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Article

Development and Usability Testing of a Virtual Reality Game for Learning Computational Thinking

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Abstract

Virtual reality (VR) is an innovative technology that immerses users within its environment, holding significant potential across various sectors, including education. Developing a VR-based application in the form of a game for educational purposes necessitates a usability evaluation. This study aims to develop and evaluate usability of a VR game, *CT Saber*, designed explicitly for learning computational thinking (CT). The name *CT Saber* is inspired by the popular VR game *Beat Saber*, with 'CT' denoting computational thinking to emphasize the educational focus of the game. The research employed a Design and Development Research (DDR) approach, encompassing four stages: *analysis & definition*, *design*, *development*, and *evaluation*. To assess the usability of *CT Saber*, pilot testing was carried out involving 36 participants (24 male, 12 female) of computer science students aged between 19-22 years. The USE Questionnaire framework was used to evaluate usability, consisting of four variables: *usefulness*, *ease of use*, *ease of learning*, and *satisfaction*. The evaluation revealed that *CT Saber* is categorized as 'acceptable' from dichotomous and conventional academic grading perspectives. Similarly, a multiple linear regression analysis confirmed that the independent variables (*usefulness*, *ease of use*, and *ease of learning*) together significantly ($p < 0.01$) influence the dependent variable (*satisfaction*). However, only *usefulness* significantly influences *satisfaction*. Responses to open-ended questions in the questionnaire also indicated predominantly positive feedback from most participants. Consequently, it can be concluded that the *CT Saber* VR game developed in this study successfully meets the established criteria for usability.

1. Introduction

Virtual reality (VR) is a computer technology that allows the simulation of artifacts and real-world environments into the digital world [1]. VR technology offers unique experiences that permit users to feel immersed in the simulated world [2]. The immersive experiences created by VR technologies transport the users to new worlds and make them feel as if they are truly present in the virtual environment [3]. Several elements contributing to the experiences are visual realism, spatial audio, user body tracking, haptic feedback system, natural interaction, free movement, and social interaction [4], [5], [6], [7], [8]. Visual realism can be generated through high-resolution displays like realistic lighting, textures, and visual effects to increase the sense of 3D objects' presence. The sense of touching a virtual object in the digital world can be provided by haptic feedback like the vibration of VR controllers. Meanwhile, interaction with multi-users in the VR environment can improve social interaction, like collaboration, sharing experiences, or even watching virtual live performance concerts [9].

VR technology can be utilized in various interdisciplinary fields like medical training [10], fire extinguisher training [11], fitness exercises [12], entertainment [13], and gaming [14]. In gaming, VR games are more effective at generating a state of flow among their players than non-VR games [15], [16]. *Flow* is a term used to describe an ideal psychological state where people are completely absorbed in a task and have high levels of focus, control, and enjoyment [15], [17]. *Flow* is also defined as a mental condition in which a person is completely absorbed in an activity with high enthusiasm and satisfaction [18],[19]. Although the terms *flow* and *immersion* frequently appear together in discussions of VR experiences, both are distinct. *Flow* is a psychological state characterized by complete absorption and focus in an activity, typically requiring a balance between the perceived challenges and the individual's skills [20]. Meanwhile, *immersion* refers to the sensory and perceptual envelopment achieved through VR technology, facilitating a sense of presence within a virtual environment [21]. The flow is obtained as the result of optimal user experience from enjoyment and effortless attention, while immersion is typically described as the objective and quantifiable attributes of a mediated environment. Compared to the computer desktop, VR produces a better game experience of flow and immersion [22].

