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Formative evaluation of immersive virtual reality expedition mini-games to facilitate computational thinking

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ABSTRACT

Recently, virtual reality (VR) technology has shown great potential in advancing education with many pedagogical benefits for building the 21st-century teaching and learning experience. This study conducted a formative evaluation of an immersive VR expedition application with the aim of understanding users' learning processes and how the application facilitates higher education students' computational thinking skills. Six participants were randomly selected to conduct this evaluation. A mixed research approach consisting of quantitative and qualitative methods was employed. The study quantitatively analyzed users' scores from gameplay to understand how the intervention supported computational thinking skills. Participants were also interviewed to collect data after playing the mini-games to investigate users' experiences. The study showcases players' computational thinking competency, assessed automatically during gameplay. Further, this study used inductive content analysis to demonstrate users' reactions to prototyped VR mini-games. The qualitative findings suggest that users found the VR mini-games interactive and immersive, which provided an opportunity to foster learners' computational thinking skills. The quantitative analysis revealed that student's computational thinking competency can be enhanced through consistent playing of the mini-games. Moreover, the expedition aspect of the VR game stimulated learners' curiosity, which sustained their learning progress. Furthermore, users gained new knowledge and found the mini-games educative. Nevertheless, several aspects of the VR mini-games need improvements, according to users' perceptions. This study contributes to the knowledge in terms of the affordances of VR in education research and provides relevant insights that can shape future studies, for example, the recent hype of metaverse in education.

1. Introduction

Nowadays, the use of virtual reality (VR) applications is permeating many areas of work and life, including entertainment, medicine, and education (Wei et al., 2019). VR is a technology with great possibilities and pedagogical advantages for creating 21st-century teaching and learning experiences (Bogusevschi et al., 2020). Notably, the use of VR applications with a low-cost head-mounted display (HMD), such as Google Cardboard and a Bluetooth hand controller, can help bridge the learning gap and constraints associated with location-based learning, a lack of expensive study equipment, and other related barriers. Indeed, VR has the potential to enhance teaching and learning at any level of education because of its features of immersion, interaction, presence, immediacy, engagement, and motivation (Jin et al., 2020; Lan, 2020; Mei & Sheng, 2011). With VR, a learner can engage in creating and interacting with learning objects within a virtual world through the sense of presence while being unaware of physical environmental conditions. Educators are currently exploring VR technologies and applications at different levels of education (Segura et al., 2020; Agbo et al., 2022). Students can gain knowledge from the visualization of abstract concepts in a three-dimensional (3D) virtual environment (Dergham & Gilányi, 2019; Hickman & Akdere, 2018).

The use of VR mini-game in the classroom to facilitate learning is gaining grounds (Sierra et al., 2019; Devisch et al., 2017; Chaves et al., 2021). According to Agbo et al. (2021a), "mini-games are small, simple games that may exist within a bigger video game, which can be played independently" (p. 2). Unlike video games (Ch'ng et al., 2019), mini-games mainly focus on one particular learning concept that contains

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rules, and the task can be easily accomplished (Chaves et al., 2021). The importance of VR mini-games, which include providing an opportunity for learners to interact directly with modeled real-life problems and deliver easy and substantial learning goals, has been emphasized in the literature (Bouali et al., 2019; Devisch et al., 2017).

As argued by Agbo et al. (2021b), the prerequisite knowledge to support students' understanding of introductory programming courses taught in computer science classes is computational thinking (CT). CT is gaining huge scholarly interest, as it facilitates 21st-century learning experiences in K–12 settings, whereas similar interests are scarce in higher education (Agbo et al., 2019a; de Jong & Jeuring, 2020). Since CT concepts have been shown to stimulate critical thinking and problem-solving skills, there is a need to mainstream their education among higher education students, especially novices, who must develop the skills necessary for future workplaces. Scholars have described CT as thought processes involved in developing problem-solving skills (Aho, 2012; Wing, 2006) that could help in mastering programming (Agbo et al., 2019b; McClelland & Grata, 2018). CT is also said to be a way of developing learners' critical thinking to approach complex problems (Ch'ng et al., 2019). Studies have revealed that having a good understanding of CT concepts, which includes algorithmic thinking, abstractions, problem decomposition, and recursive thinking skills to solve problems (Qualls & Sherrell, 2010), can facilitate students' excellent performance in programming classes (Agbo et al., 2019b, 2021a).

Furthermore, Agbo et al. (2019a, 2021b) identified the possibilities of exploring CT concepts in higher education contexts to allow learners to gain the problem-solving skills necessary for advanced classes in programming. One way to demonstrate CT competency can be through educational mini-games (Agbo et al., 2021b; Chaves et al., 2021). Deploying an educational mini-game in a VR environment could add another layer of learning outcomes (Agbo, 2022). However, shortcomings of using VR in education—motion sickness, cognitive load, and distractions—have been discussed in the literature (Checa & Bustillo, 2020). Notwithstanding, the huge potential VR provides, which are related to immersion, interaction, and presence, can enhance learners' learning processes and improve their knowledge. Apart from obtaining CT knowledge through visualization, many precursory CT tools seldomly create measurable proof of learner's results when playing the game (Segura et al., 2020, Hooshyar et al., 2021). The focus of the present study is the initial evaluation of the usability, learning process, and users' experiences of a VR expedition application—iThinkSmart—containing mini-games to facilitate learners' CT skills. The study also attempted to integrate automatic assessment into the game application to provide quantifiable evidence of players' achievement in educational mini-games during gameplay. To achieve the goal of this study, the following research questions were formulated.

RQ1. How do users find the VR application (iThinkSmart) mini-games useable?

Given that the developed prototype is user-centered, RQ1 is relevant and motivated by Smutny et al. (2019), who reviewed studies on the use of VR in different domains, such as safety, travel, history, and engineering education, but not in problem-solving and CT education. Therefore, this study intends to examine how users found the developed VR application useful from the perspective of interface, aesthetics, and functionality that aide interaction between the learners and learning objects in VR.

RQ2. What are the users' experiences after playing the iThinkSmart mini-games?

