.

Keywords: Serious games · Ludic game design · Public learning environments Underwater acoustics

1 Introduction

A fundamental distinction between traditional and serious games is that the latter do not have entertainment, enjoyment or fun as their primary purpose [1]. As such, serious games are used for a variety of professional purposes including training, education and assessment. In our digital era most serious games are software applications running either as standalone programs or integrated in Digital Game-Based Learning Environments (DGBLEs). The design and development of educational software requires the combination of different fields of expertise (scientific core, educational-, graphic-, interaction design, technical programming etc.) represented by different groups or individuals. A recent study distinguishes four main roles in the creation of an educational game (a) educational expert, (b) game designer, (c) instructor and (d) learner [2]. More roles have to be considered if the activity is to lead to a marketable product (market research, product promotion etc.). Although gameplay is commonly considered

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as a voluntary activity, participation in serious games, which is usually mandatory and pre-designed, may reduce the fun and impulsiveness of the game. Recent studies however suggest that contrary to the opinion of many game designers, being required to play a serious game does not necessarily take the fun out of the game or reduce enjoyment and learning effect [3, 4]. According to the Gameplay/Purpose/Scope (G/P/S) classification model a serious game can be designed for one, several or none of the following purposes: Training, Message-broadcasting and Data exchange [5]. The first category includes serious games used for organized training of specific individuals – or groups – in simulated virtual environments through game playing. In such environments, knowledge and training is accomplished in a binding and organized way and, although “it’s a game”, participants are aware of their training, feel dedicated to what they are doing, and willing to follow certain rules no matter how strict they might be. On the other hand, the main purpose of message-broadcasting game based learning environments is the introduction and education of the general public (or pre-defined target groups) on specific topics/policies of several disciplines (physics, ecology, economy, art, history etc.) through relaxed and self-controlled participation. In such environments access is open to the general public, there are no strict rules to follow and engagement is entirely voluntary. The third category of this model includes games designed to collect information from their players or encouraging them to exchange data.

In this work we focus exclusively on message-broadcasting public DGBLEs as we attempt to understand and analyze the particular characteristics of such environments and propose effective models for their design. To do so, we initially state a number of essential requirements that have to be satisfied as well as a number of crucial issues to be considered during the design. We then proceed to propose a model based on a set of properties satisfying the above requirements while addressing most of the issues specified. Finally, we conclude by presenting a case study of an existing game-based learning environment called “Ocean Sound Lab” having a design/structure that matches closely most principles of the proposed model.

2 A Proposed Model

An effective message-broadcasting DGBLE installed in a public area must comply with the following two essential requirements:

- Maximize the number of attracted individuals for its specific target group(s)
- Minimize the number of individuals walking away before the completion of its intended course.

A third desirable – although not crucial – requirement is the ability to assess its effectiveness and impact on each individual as a measure of its overall efficacy. This can be achieved by encouraging participants to evaluate themselves through quiz-like applications or games integrated in the learning environment.

A key issue to bear in mind during the design of such a DGBLE is that participation of individuals is voluntary and there is no guarantee that it will last throughout the entire learning session. Other significant issues include the presence of multiple competitive attractions and time scarcity. When wandering in a large hall of a museum or exhibition, most visitors' attention is continuously challenged by a variety of rival visual and audio stimulants all competing for a share of their time. Since there is always a limit to the total time a person is planning – or allowed – to spend in such places, time scarcity is another important issue. In that sense, visitors inevitably are drawn towards the most interesting attractions, opting out the rest. But even when visitors are attracted and engaged to a DGBLE – hence at least their vision is focused – there is always an increased chance of distraction due to other existing stimulants (mostly audio and haptic) that challenge their attention focus. Such stimulants include the proximity of other persons (including friends and family), public noise, loud voices, phones, music etc. Chances of distraction are further increased considering the positive emotional attitude of visitors in such places [6].

All above issues are characterized as universal since they apply to the average person. Wishing to focus on particular target groups of people there are even more person-specific issues to consider including age group, cognition level and physical condition (especially for elder people) special abilities, and communication language. When designing public DGBLEs these issues are equally important to contemplate, especially when the educational topics focus on specific target groups. A summary of all issues discussed above is presented in Table 1.

Table 1. Issues to be considered when designing DGBLEs.

