Designing Principles and Guidelines for a Pedagogical Framework of STEM Learning Through Mobile Serious Games

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***Abstract*— The urgency of improving science, technology, engineering, and mathematics (STEM) learning has been internationally recognized. However, the views on the nature and development of proficiencies in STEM education are diverse, and increased focus on integration raises new concerns and needs for further research. The complexity of these factors reaches beyond just helping students achieve high scores in STEM topics assessments. In practice, teachers struggle and lack cohesive understanding of STEM education. Also, students are most of the time disinterested in some STEM subjects and do not understand how STEM knowledge is applied to real-world problems. Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines. Therefore, a STEM education conceptual framework is needed to build a research agenda that will in turn inform stakeholders to realize the full potential of integrated STEM education. In this paper, we present key concepts to build an integrated STEM education framework through mobile serious games which reflect design principles created based on the theoretical understanding of teaching and learning.**

Keywords- STEM; Mobile Educational serious games; Pedagogical framework; Design principles; Mobile learning environment

I. INTRODUCTION

Science, technology, engineering and mathematics fosters students' creativity and design thinking [7][12]. Globally, educators hope to improve student learning outcomes, such as participation, interest, engagement, persistence, and aspiration in STEM (science, technology, engineering, and mathematics) and STEM-related fields. For Taylor (2016), STEM education is a key factor in preparing young people to deal positively and productively with 21st century global challenges that are impacting the economy and the environment. The focus of our paper will be on science, technology, engineering, and mathematics (STEM) related studies at primary and secondary school levels. As we will deal throughout this paper with the design principles and guidelines for the pedagogical framework for STEM learning through mobile serious games, recommendations, and guidelines for considering these design principles in the STEM learning design environment using mobile serious games and how these principles will be applied including concrete examples within the complete framework, will be subject of our next research work. As stated by Martin et al. [17], it has been widely argued that more active instructional methods must be implemented in classrooms. The authors refer to the general proposition of Bonwell et al. [3] to define these more active instructional methods for students to be engaged in usual tasks such as listening, reading, writing, discussing, or solving problems but also, and most importantly, to be engaged in higher-order thinking tasks such as analysis, synthesis, or evaluation and for which an inquiry-based approach to STEM subjects can produce good results.

In this context, serious games can play a special role because the quantitative and predictive models of STEM topics can be used to generate interactive environments that can be freely experienced. Serious games have great potential to catalyze and support inquiry-based approaches to STEM instruction, over-coming curricular and logistical barriers [20]. Despite a decade of research emphasis on STEM education, there has not been much game-based learning for STEM, and the existing one are not consistent in terms of activities being monitored and learning outcomes assessed [35]. Serious games as a teaching aid can stimulate students interest and improve their understanding in STEM learning. The use of serious game on STEM learning analytics provides assessment data to measure student performance and achievement of pre-defined learning out-comes [36]. The concept of STEM education is an effort to engage students in learning about science, technology, engineering, and mathematics [10].

Today, digital games are considered a popular form of activity for children and even for adults. Most students cannot imagine a world without mobile technology [31]. As the process of technological change in education evolves, it must be recognized that mobile technology is part of the new education system. They provide personalized distance learning and automatic learning using mobile devices for students of all ages and backgrounds [5]. STEM learning through Mobile devices allows interaction, collaboration, and learning in a variety of ways: through apps, videos, online presentations, and other interactive tools [15]. The added value of STEM learning games through mobile serious games is that they appeal to many players.

Students can bring knowledge with them wherever they go. The growth rate of the mobile gaming market is a force to be reckoned with. Currently, there is a lack of high quality and critically evaluated interactive educational materials or tools available for teacher's use [9]. There is a need for student-centered and design-based approaches to STEM education to engage students in STEM fields and develop skills basics needed to succeed in a technological society. Educational games have been used for decades, their affordances serving as primary vehicles of learning, but their benefits are limited by their constructivist pedagogy. According to McDonald [18], game design as an educational tool can meet the needs of contemporary STEM educators and become an essential part of future science, technology, engineering, and math education initiatives.