The characteristics of VR, including immersion, interaction, presence, and representational fidelity, provide the opportunity to investigate users' perceptions and experiences when learning in the virtual 3D environment. There is a possibility that users could perceive differently when learning in virtual environments (Geng & Wu, 2021), which motivated RQ2.

RQ3. How are users' perceptions regarding the impact of iThinkSmart mini-games on their computational thinking skills?

In RQ3, the study seeks to examine whether the developed intervention fulfils its aim by fostering CT education and problem-solving skills. Although Smutny et al. (2019) revealed other domains in which VR has been applied, there are limited studies on the domains investigated in this study.

2. Literature review

2.1. Virtual reality in computing education

Numerous studies have utilized VR in education. Nicola et al. (2018) developed a VR application that supports students in learning Bubble Sort algorithms. According to the authors, the 3D VR application was found to support students in learning the Bubble Sort algorithm by sorting balls within 130 s. Similarly, Ying et al. (2017) developed a VR educational platform called VREX, which immerses students in a virtual world to foster their learning experiences in offline and online teaching modes. According to Ying et al. (2017), VREX can support virtual teaching in different contexts, including higher education. Hu, Ng, and Lee (2019) investigated students' experiences with the use of VR applications to create content featuring cultural heritage in an undergraduate course. According to the authors, the VR approach motivates students to learn more about cultural heritage. Jin et al. (2020) presented a VR environment called VWorld to support programming education among young learners. The authors investigated how students can be immersed while learning computer programming using VWorld.

Furthermore, Segura et al. (2020) presented a VR game called VR-OCKS, aimed at teaching the basic principles of programming. The game was intentionally developed to attract young learners to computer science by building their interest in programming. The evaluation of VR-OCKS revealed that group learners performed better in terms of understanding programming concepts, such as loops, and conditional structures.

Assessment of students' learning achievement is critical for any educational intervention, particularly for personalized virtual learning environments (Chaichumpa et al., 2021; Chaichumpa & Temdee, 2018). Hu et al. (2019) evaluated VR interventions by analyzing users' survey responses, whereas Jin et al. (2020) recruited three university students to collect initial feedback on users' experiences without necessarily examining the learning achievement of their VR prototype. Similarly, Segura et al. (2020) conducted surveys to analyze the impact of their VR application. However, Ying et al. (2017) did not explicitly provide empirical evidence that showcases the impact of their study through an experimental process.

Nicola et al. (2018) assessed users' learning achievements during gameplay by analyzing the time taken to complete the tasks in the VR application (typically less than 30 s for best performance). Unlike other aforementioned studies that assess learners in VR through the survey technique, Nicola et al. (2018) demonstrated a different approach by partly integrating assessment into the VR application. Our study, which used a low-cost HMD to provide a game-based VR application for novices to learn CT concepts, was motivated by Nicola et al.'s (2018) study. However, the assessment of players' learning outcomes in our study is based on the objective distance model, unlike Nicola et al.'s (2018) approach, which is not founded on any standard model.

2.2. Overview of computational thinking education

CT requires applying structured thinking or thinking algorithmically to provide solutions to everyday problems (Denning, 2009). Some of the challenges of CT education have been described by Angeli and Giannakos (2020) to include defining CT competencies, metaphors, assessments, teachers' developments, and teaching and pedagogies. Studies have highlighted the requirements for scaffolding students' learning experiences when engaged in CT activities (Clarke-Midura et al., 2021; Doleck et al., 2017; Ruthmann et al., 2010). Today, CT education is promoted by using hardware materials, such as educational robotics and 3D printers, as well as through student-friendly programming environments (Eguchi, 2016, pp. 79–84). For example, Scratch, Bluejay, Alice, Greenfoot, codeacademy.com, and code.org have been used to demonstrate CT education (Ruthmann et al., 2010; Grover & Pea, 2013). This section presents an overview of the concepts that are integrated into CT education.

2.2.1. Problem solving

Scholars have investigated the development of problem-solving skills among learners in various contexts (Chang et al., 2017; Jordan-Douglass et al., 2018). In the context of higher education, one recently demonstrated problem-solving strategy is through a game-based learning (GBL) approach. Game-based learning is a pedagogical approach in which educational games are introduced in teaching and learning situations. Learning through the game was incorporated into education to provide innovation in teaching and learning methodologies (Tan et al., 2007). There are many activities contained in GBL that are entertaining, engaging, fun, educative, and interesting to learners (Chang et al., 2017; Crocco et al., 2016; Wouters et al., 2013). Educational games may be web-based games, VR games, desktop games, or mobile games. GBL can be explored to allow learners gain different problem-solving skills in several contexts. Mayer (1990, p. 284) defined problem solving as "cognitive processing directed at transforming a given situation into a goal situation when no obvious method of solution is available to the problem solver." The emergence of a problem brings the quest to provide a solution in which the focus is on understanding the problem and getting the right solution. In a later definition of problem solving, Mayer (2006) stated that it involves processes that are cognitive in nature, planned and organized by a problem solver, and directed toward completing or achieving specific goals. Thus, problem solving is a cognitive process that requires the skills to accomplish a specific task. In other words, problem solving involves actions taken toward problem definition, identification, the choice of a suitable solution, and the implementation of the solution. The above definitions show that skills are required for problem solving.

Shute et al. (2016) conceptualized problem-solving skills as the ability of an individual to be engaged in comprehending and resolving problems via a cognitive process in which there is no availability of immediate or ready-made techniques to solve the problem. Skills are vital in contemporary society, and learners need to have the creative ability to tackle numerous problems that emerge daily. Some of the vital problem-solving skills include creativity, critical thinking, analytical thinking, cognitive thinking, synthesis skills, and knowledge necessary for solving technical, economic, and societal problems (Amornrit, 2019). According to de Jong and Jeuring (2020), complex problems in society today are addressed by utilizing computational skills with recent technologies.