Key Issue
Voluntary engagement - Needs to be refreshed periodically in order to be maintained throughout the entire learning path
Universal issues

- Time scarcity
- Presence of multiple competitive attractions
- Increased probability of distraction -once engaged- due to
    o Proximity of other persons (friends, family...)
    o Public environment (noise, loud voices, phones, music etc.)
- Positive emotional attitude

Person-specific issues
- Age group - Cognition level - Physical condition (especially in larger ages) - Special abilities - Communication language

Taking into account the requirements and issues stated above, we initially propose two sets of properties (essential/desirable) serving as design guidelines for implementing effective and pleasurable public DGBLEs.

A. Essential Properties. A successfully designed and implemented public DGBLE must initially demonstrate a considerable level of saliency so that it stands out against other attractions in order to maximize the percentage of by passers diverting towards it. Saliency must be implemented to both software (nice screen graphics, motion, sound etc.) and the physical space area it is placed upon (signs, graphics, flags etc.). However, visitors' attraction through saliency is just the beginning. First time observers must be able to grasp the theme and context of the DGBLE in a very short time. Failing to do so, visitors will most probably walk away especially in the presence of other competitive attractions. Moreover a brief, clear and unambiguous description of context is necessary but not sufficient condition for further engagement particularly if the implemented educational topics are hard or unusual. In such cases visitors have to be guided towards the core of a theme in a series of steps of increasing complexity, starting with simple and enjoyable engagements and proceeding to the more demanding ones. In this way the visitors' overall engagement is preserved throughout the learning path. To further preserve and increase users' engagement, a public DGBLE could implement competition mechanisms among players, e.g. in the form of high scores or time records to be beaten, or even real-time multiple-player competitions if this is technically feasible. On the other hand, since some people are not very keen to rivalry and competition, another way to boost engagement is through more relaxed reward mechanisms where visitors are evaluated for their newly acquired skills or knowledge and not for their competitive abilities. Reward-through-evaluation can be implemented in various forms, like overall performance analysis classification, or post-game knowledge evaluation through quiz-like games.

Finally a successfully designed and implemented public DGBLE must create a positive post-engagement affection so that people continue to reflect upon it later on and discuss it further encouraging others to also try the experience. This type of social advertisement works in tandem with saliency to increase the spreading of knowledge to the general public.

B. Desirable Properties. The properties/guidelines discussed so far are essential for the proper design of an effective DGBLE. We further suggest some additional features/properties that – although not essential – could further boost the effectiveness of the design.

In theory the educational value of a public DGBLE should be similar for all participants, however this is not always the case. In fact the spectrum of people addressed by a public learning environment is very wide, as it includes people from different countries, different ages, and even different educational levels. To maximize the effect on all these people, a public DGBLE must be customizable in different ways. Initially if the learning environment is addressed to people from different countries – as in the case of large museums and exhibitions – then it must have a multilingual user interface supporting at least the most common languages of the expected visitors. Moreover a customizable learning environment may implement different pedagogic approaches for different people groups such as children and adults. The different modes in a customizable DGBLE can be presented as options through the user interface as in the typical example of language selection.

Dynamic adjustability of a DGBLE should not be limited to the example above. In fact, this is another desirable property of a learning environment that contributes to user experience optimization. In fact an intelligent DGBLE can be dynamically adjusted to current user's capabilities by monitoring his actions and fine-tuning the desired level of difficulty accordingly. Moreover, during the course of time the system may collect a number of statistical parameters, analyze them from time to time and use the analysis results to re-adjust several key parameters like speed and difficulty of a game, time to complete a learning course, etc. Finally, another highly desirable – although not essential – design property is system modularity, since it allows large and complex DGBLEs to be configured in alternative ways by adding, substituting or removing separate system components. A summary all properties discussed above is given in Table 2.

Table 2. Essential and desirable properties/guidelines for the design of effective public DGBLEs.

Essential properties
- considerable level of saliency - brief, clear and unambiguous description of context - gradually increasing complexity to preserve engagement - competition mechanisms - reward-through-evaluation mechanisms - positive post-engagement experience broadcast
Desirable properties

- customization
    o for several target audiences
    o interface language
- dynamic adjustability
    o to current user capabilities
    o to statistical analysis of results
- modularity

Model Description. The core component of a public DGBLE is one or several standalone games, tutorials, presentations, etc., covering all topics and issues that need to be learned (and absorbed). In several situations however, the topics to be taught present an inherent complexity that necessitates the implementation of intricate interfaces with steep learning curves. This might be especially true in topics related to science or mathematics. Consequently even if a person is initially attracted to an educational game, an increased interface complexity might reduce his motivation for further engagement, especially in public areas with other nearby competing attractions and distractions. This becomes even more challenging if we consider that in public DGBLEs the target users are just visitors strolling leisurely around. Hence, users have to be attracted in a voluntary engagement, which in addition must be periodically refreshed in order to be preserved throughout the entire learning path.