One of the most popular VR games that make players flow and immerse is *Beat Saber*, a rhythm game that requires players to slash the beats which perfectly fit into the precisely handcrafted music provided. Provided features in this game are: (a) music rhythm matches to the slashing of lightsabers; (b) music and levels are drawn precisely by hand to improve the music experience; (c) support multiplayer; (d) easy to learn; and (e) support physical exercise while dancing and slashing the beats. The game was initially developed by a game company studio, *Beat Games*, then acquired by *Facebook* and integrated into *Oculus Studio* in 2019 [23]. According to the official website (https://beatsaber.com), this game achieved many awards, such as Best VR/AR Game 2019, best VR Game 2018, and immersive reality game of the Year 2018. As previously mentioned, *Beat Saber* employs music as the core of gameplay by letting the beat or rhythm combined with visual effects lead the actions players have to perform. Players have to slash the spawned objects by beating the sabers, and sometimes on several levels, they have to avoid obstacles or spawned objects that should not be slashed by physically moving the body or limbs. Therefore, the game forces the players to do physical activities, where the combination of both music and physical actions increases the interest and concentration of players, contributing to the flow or immersion [24].

VR has transcended beyond entertainment and gaming, emerging as a transformative technology across diverse domains. In education, VR is a powerful tool due to its ability to create immersive learning environments that facilitate active learning and even enhance learners' concentration through visualization and interaction [25], [26]. For instance, in medical training, VR allows students to perform virtual surgeries [27], offering a risk-free platform to practice and refine their skills before operating on actual patients. Similarly, in history education [28], VR can transport students back in time, providing a visceral experience of historical events that traditional textbooks cannot offer. The inherent interactivity and immersive nature of VR cater to various learning styles, significantly enhancing engagement and retention of information. Moreover, it aligns with the constructivist learning theory [29], which posits that learners construct knowledge best through experiences in realistic, contextrich environments. Therefore, VR's application in education is not merely fitting but also has the potential to revolutionize traditional pedagogical approaches by offering unparalleled experiential learning opportunities that are both scalable and customizable to individual learner needs.

Expanding on the transformative impact of VR technologies in educational frameworks, VR provides learners with a more immersive and interactive learning experience [30]. Even [31] stated that VR is one learning aid for the 21st century that allows users to retain more information and better apply what they have learned after using it. Therefore, VR will also become very suitable when used for learning 21st-century skills. One of the 21st-century skills that is becoming a concern today is computational thinking (CT) [32], [33]. Research trends on CT have also increased in recent decades [34], [35].

CT promotes a thinking way inspired by computer science (CS) problem-solving styles. CT is defined as thought processes involved in formulating problems and their solutions that are represented in a practical form to be tackled by an information-processing agent [36]. Even [37] stated that CT is not only for CS pupils but also a fundamental ability that should be understood by everyone outside CS learners, like reading, writing, and arithmetic. Children who learn CT may benefit from commonly applied CS principles, concepts, and approaches. Many studies also reported that infusing CT into the education curricula has been beneficial for students' cognitive and non-cognitive learning processes [38], [39], [40]. In the CS scope, CT is regarded as the core of topics like computing, programming, and problem-solving [33]. However, CT is not only about CS but also a combination of thinking abilities essential for solving complex problems, including theoretical or mathematical thinking, engineering thinking, and scientific thinking [41].

Inspired by one of the most successful VR games, *Beat Saber*, this study seeks to develop a VR game with similar mechanics in several cases but with different goals and features that may be used for learning CT, named *CT Saber*. The acronym CT on the *CT Saber* comes from computational thinking. Research on the usage of VR technology for learning CT still needs to be widely conducted, whereas research trends on CT show an increase [35] [34]. Recently, one research about learning CT using VR was conducted by [42], but the main focus of this study was to examine the relationship among (1) game elements like challenge, goal clarity, and feedback as a pedagogical approach; (2) VR features like immersion and interaction; and (3) perceived cognition of learners. They employed design science research (DSR) methodology as the approach and used the Unity game engine as the tool to develop the VR game. Three kinds of mini-games as the learning approach provided in the VR game apps are (1) River Crossing, (2) Mount Patti Treasure Hunt, and (3) Tower of Hanoi. However, the device used to deploy the game was VR Google Cardboard, a low-end VR technology [43].

One critical aspect to consider in the development of the VR game *CT Saber* is its usability and ability to fulfill users' requirements. Thus, evaluating the game to ascertain its usability and appropriateness for educational purposes becomes imperative [44]. Usability assessments aim to collect data on the system's usability by eliciting user feedback through various methods, such as field observations, questionnaires, interviews, focus groups, and standardized usability questionnaires. These diverse techniques for usability evaluation share the common goal of capturing users' perceptions regarding the interface to ultimately gauge user satisfaction.