2.2.2. Algorithmic thinking

The concept of algorithmic thinking emerged from the term algorithm, which typically refers to problem solving through a set of steps in sequential order to attain the desired result (Katai, 2014). Algorithms are designed with the aim of providing a solution to a particular problem. According to Futschek (2006), algorithmic thinking skills require a cognitive aptitude for comprehension and analysis of problems, developing a sequence of steps toward a solution, and refinement of steps to obtain alternative approaches to the solution. In other words, algorithmic thinking is a creative thought that is well defined into procedures that contain a series of steps to provide a solution to a problem. Algorithmic thinking is one of the concepts of CT. A successful algorithmic thinker can easily develop or create specific techniques that may be used to solve a particular task successfully, correctly, and consistently (Lamagna, 2017). As defined by Lamagna (2017), algorithmic thinking refers to the ability to innovatively create a computing process to solve a problem through understanding, executing, and evaluating the procedure.

In the twenty-first century, computing skills are required in several disciplines, and algorithmic thinking is essential for solving different kinds of problems. The teaching and learning of algorithmic thinking in K–12 is widely encouraged to allow learners to possess the preliminary skills needed for introductory programming in higher education (Kiss & Arki, 2017).

2.2.3. Problem decomposition

Decomposition is one of the concepts of CT. In making a complex problem easier, the problem needs to be decomposed. The process of thinking through a problem can complicated, which makes it necessary to break down the complex problem into smaller sub-problems. One of the major components of CT methods is the breaking of complex problems through decomposition into smaller and less complex problems (Fried et al., 2018). Decomposition is a common step in several processes of solving a problem (Wieringa, 2009). In computer science, decomposition is done by breaking down a computational problem into functions, structures, dependence, and sequences (Rich et al., 2019). According to du Boulay (1981), most problems before decomposition are called a "black box," whose internal formations are not yet known by the solution provider. The term black box could mean "a device, process, or system whose inputs, outputs, and relationships to other processes or systems may be known, but whose internal structure is unknown" (du Boulay et al., 1981).

Rich et al. (2019) explained decomposition as classifying a major problem into smaller elements, noting the importance and relationships that exist between them. During problem decomposition, the utilization of specific techniques may be required, and repetition of the execution process is also possible. To teach programming in higher education, problem decomposition can be visualized by breaking down the computing problem into programming sequences, structures, functions, and classes, depending on the programming language. Selby (2012) revealed that decomposition is sometimes difficult for some students in higher education, and an absolutely good teaching method is required for students to learn and become acquainted with problem decomposition. Therefore, one way to visualize problem decomposition in higher education is through VR games (Agbo et al., 2021a).

2.2.4. Recursive thinking

Recursion is one of the essential concepts of CT for problem solving, in which complex problems are handled by formulating a solution to address a smaller chunk of the problem, and the solution can be iteratively applied to solve the entire problem. Hulst (2010) defined recursion as an implant of a component of the same form. From Karlsson's (2010) viewpoint, recursion entails getting a simple output through an in-depth embedded iteration within a complicated structured system that uses previous information. Recently, Lee et al. (2019) explained that the major component of recursion includes recognizing iterative formats in the problems and solving them by utilizing smaller format solutions. Recursion is building an incremental system whose functionality depends on prior information. The study of recursion in the context of higher education has revealed that students' prior knowledge of the theoretical aspects of recursion and motivation affects their learning and understanding of the concept (Lacave et al., 2017).

McCauley et al. (2015) indicated that novices find recursion a challenging programming concept, whereas understanding recursion can be advantageous to students' programming skills (Dann et al., 2001). This implies that students are expected to have a prior understanding of recursion before enrolling in programming courses and enhancing their computer programming skills. Another study on recursion in the context of higher education by Gunion et al. (2009) explained that recursion can serve as an effective technique for implementing sorting and searching algorithms, which is one of the key concepts in problem solving. Furthermore, Lee et al. (2014) revealed that students complicate their problems by building an incorrect model of recursive processes, confusing and mixing the wrong processes of iteration with recursive processes.

Although some of the previous studies presented in this section provide an overview of efforts made to integrate CT education in different contexts through the facilitation of the aforementioned CT concepts, the approaches demonstrated in terms of interventions are predominately course design and computer-based applications, which may provide a minimal level of engagement and interaction for learners. Therefore, the affordances provided through the use of an immersive VR game-based approach could make learning and teaching CT more engaging and interacting to facilitate learner's comprehension (Segura et al., 2020).

2.3. Game elements and mini-games

Before educational games became popular, digital games are considered to provide entertainment, collaboration, and participation (Iacovides & Cox, 2015). However, there is a growing body of knowledge on advancing digital games beyond the normal "fun" to promote other characteristics such as empathy, reflection and even persuade players to change some forms of behaviors. Crawford (2003) presented a summary of digital game conceptual framework in three words which includes rules, play, and culture. Similarly, Tang et al. (2009) summarised rules and culture as the definition of the technical and inherent depiction of the virtual environment to aid the game play activities, whereas Koster (2004) refers to play as the activities for exercising the brain. Panagiotakopoulos (2011) classified games into seven different groups, which include action games, role-playing games, strategy games, adventure games, simulation games, puzzle games, and educational games.

Educational games are aimed at teaching through entertaining activities, and the purposeful combination of entertainment and education translate into efficient learning tools with elements that are interactive, reflective, and challenging (Bertozzi, 2014; Panagiotakopoulos, 2011). Furthermore, educational games which is popular in the domain of GBL are design for the purpose of learning. indeed, Novia et al. (2021) described educational game as an object-based learning games that uses collaborative contents and devices to communicate with a server. According to a recent study, GBL fosters learning through engagement and interaction (Agbo et al., 2021b). Nowadays, there is a persistent rise in studies that promote the development of educational games for enhanced learning experience.

On the other hand, mini-games are a simple and short - single episode – type of games, with guided rules, that allow users to play with ease. Mini-games does not require long hours of play time, but can be completed in a short time, and allow for replaying (Jonker et al., 2009, pp. 202–210). Mini game can be used to teach a short topic with a simple learning outcome. Indeed, educational mini games are integrated into a VR environment to provide quality learning attainments via immersion, interaction and engagement (Bouali et al., 2019; Chaves et al., 2021). With VR mini-games, learners can interact with real-world problems modeled through a GBL approach to provide a simple and quantifiable learning outcomes (Bouali et al., 2019). In addition, mini-games can be deployed within a bigger (serious) game, which can be independently played (Devisch et al., 2017).