An approach to overcome this obstacle is to enrich the learning environment with other attractions and activities that initially "allure" visitors to attend and gradually escalate their engagement towards the subject. Such attractions may include, for example, brief multimedia presentations of certain thought-provoking facts or implications related to the topic. They can also include several stimulating, very simplistic, hands-on interactive digital experiments on the basic principles of the topic. Engagement can be further increased by implementing mechanisms of gratification-through-competition or evaluation such as multiple-player games, high score beating, and self-evaluation procedures. The combination of all the above results in a more "casual" arcade-like digital environment for a person to wander, play, enjoy, compete, and eventually grasp and absorb the basic concepts of the educational topic. In the context of the previous discussion we propose a structural model for the design of digital public game-based learning environments based on the following general scheme:

$$\text{Attract} > \text{Engage} > \text{Educate} > \text{Evaluate}$$

Our model envisions public DGLEs as integration of a number of discrete application modules under a global shell acting as a home, covering all four stages of the above scheme. Each stage of the proposed model contains one or more standalone application modules that can be invoked either by the user, or run in a demo mode. In the following we present in detail the concept and a general description for each of the four stages of the model, a general outline of which is presented in Table 3.

Stage I. Initial Attraction through Excitement and Curiosity. The main purpose of this stage is to attract the attention of visitors passing-by and make them stop for a while to see what is going on. At this stage visitors will try to assess the situation and decide if they are interested in the subject, or continue with their tour. This is the most critical stage, since all other stages depend on whether or not the visitor remains attracted or walks away. To make a visitor initially attracted, the learning environment must offer an introduction which is (a) brief and accurate so that its context becomes immediately clear and (b) creates excitement and inspires curiosity. Such an introduction may be implemented as one or several brief multimedia presentations running either in standalone or in interactive mode. The content of such presentations must be delivered in a vibrant and playful style, highlighting a combination of well-known aspects of the subject mixed with several strange or unusual ones. Since curiosity-triggering events and surprises can have a positive effect on learning [7] introductory presentations may also contain thought provoking questions, trivia and other stimulating fun facts that entice visitor's attention and curiosity leading them eventually to further engagement.

In public areas such as museums and exhibitions this stage should be backed up with a carefully designed salient physical layout (consoles, booths, posters, flags etc.) to further intensify the attraction effect.

Table 3. Outline of the proposed model

Stage I. Initial Attraction through Excitement and Curiosity.
Purpose: Invite / attract / allure visitors to the topic. - Interactive multimedia presentations - Interesting and fun facts on the topic - Thought-provoking questions and trivia Works in tandem with a carefully designed salient physical layout
Stage II. Motivation Boost through Relaxed Participation
Purpose: Encourage / motivate visitors to interact with the topic - Self-explanatory simple and attractive interfaces - Requiring low mental effort so that people are not discouraged or overwhelmed - Boost enthusiasm / fortify engagement
Stage III. Core Learning through Game Playing.
Purpose: Engage individuals to core learning of subject through game-playing - More than one games with overlapping topics - Progressive difficulty - Single-player (also multiplayer whenever possible)
Stage IV. Knowledge Confirmation through Self-Evaluation
Purpose: Use rewarding techniques to reinforce attachment to the subject - Quiz / game like - Comprehensive answers, further elaborating the subject - User performance statistics

Stage II. Motivation Boost through Relaxed Participation. As soon as visitors are attracted to the learning environment most of them will start exploring the available content. To further encourage and motivate users, this stage should offer a gallery of elementary simulation games and/or simulation experiments relevant to the fundamental scientific principles of the educational topic. These games/experiments should be kept simple and self-explanatory, having attractive interfaces and requiring low mental effort so that users are not discouraged or overwhelmed. Ideally, this stage must boost the curiosity and enthusiasm of participants and further reinforce their engagement to proceed to the more complex and demanding educational games to follow.

Stage III. Core Learning through Game Playing. This is the fundamental stage of the DGBLE. Visitors proceeding to this stage have already the basic knowledge and enough motivation to engage to more complex and demanding games that require additional mental effort and concentration. If the topics to be covered in this play-and-learn approach are numerous then this stage may contain more than one games each based on a subset of these topics with as much as possible overlapping of topics among games. Ideally games should have a progressive difficulty but not too many levels, since they have to be kept as short as possible, just long enough for the players to ensure that they have mastered the basic laws and principles behind the game. Although all games should be designed primarily as single-player games, a multi-player option could be considered, since the chance of competition with other players – whenever given – enhances the experience and boosts learning.