The main objective of this research is to evaluate the usability of the developed VR game, *CT Saber*, for learning CT. The developed game application is deployed in a VR device with high-end technology, *Oculus Quest 2*, a head-mounted display (HMD) VR device with two external controllers that make it more interactive and immersive[45]. The game design and mechanics are also distinct from previous studies but have concepts similar to those of the most successful VR games, *Beat Saber*. Several features that make users learn CT by action were added, but they are also easy to play. It is important to note that while this study lays the groundwork for understanding how the game might facilitate learning, it does not directly measure the learning outcomes. Instead, it seeks to establish whether the game's design and interactive features meet the usability criteria necessary for an effective learning tool in the context of CT learning.

2. Methods and Material

This study aims to evaluate the usability of the developed VR game application, *CT saber*. The method used to reach the objectives is design and development research (DDR). DDR is described as the systematic study of design, development, and evaluation to establish an empirical foundation for creating instructional and non-instructional products and tools and new or improved models that govern their development [46], [47]. This method encompasses a broad spectrum of activities and interests that can be either: (1) the study of process and impact of specific design and development efforts or (2) the study of design and development process as a whole or particular process components [48]. The first type relates to the studies of the design and development of products and tools, while the second focuses on the design and development of models and processes rather than demonstration. This study employs the first one since the VR game product is developed as a learning tool. Figure 1 depicts the detailed stages of this study, consisting of analysis & definition, design, development, and evaluation. The approach model is developed based on previous research [49], [50].

2.1 Research Stages

2.1.1 Analysis & Define

The first stage is analysis, examination, and digging for information related to VR application developments. Once the analysis was completed, we decided and defined the requirements for the research. We analyzed several things: previous scientific research, VR devices, online courses, game engines, relevant games, and CT competitions like the *Bebras challenge*. Analyzing previous scientific research was needed since it can provide a baseline for comparison so that research gaps and novelty can be identified. Previous research provides a basis for knowledge and insights on this conducted research. The existing body of knowledge and other research can be understood by performing this. Several previous researches that we analyzed were about VR games for learning CT, *Beat Saber*, and related, such as [14], [15], [17], [23], [42], [51].

Afterward, we analyzed potential VR devices to understand their performances, requirements, and limitations. The VR devices considered in our analysis included the *Meta Quest 2* (formerly *Oculus Quest 2*), *HTC Vive*, and *PlayStation VR*. We ultimately selected the *Meta Quest 2* due to its high-end performance features, affordability, and wide availability of documentation and tutorials. This device was chosen since it provides features that contribute to the immersive experience, availability of documentation, and tutorials on the online course platforms.