3. Description of VR expedition mini-games to facilitate computational thinking

This study developed a VR application that allows learners to experience expeditions and play mini-games that can foster thinking skills. This VR expedition application (iThinkSmart) demonstrates how learners can immerse themselves on ships or land to explore historical sites. The VR expedition is one of the strategies that scholars have used to demonstrate the relevance of VR in education (Cardullo & Wang, 2021; Craddock, 2018). Through VR expeditions, learners are transported to a virtual space to experience a contextual environment and gain new knowledge. In the iThinkSmart VR expedition application, learners try to explore an African contextual mountain top (Mount Patti) and are prompted with challenges (mini-games) that require short solutions before unlocking relics found in the sites. Playing mini-games requires a short time and simple steps to resolve challenges. Game rules, mechanics, and goals are interactively presented to users. Tutorials and personalized feedback are also provided in the virtual world.

The iThinkSmart VR application was developed with the Unity game engine, C#, and Firebase cloud resources. The VR application can be installed on a smartphone, which can be inserted into a lost-cost Cardboard HMD with the support of a Bluetooth hand controller to facilitate virtual interaction between the player and the game elements. Recently, the use of low-cost immersive HMD to facilitate teaching and learning is gaining ground (Cheng & Tsai, 2020). Hence, the iThinkSmart VR application was developed with the intention of delivering affordable and accessible education to learners.

3.1. About the mini-games

Three mini-games were integrated into the iThinkSmart VR application: (a) Mount Patti Treasure Hunt (MoPaTH), (b) River Crossing, and (c) Tower of Hanoi (see Fig. 1). The first mini-game was conceptualized by students from a university at the same location as Mount Patti. The second and third mini-games were adapted from well-known concrete games that have been used to demonstrate critical thinking and facilitate programming education (Tsalapatas et al., 2012). The rationale for conceptualizing MoPaTH is to demonstrate the expedition of a contextual African historical location connected with civilization and Western education, whereas the choice of River Crossing and Tower of Hanoi was informed by their use in classrooms to teach different concepts internationally (Roberts, 2006). The MoPaTH mini-game is a contextual game that engages the player through a puzzle-like challenge while on an expedition to climb a historical mountain (Mount Patti) located in the north-central region of Nigeria. The MoPaTH mini-game simulated a fallen rock directed at the player, who will provide a correct solution to a puzzle in order to escape the rock. For every correct solution to a puzzle, the player gains a reward on score cards and progresses in the climbing of the mountain to the top. However, a wrong solution allows the falling rock to fall on the player and decreases his/her points and distance from reaching the top of the maintain.

The River Crossing mini-game is an age-long challenge that requires players to carry a set of items from one bank of the river to another by following predefined conditions that must not be violated. This challenge is capable of demonstrating the concepts of CT, such as problem decomposition, algorithmic thinking, and recursive thinking (Ratnadewi, 2018). For example, students are required to solve the River Crossing puzzle by applying computational concepts, such as reverse engineering, combination, and algorithmic thinking skills. Finding an optimal solution to the River Crossing puzzle is an optimization problem that remains a critical problem to deal with in computer science.

The Tower of Hanoi mini-game also focuses on improving players' problem decomposition and algorithmic, recursive thinking skills. The Tower of Hanoi is an age-long mini-game that has been used to teach mathematical and computing concepts (Butgereit, 2016), particularly in teaching recursion (Roberts, 2006). Fig. 1 shows the ship and land views of the VR expedition and the screenshots of the mini-games.

4. Research methods

The research design adopted in this study was a mixed research method, which integrates both qualitative and quantitative study techniques.

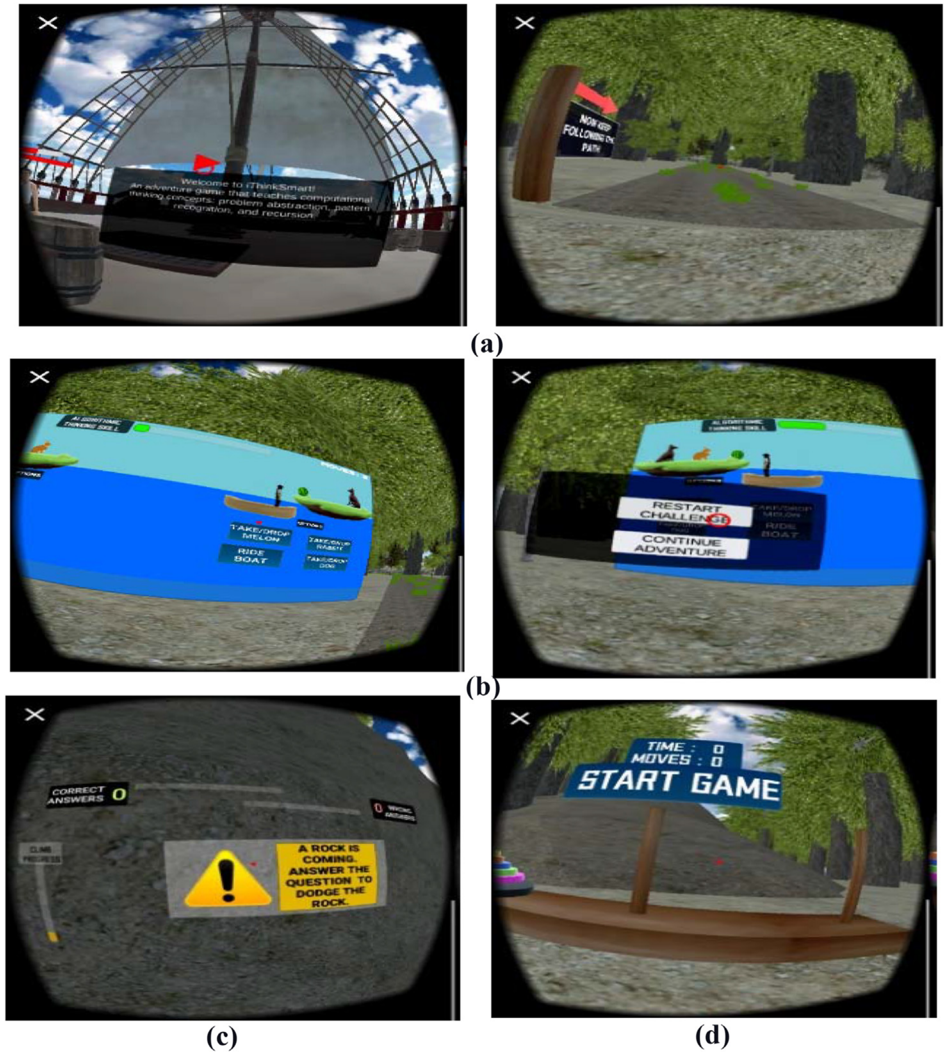

Fig. 1. Screenshots from iThinkSmart VR mini-games: (a) expedition on the ship and land; (b) the River crossing mini-game; (c) the MoPaTH mini-games; (d) the Tower of Hanoi mini-games.