These principles and guidelines for a pedagogical framework of STEM learning through mobile serious games will be useful for primary and secondary teachers in the design of STEM lessons, for example, choices of types of tasks and activities, ways of learning, teaching, and learning content in the context of STEM subjects. Teachers will be able to choose the design principles they deem most relevant to consider each time, depending on the specific learning objectives, instead of trying to keep all the principles in mind. Obviously, Teachers may also choose to focus on specific design principles based on their personal professional development needs.

II. State of the Art

Throughout this section will present principles to inform the design of innovative learning environments using mobile technologies. We will discuss how such design principles are an important outcome of creating a learning framework using mobile devices.

A. The role of mobile technology in serious game

As the world has become a global village because of the technological advancement in the world, mobile teaching and learning in recent years has become a valuable and real contribution to learning environment rather than what it used to be in previous years as a theory, academic exploration, and technological idea [1]. Obviously, with the rapid development of mobile communication technology and wireless internet technology, a new learning mode named mobile learning is quietly emerging. The characteristics of personalized learning at anytime and anywhere attract the attention of many scholars at home and abroad. However, it has become an urgent problem to ensure learners to focus on learning in a mobile learning environment for a long time, and that fragmentation learning can be effectively integrated into system learning. It is a meaningful attempt to integrate edutainment into mobile learning. For Husheng et al. [8], with the implementation of 4G technology, mobile games have made great leaps both in the game quality and the game platform. It also provides great opportunities for the combination of serious games and mobile learning.

Mobile serious game is serious game in the mobile device on the realization of the carrier. It has the characteristics of mobile games and serious games and has unique advantages in portability and entertainment. Users can use mobile phones to play games at any time and place, actively acquiring knowledge and skills, and achieving changes in attitudes and behaviors.

Given the fact that there is no single definition for mobile learning and stressing that mobile learning has not yet been defined, many researchers have put forth proposed definitions of the concept. Mobile learning has been described as a subdivision or subset of electronic learning [22]. Therefore, mobile learning focuses on the mobility of the learners, interacting with portable technologies and learning that reflects a focus on how society and its institutions can accommodate and support an increasingly mobile population.

B. Design principles for mobile learning

For van den Akker [32], design principles can refer to characteristics of a planned learning design (what it should look like), or its procedure (how it should be developed). Above all, design principles must be expressed in a way that can inform practice [33]. Design principles are best expressed in active terms that enable their ready use by teachers and designers presented with similar contexts and problems. They are often presented in a form that lists criteria of particular learning environments and outcomes, and when presented this way, often start with a verb. Again, design principles are not fixed, and are offered as advice on how others might benefit from the findings of a particular development and research endeavour. As noted by Reeves [24]: 'Instructional technologists engaged in [design-based] research are above all reflective and humble, cognizant that their designs and conclusions are tentative in even the best of situations'.

Herrington et al. [6] have outlined design principles for mobile learning and the following characteristics are recommended for the incorporation of mobile learning into an education learning environment:

TABLE I. DESIGN PRINCIPLES FOR MOBILE LEARNING

PRINCIPLES	DESCRIPTION
REAL WORLD RELEVANCE	USE MOBILE LEARNING IN AUTHENTIC CONTEXTS
MOBILE CONTEXTS	USE MOBILE LEARNING IN CONTEXTS WHERE LEARNERS ARE MOBILE.
EXPLORE	PROVIDE TIME FOR EXPLORATION OF MOBILE TECHNOLOGIES
BLENDED	BLEND MOBILE AND NON-MOBILE TECHNOLOGIES
WHENEVER	USE MOBILE LEARNING SPONTANEOUSLY
WHEREVER	USE MOBILE LEARNING IN NON-TRADITIONAL LEARNING SPACES
WHOMSOEVER	USE MOBILE LEARNING BOTH INDIVIDUALLY AND COLLABORATIVELY
AFFORDANCES	EXPLOIT THE AFFORDANCES OF MOBILE TECHNOLOGIES
PERSONALISE	EMPLOY THE LEARNERS' OWN MOBILE DEVICES
MEDIATION	USE MOBILE LEARNING TO MEDIATE KNOWLEDGE CONSTRUCTION.
PRODUCE:	USE MOBILE LEARNING TO PRODUCE AND CONSUME KNOWLEDGE.