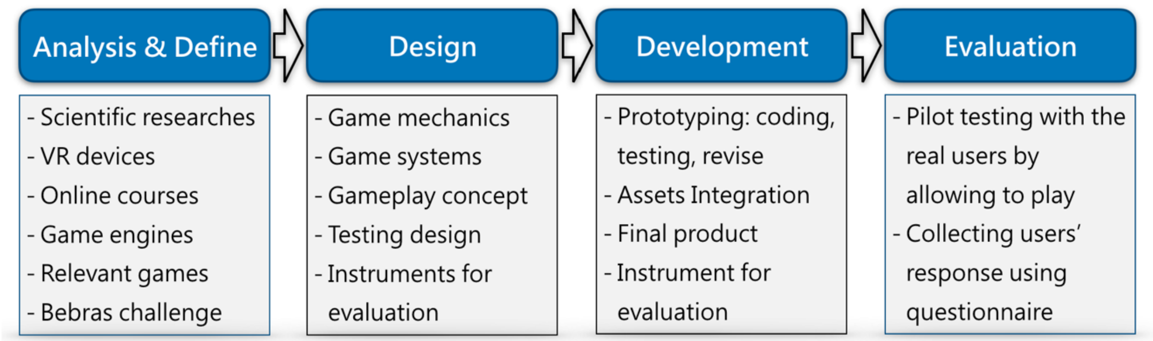


Figure 1. Research stages employed in this study

After defining the device, the next step was browsing tutorials on the online course platforms to boost the development. We selected *Udemy* as the online learning platform that offers various courses on various subjects, including programming, web development, photography, design, and VR game development. Before defining the most suitable course, we analyzed several potential courses by looking at the content material lists, number of students who joined, ratings, and comments from the other users. We chose the course with a rating of more than 4.3, which has a good reputation. The selected course entitled "*VR Development Fundamentals With Oculus Quest 2 And Unity*" was created by Tevfik Ufuk DEMİRBAŞ.

While browsing courses, we also analyzed the game engines used in the available courses. We eliminated the courses that did not use the *Unity* game engine. This is because, in addition to the many tutorials and documentation available on the internet, we also have fundamental knowledge of this game engine. Concurrently, an analysis of relevant games on the *Oculus Quest* app store was also carried out, such as the *Enhance VR*, and *Beat Saber* games. One of the criteria is the game is installed on the Oculus platform. We were amazed by one of the popular games built into the *Oculus Quest 2* platform, *Beat Saber*. Inspired by this game, an idea emerged to develop a similar VR game that is not only for entertainment but also for learning CT. To develop a VR game with content for learning CT, we analyzed many tasks and questions contested in the *Bebras Challenge*. This international CT competition aims to promote and enhance the problem-solving skills of students [52]. Then, choose several potential learning themes from the challenge before deciding on the most suitable one. We chose the theme based on the possibility that it can be integrated and combined with Beat Saber's gameplay. We decided that the learning theme included in the game for learning CT was about finding the best route in a maze space. This theme is similar to the shortest path algorithm so that the users can learn CT concepts with it.

2.1.2 Design

The second stage is design, activities to devise the game core such as mechanics, game systems, and gameplay. Designing game mechanics refers to conceptualizing, creating, and refining the rules, systems, and interactions. The design of mechanics is like *Beat Saber*, the player slashes the flying virtual cube toward them, but it is different. If gameplay in *Beat Saber* slashes the cube as much as possible to get the best score, the designed mechanics in this study are not only to slash a cube, but they have to define the best route by picking out the suitable arrow attached. More details about game mechanics and systems are explained in a separate sub-section.

Other activities in this stage are designing the strategies to test and evaluate the game and the instruments used for evaluation. The design for testing is essential to help detect and prevent bugs early before continuing to the next steps. It also improves the overall quality of the application and may enhance the user experience in learning CT by playing the game. For testing, we recruited volunteers from university students and designed the testing by allowing them to play the developed game application. Afterward, they fill out the questionnaires distributed to them. The designed questionnaires in this study were adapted from USE questionnaires that contain several statements [44], [53].

2.1.3 Development

The development stage is the actual creation of the game, including prototyping, integrating assets into the final product, and then developing instruments for evaluation. Prototyping refers to making a draft version or early shape that will be the final product of the VR game. It was based on the analysis and design stages conducted previously. We explored the ideas and features embedded into the application by coding, testing, and revising before deploying a project from Unity to the actual device, Oculus Quest 2. We also evaluated how well the coding is running when deployed to the device and whether it has been appropriate to the desire or needs improvement. Testing was carried out on the existing or additional features, whether acceptable or necessary to refine.

Before developing the prototype, we learned the basics of VR development from the online learning course bought from *Udemy*. It was also not only watching the videos in the course but also trying to comprehend new knowledge and information and then trying to code the scripts. Sometimes, it is even required to play and replay the course again to explore and conceive more details of the material contents. Although the course duration is short, the actual activities for it can be longer than the duration.

Prototyping and asset integration are two complementary activities. Assets were integrated into the prototype when adding new features, improving, or revising it. The assets are obtained from *Unity Assets Store*, for example, *Volumetric Lines*, a free GPU-based volumetric line renderer. It was used to create a lightsaber-like sword in a *Star Wars* movie and implemented as the lightsaber in the developed VR game. The assets are also created manually from the *Unity* editor and acquired from the online course provided by the tutor, with modifications as needed.