4.1. *Participants, context, and ethics*

This study engaged participants who were bachelor's or graduate students from different fields of learning. Some of the participants did not major in computer science; hence, they were not very familiar with computing education and problem-solving concepts. Indeed, the sample participant consist of students that have no background in virtual reality mini-games, and were novices to concepts of computational thinking. Particularly, the targeted users of the iThinkSmart VR expedition are early university entry students in Africa who enroll in computer science degrees but are novices and do not have prior computer science or programming knowledge.

Since CT skills are not related to computer science alone but are required for learners in different disciplines, it makes sense to test the initial prototype of the iThinkSmart application with users from varied fields. Therefore, its usability among higher education students studying in Finland is explored in this study (Hunter et al., 2019). The rationale for recruiting participants from Finland is mainly to examine their experience in using the developed application, since the researchers are based in Finland and could easily recruit Finnish bachelor's and master's degree students for this initial evaluation. The authors intended to incorporate the outcome of this study into their future research and improve the current version of the VR prototype before conducting a summative evaluation with African undergraduate students.

The participants were recruited randomly. First, we obtained their consent to voluntarily participate in the research. Out of 14 students that were invited, only 6 students, including 5 males and 1 female, participated in the study. According to a previous study (Butt et al., 2018), a usability study of a VR application may require a few subjects to be considered adequate for collecting the data necessary for the initial evaluation. Additionally, the use of small subjects for the initial evaluation of a VR prototype to understand users' experiences has been demonstrated in recent studies (Asghar et al., 2019; Jin et al., 2020). Hence, in this study, a convenience sampling technique was used. We obtained permission from the participants to anonymously use the data collected during the study (including the voice-recorded interviews and images) for research purposes. After each participant played the iThinkSmart mini-games with the HMD and a hand controller, as shown in Fig. 2, a short oral interview was conducted. Audio recordings of the interview conversation between the researcher and the participants were collected using a smartphone.

4.2. *Data collection*

The quantitative data were collected from the participant record in the database, which was generated as the participants played the game. The qualitative data were collected via semi-structured interviews. The semi-structured interview questions were adapted from Aloweni et al.

Fig. 2. Images showing how the participants engaged in playing the VR expedition mini-games.

(2021), with slight modifications made by the authors to fit the context of this study. Aloweni et al. (2021) utilized a similar approach to qualitatively evaluate learning experiences and collected feedback for improving a GBL system. The rationale for adapting these questions to conduct interviews for this study is because they are short, straightforward, and unambiguous, such that respondents could provide answers that are relevant to address this study's research questions (Buschle et al., 2022). These questions were used to collect information on the usability and experience of the participants. According to Holloway and Wheeler (2010), semi-structured interviews produce data that are comparable from all participants while still allowing for scope flexibility.

The procedure for the experiment included first giving each participant a brief orientation about the research goal and the materials (software and hardware) involved in the experiment. The orientation talk lasted for an average of 10 min. The participants were then allowed to play the iThinkSmart VR expedition mini-games, which lasted for an average of 30 min per participant. After playing the mini-games, the interview questions were administered to the participants in face-to-face mode between the researcher and the participant, which encouraged more engagement to obtain detailed responses from the participant on each question. The interview period varied from one participant to another but, on average, took about 20 min per participant. To limit the tendency of influencing the participants' opinion, the researcher documented the questions on a paper before administering the interview and consistently asked them one after another.

Some of the questions asked during the interview included the following:

What are your thoughts as you played this game?

Can you share your experience playing this game?

How did the game impact your learning of computational thinking?

How can we improve the learning quality assessment or any other aspects of the VR application?

4.3. Data analysis

An inductive data analysis following the thematic steps demonstrated by Aloweni et al. (2021) was employed in the qualitative study. After the transcript of the recorded audio from the interviews was performed, the authors independently read through the transcripts several times before highlighting the concepts that formed the codes. These codes were further classified independently into themes. Afterward, the authors jointly refined and agreed on three main themes and six sub-themes, as shown in Fig. 3. The procedure for data analysis followed in this study provided the opportunity to minimize the tendency to skip important and

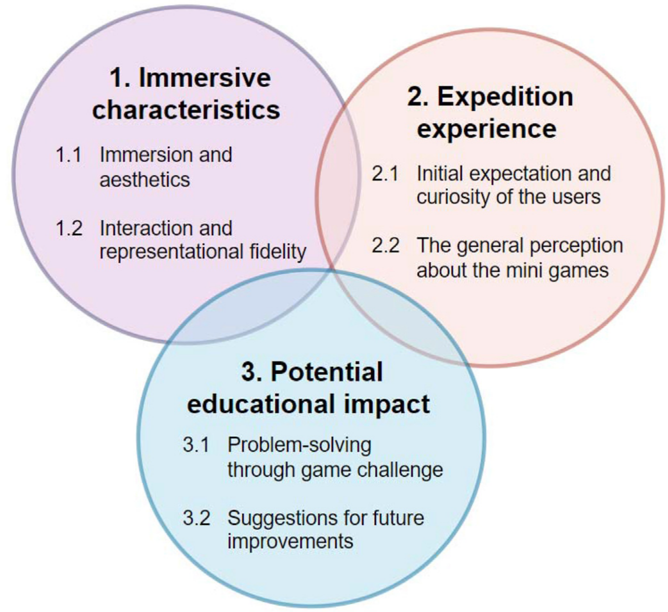

Fig. 3. Venn diagram of themes and subthemes emanating from the inductive data analysis.

uncommon findings while also strengthening the credibility of the method.