III. PEDAGOGICAL FRAMEWORK FOR STEM LEARNING AND DESIGN PRINCIPLES

STEM education is the preparation for STEM fields and encouragement of STEM literacy. A commonly accepted definition of STEM education is provided by Tsupros et al. [30]: STEM education is an interdisciplinary approach to learning where rigorous academic concepts are coupled with real-world lessons as students apply science, technology, engineering, and mathematics in contexts that make connections between school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new economy. As stated earlier on, the importance of engaging and effective learning environments for science, technology, engineering, and mathematics (STEM) has been internationally recognised [27]. There is a need for learning environments that raise interest and motivation towards STEM studies and careers (Salmi et al., 2021) and better connect STEM competencies to cross-curricular, so-called twenty-first century skills, as well as to future workplace skills [27]. However, the creation of frameworks that gather and represent design principles [34], i.e. organisational units for synthesising design knowledge to guide the design of hybrid STEM learning environments is much needed [11].

Considering (a) the lack of a pedagogical conceptual framework to guide both educators and developers in the design of a learning environment, in the selection of effective teaching and learning, methods of teaching and learning, particularly in the context of STEM subjects; (b) the benefits of a participatory co-design approach for STEM educational serious games; (c) the impact of the pedagogical framework of STEM learning through mobile serious games. The following section will describe how design principles have been developed based on the research literature. These principles will serve as a research-based introduction to the topic after which priorities can be defined based on the concrete design target and goals.

A. Pedagogical Framework structure

The current state of research on the design of Digital Game Based Learning (DGBL) environments call for an updated review of the best practices in recent years for developing Digital Game based learning environments, which prompted our literature review. As outlined by Tetyana [30], it draws from successful examples of educators implementing STEM learning games in classes, and it highlights five key principles that facilitate the effectiveness of STEM learning: (1) interactivity; (2) immersiveness; (3) adaptive problem solving; (4) feedback, and (5) freedom of exploration. Practical examples are used to illustrate the effective implementation of these principles in STEM learning games environments and to underscore the significance of each component.

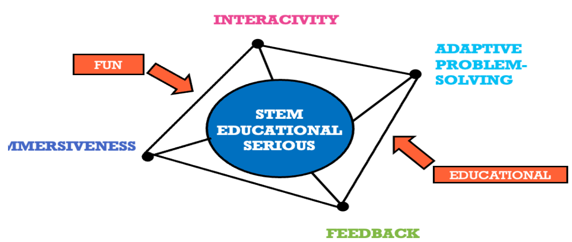

Figure 1. Principles in STEM learning games

Using the Pedagogical Framework for STEM Learning and Design Principles in the development of educational serious games can provide students with a more engaging and effective learning experience that helps them develop a deeper understanding of STEM concepts. As a result, it can help address the challenge of students having little or no understanding of the relevant ideas in individual STEM disciplines and can promote increased interest and participation in STEM fields. As stated by Martin et al., [17], it has been widely argued that more active instructional methods must be implemented in classrooms. The authors refer to the general proposition of Bonwell et al. [3] to define these more active instructional methods for students to be engaged in usual tasks such as listening, reading, writing, discussing, or solving problems but also, and most importantly, to be engaged in higher-order thinking tasks such as analysis, synthesis, or evaluation and for which an inquiry-based approach to STEM subjects can produce good results.

In this context, serious games can play a special role because the quantitative and predictive models of STEM topics can be used to generate interactive environments that can be freely experienced. Serious games have great

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potential to catalyze and support inquiry-based approaches to STEM instruction, over-coming curricular and logistical barriers [20]. Also, Young et al. [35] also noted that: Despite a decade of research emphasis on STEM education, there has not been much game-based learning for STEM, and the existing one are not consistent in terms of activities being monitored and learning outcomes assessed. According to Zaki et al. [36], the use of serious games as a teaching aid can stimulate students' interest and improve their understanding in STEM learning. The use of serious game on STEM learning analytics provides assessment data to measure student performance and achievement of pre-defined learning out-comes. As stated in the previous paragraph and similarly by Johnson et al. [10], the concept of STEM education is an effort to engage students in learning about science, technology, engineering, and mathematics. Today, digital games are considered a popular form of activity for children and even for adults.