Stage IV. Knowledge Confirmation through Self-Evaluation. The main purpose of this stage is to rehearse and reinforce the new knowledge using rewarding techniques through game-based self-evaluation. Participants coming through the previous three stages of skilled games and experimentation have already expanded their knowledge on the topics of the DGBLE. Some participants will just walk away at this point, however several others will probably be willing to be challenged further by proving to themselves, to their companions and any watching by-standers how well they master their newly-acquired knowledge. This stage may contain one or more quiz-like evaluation tests with multiple choice answers. To match the overall spirit of the game environment such tests may be also implemented as simple games e.g. with a token-like character having to reach to a target destination by moving forward with right answers and backwards with wrong ones. Evaluation tests/games should feature several user-selected difficulty levels allowing participants to adjust their amount of effort. Tests should terminate giving a total score and a detailed evaluation report containing complete but concise explanations for both right and wrong answers. The report may finish with a short qualification verdict written in high-spirit and maybe containing some well-placed humor. This is especially helpful in case of lower-than-average scores, so that participants are not intimidated but rather encouraged to try again for a better score. Performance statistics taken from this stage from all test scores may be used as a primary indication of the overall value and effectiveness of the learning environment.

Additional GUI Guidelines

To ensure the GUI integrity and uniformity of DGBLEs designed according to this model, the following additional guidelines are proposed:

- Application/game modules may be accessed from within a global "Home Interface" through which participants will be guided along the learning path. Such an interface physically integrates and homogenizes the various components of the DGBLE while it also manages global settings common to all components like for instance interface language, sound preferences, etc.
- Application/game modules should have similar thematic backgrounds and offer identical controls and behaviour for most common actions like getting help, manage settings or getting back to the Home Interface.

– Help and guidance should be provided in a uniform style throughout the environment by means of a theme-related animated pedagogical agent that will be continuously visible and available.
– Content navigation should be clearly suggested but not strictly enforced. Although the stages of the proposed model are logically sequential, some visitors may feel oppressed and discouraged if they are forced to follow a strict roadmap. This is especially true for recurring visitors or users with a partial knowledge of the subject, who want to engage directly on specific game/applications skipping introductory material. The environment should clearly suggest the logical sequence of actions to be taken by novice users but at the same time provide a discrete indication that they can freely navigate around. Chances are that novice visitors will stick to the suggested route, while the more experienced ones will successfully attempt to circumvent it.
– Content redundancy is crucial and should be implemented through dispersion and overlap of the topics to be covered in multiple application modules. In that sense it is desirable to have an arcade of several different games of varying difficulty based on overlapping sets of principles. This variety will permit different visitors to be familiarized with the same set of principles while engaging with different game-learning activities.
– Mechanisms for monitoring user actions and preferences should be implemented throughout the learning environment. Monitoring results may be analyzed in real time predicting users' behaviour and triggering the intelligent help subsystem to provide instructions and guidance [8]. Selected monitoring parameters should be archived for periodical statistical analysis of users' behaviour and system performance. Analysis results may be used as a feedback for adjustments to optimize the efficiency of the system (Fig. 1).

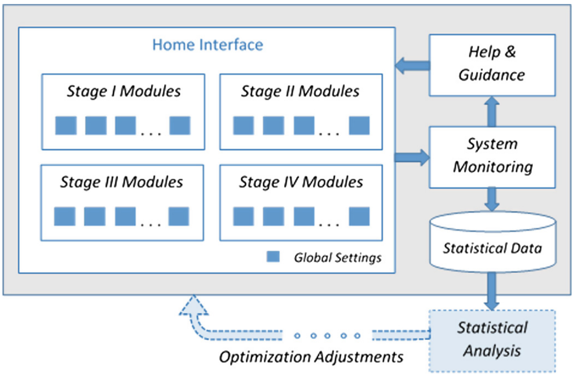

Fig. 1. Intelligent help & guidance and optimization through dynamic system monitoring and statistical analysis

3 Case Study: OCEAN SOUND LAB

Underwater acoustics is the study of sound and sound propagation in water, e.g. in the ocean. OCEAN SOUND LAB (OSL) is a digital game-based learning environment developed by the Institute of Applied and Computational Mathematics of the Foundation for Research and Technology-Hellas (IACM-FORTH). It is designed for installation in public aquaria and museum exhibitions, aiming to offer to the general public a pleasurable introduction to the ocean soundscape and the basic principles of underwater acoustics [9]. It contains a variety of play-and-learn activities, from presentations of underwater sounds and basic physics for the non-expert, to interactive applications and games around ocean acoustic propagation effects. Figure 2 illustrates some representative screenshots of OSL.