Regarding the quantitative analysis, we integrated the objective distance (OD) model adapted from Chaichumpa and Temdee (2018), which was slightly modified to fit our design. The OD model is capable of assessing player's CT competency during gameplay (Temdee, 2021). The OD model is defined as follows:

$$OD_i = \left(\frac{S_i - C_i}{T_i}\right)\left(\sqrt{(C_i - S_i)^2}\right)$$

where.

OD_i = Objective distance for sample i of a learning object
S_i = Satisfactory score for sample i of a learning object
C_i = Current score for sample i of a learning object
T_i = Total score for sample i of a learning object
$i = 1, 2, 3, \ldots$

The equation depicts that for any instance of gameplay i, the objective distance (ODi) is computed by calculating the differences between the satisfactory score (Si) and the current score (Ci), multiplied by the square of their reversed difference, and diving the result by the total score (Ti). According to Chaichumpa and Temdee (2018), experts can weigh total and satisfactory scores. For example, we defined the learning objectives for the River Crossing puzzle with the following weights for the total and satisfactory scores: To obtain the OD, the optimal moves equal the total score = 7; the satisfactory score = 10 (optimal moves increased by 43%). By applying this model, if the OD > 0, the player gained higher competency, if OD = 0, the player gained moderate competency, and if OD < 0, the player's competency is poor, and the game would suggest a replay with hints.

This study used a quantitative approach that leveraged the OD model to assess users' competency during gameplay and record their data for personalized learning feedback, which, to a large extent, reduced the potential for bias in the study analysis compared to assessing users with surveys. Further, the OD model was previously investigated with two classifier algorithms (K-nearest neighbors and artificial neural network) to assess learners' competency in a personalized learning environment and was found to perform optimally (Chaichumpa et al., 2021).

5. Results

First, this study presents a quantitative analysis of the players' scores obtained during gameplay. The assessment of players' scores was automatically computed using the OD model presented in Section 4.

As shown in Table 1, the first player (P1) attempted to play the game once and was able to solve the problem with 9 moves, which is within the satisfactory level. Therefore, P1 OD = 0.1 implies moderate CT competency gained. By contrast, P2 attempted to play the game twice and was able to solve the River Crossing puzzle with 11 total moves, which is greater than a satisfactory score. Therefore, P2 OD = −0.1, implying that this player had poor CT competency. From the result, only P3 played the puzzle once and obtained an optimal score with 7 moves (OD = 1.0), thereby demonstrating excellent CT competency. Although P4, P5, and P6 all showed good CT competency by playing the puzzle with 7 moves (OD = 1.0), they attempted to play the puzzle two or three times before attaining the optimal score.

Regarding the qualitative study, our findings are presented based on Kirkpatrick's first-level user's reaction (Wu et al., 2016). The results are organized and presented following the themes identified during the data analysis, such that they provide answers to the research questions formulated for this study. Fig. 3 showcased the themes developed from the analysis of the data, in which a broad classification of the themes included immersive characteristics of VR mini-games, expedition experience of the VR mini-games, and the potential educational impact of the VR mini-games.

RQ1. How do users find the VR application (iThinkSmart) mini-games useable?

To address this question, the themes—that is, the characteristics of the VR mini-games—consisting of immersion, interaction, representational fidelity, and aesthetics are presented based on participants' reactions.

5.1. Theme 1.1: Immersion and aesthetics

Immersion is a common characteristic of VR and game-based applications, which participants perceived was demonstrated in the VR mini-games to provide a true virtual experience in a learning environment.

> "Hmm, yeah! I can see that I was very immersed, I felt immersion while playing the game …" [P4]

> "I felt like I am in a kind of wilderness, I am on an adventure, …I am in truly on an adventure, trying to see new thing, trying to understand new terrain, …" [P2]

> "… so is amazing trying to play a VR game … and making the sound that is very interesting." [P3]

In addition, the aesthetic features of a VR game measure the beauty of the game. In the case of this study, properties such as graphics, sounds, and colors were among what the participants discussed as aesthetics that enhance the usability of the iThinkSmart VR mini-games, although some participants also expressed mixed reactions about the aesthetic. For example, some comments related to immersive and aesthetic features are presented in quotes.

> "The graphic was very nice; I think it was a very good experience." [P5]

> "… The game was a good thing, but I think the graphics could have been improved because I did not see everything clearly or maybe because I did not use my glasses at the moment apart from that I think it was a smooth one." [P2]

These mixed reactions from users of the VR application regarding their experiences related to the aesthetics of the mini-games could be unconnected to the difficulties arising from the settings of the HMD lenses. Each player may require different adjustments to the HMD to experience an optimal virtual experience.

5.2. Theme 1.2: Interaction and representational fidelity

Interaction and representational fidelity are analogous. Whereas interaction in a VR application helps foster personalization through feedback, representational fidelity describes important features that allow for interactivity within the virtual environment. Regarding this study, participants commented on the features of VR mini-games that enhance their usability. Indeed, some of the participants felt that the inherent contextual sound in the virtual world contributed to their ability to interact with the game elements, including the challenges. Examples of some responses from the participants are shown in the following quotes:

> "Yeah! I think is a very interactive game, and the first impression was good because the ship in the beginning …" [P4]

> "It is basically interesting, and, but you need to follow the instruction and make the movement by arrow …" [P1]

> "Yeah! I think voice control, voice assistance is very good it makes it more interactive, you know, …" [P5]

RQ2. What are the users' experiences after playing the iThinkSmart mini-games?

Understanding users' experiences with an educational mini-game can be challenging, since they could develop diverse perceptions based on different factors. Therefore, this study addressed the second research question by aggregating the subthemes from the interview data, which are broadly classified into two categories: (i) the initial expectation and curiousness of the users, and (ii) the general perception of users.