Their ease of access and mobility allow people, young children to play on their smartphones. According to Sauvé et al. [26], although playing such games can be considered individualistic, studies indicate that online digital games allow individuals to connect with others in online virtual worlds. Currently, there is a lack of high quality and critically evaluated interactive educational materials or tools available for teacher's use. Again, for Jagoda [9], there is a need for student-centered and design-based approaches to STEM education to engage students in STEM fields and develop skills basics needed to succeed in a technological society. Educational games have been used for decades, their affordances serving as primary vehicles of learning, but their benefits are limited by their constructivist pedagogy. In fact, the game design as an educational tool can meet the needs of contemporary STEM educators and become an essential part of future science, technology, engineering, and math education initiatives [18].

These principles as outlined above, derived from successful implementation of digital gaming elements in learning, and they provide suggestions and strategies for incorporation of these elements based on real-life examples. The table below show how each of these elements are effectively adopted in STEM educational games and may offer ideas for the development of future STEM Digital game-based learning designs. Particularly learner-centred pedagogical principles have been guiding the framework development. The conceptualization of student-centered learning is influenced by authors such as Hayward, Dewey, Froebel, Piaget, Rogers, and Knowles [21]. All this, relate primarily to the constructivist view emphasizing the importance of places on activity, discovery, and independent learning but also cognitive theory highlighting the activity. It also has connections with social constructivist views emphasizing the importance of peer interaction in learning. O'Neill et al. [21] view student-centred and teacher-centred learning as a continuum:

- Low level of student choice - High level of student choice,
- Student passive - Student active,
- Power is primarily with teacher - Power primarily with the student.

In the table below, we will present general principles and description as well as some examples of how these aspects will be considered in the pedagogical framework of STEM learning through mobile serious games.

TABLE II. DESCRIPTIONS OF PRINCIPLES IN STEM LEARNING GAMES

Principle Indicator	Description
Interactivity	Games that offer meaningful interactions demonstratively maintain high levels of engagement in students and positively contribute to their performance on tests when compared to regular project-based instruction (e.g., An & Bonk, 2009; Barab et. al, 2007).
Immersiveness	Immersive details and students‟ absorption in the activity may lead to the mental state of flow (Csikszentmihalyi, 1990), meaning that students would intrinsically enjoy the game and perceive the involvement in the game itself as its own reward (DeCharms, 1972; Deci, 1975; Nakamura & Csikszentmihalyi, 2002).
Adaptive problem solving	Many cognitive psychologists report that engaging students in solving real world problems positively affects their learning gains (e.g., Mayer, 1992; Merrill & Gilbert, 2008). The challenge to resolve these problems needs to be effectively aligned with the student‟s ability and skill level to ensure effective learning. Therefore, I coined the term adaptive problem solving to accurately reflect this need. A well-designed DGBL should offer skill-level adjustments to the problems that students are facing which will ensure gradual learning for all students (Wilson et al., 2009) and create motivational tension (Driskell & Dwyer, 1984) when the challenge of the game is optimal for students‟ skills.
Feedback	As in any form of learning, quality feedback helps students evaluate their progress, recognize their strengths, and identify areas that need improvement (Charles et al., 2009). Effective feedback should provide timely and relevant information on students‟ progress towards their learning goals.

IV. CONCLUSION

Designing an effective STEM Learning environment using mobile serious games that can engage and motivate students as well as facilitate their learning is a challenging task. In many cases, teachers' pedagogical expertise does not directly translate into game design, and it leaves educators with no help regarding the effective ways to introduce STEM learning games in a class and what elements of games and learning should be prioritized. While there is no one correct way to design a digital game-based learning that would guarantee its effectiveness for all students, previous research can offer successful examples of digital games incorporated in classrooms that share common principles. The implementation and the effectiveness of these principles depend on students' goals, interests, subject matters, available resources, but they constitute a solid foundation for designing or adapting a digital game according to the desired learning objectives. The principles outlined in this paper provide insights into the potential to combine different STEM subjects, learning contexts, scenarios, and goals. As educational technologies continue to develop, more tools will be available for teachers to experiment with and uncover additional benefits and effective practices of using STEM digital-based games.

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