Fig. 2. Screen snapshots of OCEAN SOUND LAB: Main screen (top left), Sounds of the Sea (top right), MultiPath (bottom left) and Squid Hunt (bottom right)

OCEAN SOUND LAB is a game-based learning software environment that fits to the principles mentioned in this work. It exhibits a modular design currently featuring seven modules that span all 4 stages of the proposed model. Initial attraction to the environment (model stage I) is accomplished through two interactive shows/tutorials, called "Sounds of the Sea" and "About Sound". Motivation boost (stage II) is achieved through two other modules called "Frequency Lab" and "Sound Tracing". The core of

OSL (stage III) contains two game-modules called “Squid Hunt” and “MultiPath” and finally knowledge confirmation through self-evaluation (stage IV) is attained through a quiz-like game module of multiple choice type questions of user-selected difficulty levels.

All OSL modules share a global thematic background and offer similar controls and behavior. Help and guidance throughout the environment is provided through an iconic diver “swimming” around the underwater environment (see Fig. 1). The names of the applications and game modules on the main screen are arranged to imply an ordered list that will most probably be followed by first-time visitors. This list is ordered to represent the intended roadmap, and will equally probably be skipped by recurring visitors aiming for specific games.

A standard physical layout for OSL is a single custom-made console with a touch screen running all modules through a main menu that suggests a learning path. Since OSL has a modular design, distributed layouts can be implemented alternatively, provided that sufficient room space is available. In such layouts, OSL modules could be spread at several physical locations (consoles) arranged in a sequential pattern that emulates the suggested learning path.

User activities are monitored throughout the entire learning environment producing statistics about their preferences and action-patterns. OSL does not support dynamical adjustment of its parameters through real-time data analysis, however the collected statistics can be periodically analyzed off-line in an attempt to evaluate its educational efficiency. A systematic analysis of usability tests conducted during the development and testing of Ocean Sound Lab revealed that users/players devote twice as much time in gameplay and quiz solving compared to other activities such as interactive multimedia presentations and simulation/experimentation applications Another interesting observation is that participants are rating the integrated OSL environment higher than the sum of its individual components [10].

4 Discussion

The effective design of public DGBLEs is a challenging task because it presumes voluntary engagement of participants in highly distractive and competitive environments. Moreover the inherent complexity of certain educational topics necessitates the implementation of games with intricate interfaces and steep learning curves that may discourage players to engage. To challenge these issues we have proposed a number of properties serving as guidelines for the design of public DGBLEs. These properties, categorized as either essential or desirable depending on the importance and impact they have on the design, serve as foundations to a comprehensive multistage model for the design of public DGBLEs based on the general scheme “attract > engage > educate > evaluate”. The key idea behind this model is to initially attract perspective participants through excitement and curiosity, then gradually increase their motivation through relaxed participation to simple ludic activities on the basic principles of the educational topic. These activities will eventually strengthen participants’ engagement which is especially helpful for topics of inherent complexity. When the desired level of motivation is achieved, participants are more prone to enthral to the core game activities of the DGBLE and stay engaged throughout the end. The model completes with a last stage offering ludic self-evaluation to participants wishing to do so. Knowledge confirmation through self-evaluation also provides a way to assess the efficiency of the DGBLE itself by performing statistical analysis of the temporal collected results. In a more flexible and agile scheme the same results could be used to fine-tune the environment in real-time by adjusting certain of its key operational parameters. To complete the model description and ensure its integrity and uniformity a set of additional GUI guidelines are also proposed. This set includes guidelines about the home interface, thematic backgrounds, help and guidance, content navigation and more.

Ocean Sound Lab is an existing DGBLE for introduction to the world of underwater sound and the basic principles of underwater acoustics; an interesting, unusual and rather challenging topic. Since its overall design and organization is largely based to the principles discussed here, we present it as an example of how a DGBLE designed according to the proposed model will look like and behave.

There are more challenges in the design of public DGBLEs that have not been addressed here such as the support of content and GUI adaptation to different target groups, the implementation of adaptive instructional scaffolding techniques for promoting deeper levels of learning and more. Future studies taking into account these and similar issues will definitely produce enhanced models for the design of more effective DGBLEs for public education.

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