5.3. Theme 2.1: Initial expectation and curiously of the users

The results revealed that some of the participants did not have prior experience of VR applications, whereas there were those who did not grasp the understanding of what thinking meant prior to the experiment. Some of the participant's responses are shown in the following quotes:

> "I don't really have much knowledge about computational thinking, but at least now I have a basic understanding of what computational thinking is." [P5]

> "… Now, I know what computation thinking meant and how it benefits people, so those were interesting to learn about, not only the definition of computational thinking one should know but also how it can benefit people." [P3]

Table 1
Players' computational thinking competency from playing the River Crossing mini-game.

Players (P)	Number of trials	Total score	Satisfactory score	Player's current score	Computed OD
P1	1	7	10	9	0.1
P2	2	7	10	11	−0.1
P3	1	7	10	7	1.0
P4	2	7	10	7	1.0
P5	3	7	10	7	1.0
P6	2	7	10	7	1.0

"When I first started the game, it was not quite easy but at some point, I realize it's making more sense … it makes me want to think more which if I have to play it like one more time, …" [P6].

"I already have played a similar game back … I did not give it much attention trying to take the melon away in the first time and of course, the dog eats the rabbit, …" [P4]

Notably, these findings from most of the participants provide insights into how novices, who are the targeted users of the iThinkSmart VR mini-games, would react when they use the application.

5.4. Theme 2.2: The general perception about the mini-games

Almost all the participants perceived that the mini-games contained educational content that could improve players' critical thinking skills and, yet, interesting. Further, the expedition experience (on ship and land) within the VR world was seen to create curiosity and arouse interest.

"A very fascinating game that will definitely improve the computational thought of any human being who actually wants to solve a real-world problem." [P1]

"It is a very interesting game, and one can actually develop computational thought." [P3]

"It is a very good game that, possibly not just for kids but for the adult as well." [P4]

"Yea, if I should rate let say from 0 to 10, I will say 6, because I don't really have much knowledge about computational thinking but at least now I have a basic understanding, …" [P5]

"I was on a ship, and it was not even related to anything educational, so I was already interested in the movement from the beginning." [P6]

RQ3. How are users' perceptions regarding the impact of iThinkSmart mini-games on their computational thinking skills?

The participants felt that the iThinkSmart mini-games contained educational content that could improve novices' knowledge of CT concepts. Some of the participants asserted that the mini-games posed some level of challenge, which caused them to improve on how they thought of solving problems presented within the mini-games.

"The fact that you have to read the question very well because they are very logical, they are very logical question, sometimes you have to use your idea to think around the stuff …" [P1]

"I found it so interesting, because without doubt, there no way you play this kind of game you will not improve with respect with the way you think, definitely it's going to speed up your IQ as to how you need to solve problems that have to do with everyday life, …" [P5]

For most of the participants, the challenges in the mini-game demonstrate good ways of visualizing CT that can enhance players' understanding of real-world problems that could be approached by applying the CT principle.

"My moves for the first time were wrong … my first attempt was thoughtless." [P4]

"… There is a lot of things one can actually pick from these games, developing the computational thought, …developing your reasoning skills, …" [P6]

5.5. Theme 3.1: Suggestions for future improvement

This study revealed many aspects of the VR expedition mini-games that would need improvement, which is a key finding from the pilot testing. Among other themes that participants felt could be improved include aesthetic aspects (sound and graphics), game elements, game challenge, navigation, and speed. Some participants felt that the level of challenge could be further improved to gradually progress from very simple to complex challenges.

"… I think some alternative should also be implemented may be a less difficult challenge for those people who are really challenged by the game, let say maybe an easier version …" [P3]

"but I feel probably there is a need to simplify things more than the way it is now … when I was playing the computational thinking game, I realized that as educative as the game was, there are still some things that are not so clear … especially when you want to recommend this kind of game for kids you need to look for a way to simplify things more and probably you need to give more information about how to achieve that aim not necessary being direct on this. (the main solution) but just giving a clearer view on what is expected of you." [P5]

Regarding the behaviors of some of the mini-games and the feedback or assessment of players, participants suggested that voice interaction can also be integrated into the games, such that instead of using the hand controller to respond to the game's interactive elements, players can use their voices.

"I think different types of games can be implemented, of cause, there are sounds in the game, the sound of birds, …you see some rock falling but the quiz themselves could be based on hearing or listening …

"I like that the sounds be more integrated into the game as well. I like that you could hear ocean waterfall and the bird. They could somehow be more integrated into the quizzes. I don't know how, but this is just a recommendation." [P3]

"We could have some kind of level of assessment, probably within our answer." [P6]

6. Discussion

This study presents an initial evaluation of educational VR mini-games to foster CT. The quantitative analysis of players' data retrieved during the gameplay by integrating a personalized learning assessment model (Chaichumpa & Temdee, 2018; Temdee, 2021) revealed how students practically gained CT competency from playing the mini-game. For example, our findings show that the majority of the players (3 out of 6) played the mini-game more than once to gain CT competency, and two players out of six played the mini-game once to obtain the best score. The implication from this finding is that repetition of gameplay provides the opportunity for learners to gain in-depth learning outcomes (Ebner & Holzinger, 2007), as in our case, players gained CT competency after they repeatedly played the mini-game. Likewise, the need to integrate assessment mechanisms into educational games to achieve a truly personalized learning experience has been proposed for more than a decade (Bellotti et al., 2013; Moreno-Ger et al., 2008). Therefore, this study experimented with the integration of the OD model to access players' learning outcomes using their direct playing logs. The integration of the assessment model into the mini-games is in line with Carr et al. (2022), who asserted that assessment during gameplay does not obstruct the player experience and that measuring the players' real-time performance without their knowledge is very effective and may reduce anxiety.

RQ1. How do users find iThinkSmart mini-games useable?

This study analyzed users' responses and first-level reactions to the usability and perceived experience of an educational VR application containing mini-games to facilitate CT skills. The participants found the VR mini-games interesting and engaging, as there was a combination of expedition experience and sets of challenges to be resolved in order to progress in the virtual world. The expedition experience of learners using immersive VR for a field trip has been reported to foster student learning attitudes toward science education (Cheng & Tsai, 2020).

Our findings, which align with a previous study by Cheng and Tsai (2020), revealed that the aspect of the VR expedition is an interesting part of the mini-game that motivates players. Research has shown that motivating learners within a technology-mediated learning environment can create a positive impact (Butgereit, 2016; Dias et al., 2019; Mei & Sheng, 2011), such that even when some of the challenges in the mini-games were not familiar to the players, they were motivated to think more and resolve the challenge. An example of an educational VR expedition application was developed by Google to allow learners to take a virtual field trip and learn in different contexts (Google Arts and Culture, n. d.).

RQ2. What are the users' experiences after playing the iThinkSmart mini-games?

The participants of this study agreed that the prototype developed for the VR application was useable. Users feel that the VR application is useable from the perspective of immersion and interaction. This finding is in tandem with previous research findings indicating that immersion and interaction are part of the characteristics of VR technology that can positively impact teaching and learning (Lan, 2020; Segura 2020; Ying, 2017; Hu et al., 2019; Jin, 2020). Although some of the participants were not familiar with playing VR mini-games or had not used any VR applications for learning, they were curious to know what was embedded in the virtual world and managed to interact with the mini-games and other interactive elements in the VR world. The curiosity of some of the players was even boosted, since they had to resolve a challenge before progressing to the next virtual sites for more expedition experience. While it is not evident whether the curiosity exhibited by some of the participants was a demonstration of novelty effects which may emanate from the excitement of being exposed to a new technology, our future (follow-up) study will explore this phenomenon as suggested by All et al. (2016). Moreover, research has shown that modeling educational challenges into mini-games is one way to arouse learners' critical thinking (Chaves et al., 2021), as demonstrated in the iThinkSmart VR mini-games.

In addition, this study also received a few comments from users suggesting areas where the iThinkSmart VR application and its mini-games could be enhanced to further support learners and improve users' experiences. The study revealed that some of the users desired voiced assisted instruction; that is, the instructions should also be given in audio form. In addition, the participants suggested graphic improvement to aid in the interactions between the users and the text instructions and other game objects. Further, an improvement in the way players' assessments and feedback are displayed during gameplay was suggested. The prototype of the VR application simultaneously monitors players' progress as they play the game, revealing poor, average, or high gains in CT skill competency.

RQ3. How are users' perceptions regarding the impact of iThinkSmart mini-games on their computational thinking skills?

The assessment of the educational impact that iThinkSmart expedition VR mini-games provides revealed that users could think, reflect, and apply their knowledge by providing solutions to the challenges demonstrated in the mini-games. Similarly, this study also shows that a basic understanding of the concepts of CT could enhance novice learners' ability to build problem-solving skills (Butgereit, 2016; Ratnadewi et al., 2018). Thus, GBL with appropriate challenges in interactive virtual learning environments has the potential of fostering students' problem-solving skills and learning achievements (Kim & Ke, 2017). Consequently, findings from users regarding the impact of the VR mini-games support the main aim of developing the iThinkSmart VR application, which is to allow students who are struggling with understanding programming concepts to gain problem-solving skills.

6.1. Study limitations

The main limitation of this study is the small number of participants recruited. Even though this is a pilot study, the analysis of users' reactions could have been more revealing if more participants were recruited. Thus, the results obtained in this study cannot be generalized but rather provide a direction for future study. This study used convenience sampling, which is a nonprobability sampling technique that has the possibility of making the study subjective in nature, and the findings cannot be generalized. Further, it is difficult to generalize findings from a study with a small sample size (Twining et al., 2017; Varoquaux, 2018).

Notwithstanding, it is important to evaluate an educational technology system as showcased in this study, even in a small user's group. Thus, study focused on essential topics such as VR, GBL, and human-computer interaction, as revealed by Chen et al. (2020). Thus, it is important to investigate this established but evolving field through a systematic approach to understand learners' reactions and learning process. As demonstrated in similar studies that utilized small samples (Asghar et al., 2019; Jin et al., 2020), the outcome of this evaluation could guide future improvement of the emerging learning technology, which can also lead to a summative evaluation.

7. Conclusion

This current study is a part of the research whose focus is to demonstrate how to facilitate CT in higher education by employing immersive VR technology to mediate teaching and learning through a game-based approach. The study employed a mixed research analysis of task-based semi-structured clinical interviews and participant instantaneous performance records, in which design researchers could deeply understand students' learning processes by using educational software (Clements & Battista, 2000). Understanding the effect of software on students' learning processes can inform designers and researchers on how to scale up the application. This study shows that VR mini-games provide an opportunity to engage learners in an immersive environment while solving different challenges to improve their CT skills and enjoying a contextual expedition within a virtual world. Although the focus was to investigate how users found the VR application useable, findings include feedback from players regarding educational benefits derived from the mini-games and what they felt could be improved in the prototyped VR application.

Study contributions and implications

This study contributes to the field of VR in education and educational technology in general. In particular, the empirical findings contribute significant knowledge on how a VR-based application can facilitate students' learning processes. The study also provides evidence that supports the affordances of VR in education. This study contributes to the design research theoretical framework, particularly the design science research that seeks to demonstrate how a user-centered study can be conducted to address an identified problem and impact users. Moreover, a design science research study requires a formative evaluation of a developed artifact to iteratively refine and improve the outcomes based on users' experiences. Therefore, we recommend that educational technologists and researchers consider qualitative and quantitative user-focused research as an additional step toward understanding the students' learning process when designing interventions to facilitate teaching and learning. Our findings suggest that the integration of learning assessment during gameplay could provide a better understanding of how educational games facilitate players' learning processes and achievements.

Statement on funding

Not applicable.

Statements on open data and ethics

The data generated and analyzed in the current study are available from the authors on reasonable request. In addition, this study conforms to the ethical principles and guidelines of the Finnish national board on research integrity regarding responsible conduct of research (RCR).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

List of Acronyms

virtual reality VR
head-mounted display HMD
three-dimensional 3D
computational thinking CT
VR educational platform VREX
VR environment VWorld
Mount Patti Treasure Hunt MoPaTH
objective distance OD
current score C*i*
instance of a gameplay *i*
the objective distance OD*i*
satisfactory score S*i*
Game-based learning GBL

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