Both prototyping and asset integration were iteratively conducted until the final product was achieved. Hence, this stage is the longest compared to all the other stages conducted in this study. It is because this step involves not only learning from the course but also demonstrating the programming skills needed to develop a prototype into the final product that will be used for experiments with real users. Therefore, this step must be completed since the experiment can only be conducted after the final product of the VR game is established.

2.1.4 Evaluation

Evaluation is the final stage in this study to assess the performance and its quality to determine the strengths, weaknesses, and overall suitability to achieve the objectives. To evaluate the VR game that has been developed, we employed pilot testing. It involved real users as participants by allowing them to play the game. Afterwards, they were asked to provide feedback through a questionnaire adapted from the USE questionnaire to measure the usability of the developed VR game. They can also give comments and suggestions in the last section of the provided questionnaire based on their experiences while playing the game. Their feedback is essential since it can improve the quality and help get better results when conducting experiments.

2.2 Game Mechanics

Game mechanics are systems of interaction between a player and the game. Mechanics impact the play experience or, in other words: *what happens during play that affects the player* [54]. They define the actions players can take, the consequences of those actions, and the objectives players are attempting to attain. The mechanics of the VR game CT Saber in this study can be seen in Table 1.

When the game starts, and the player enters the arena, the system creates a map in front of the player. The map is represented in 8 x 5 tiles containing obstacles, rewards, and start and finish symbols. The first tile is located in the bottom left corner, arranged to the right by 8; then the 9th tile is located above the first tile, arranged to the right until the 16th tile, and so on until the 40th tile is located in the top right corner. Obstacles are generated in random map locations, and each level has different positions. Obstacles are depicted in the shape of cactuses and rocks. The game is over when the created route crosses an obstacle. The route can be created by slashing a cube having an arrow direction. The cubes and their direction are generated randomly by the system, then move toward the player so that they can be slashed. The direction defines where the route will be created from start to finish positions.

Table 1. Game mechanics of VR game *CT Saber*

Game Mechanics	More Explanation
The system creates a map	The game system creates a map that contains obstacles, a heart, start, and finish positions.
System generates cubes	The system generates cubes randomly that contains arrow with random direction.
The player makes a route	The game system allows players to make a route from start to finish position using an arrow stuck in a cube.
The player slashes a cube	Cubes that are randomly generated by the system can be slashed by players using lightsabers.
Scoring system	Players get a point when slashing a cube. The point system is designed by dividing the maximum score 100 with step total numbers from start and finish positions.
Double score system	Players get a double point when the route created passes through a heart symbol.
Game accomplished	The game is accomplished when a player makes a route from start to finish, then continues to the next level.
Leveling system	The game consists of six levels with different maps and obstacles on each level.
Timer system	The timer is set based on the audio clip length for the back sound.
Game over	The game is over in two conditions, time is over, or the route created by the player is crossing an obstacle.

The game is over when the direction crosses an obstacle, and the player has to replay until accomplished to continue to the next level. The game is accomplished when the map's route is created from start to finish positions. The player gets a point by slashing a cube and doubling if hitting a heart symbol. The point is obtained when the slashing amount is no more than the total steps of the best route. For example, when the best route can be reached in 7 steps, but the player steps more than seven means the point is no point and even minus. Therefore, a player has to notice their steps and think about avoiding them and getting the best score.

2.3 Participants

Participants involved in this pilot testing were 36 (24 males, 12 females) undergraduate computer science students aged between 19 and 22. They were in the second semester until the 8th semester, and they all learned programming starting from the first semester since it is a compulsory subject. They were surveyed to see if they had ever learned about CT and had experience using VR devices or something related. Related to learning CT, 26 students have ever learned CT (72%), while 10 students have never (28%). Related to experience using VR devices or related, 21 students have ever used a VR device or related (58%), while 15 students have never used it (42%). It means that most students have skills in operating VR devices, so their experience is beneficial to improving the quality. The participants are recruited voluntarily, and they can leave anytime if they feel uncomfortable with the research activities. They were explained about the research and purposes, why they were selected, the scope of participation, and their rights. After receiving and understanding all the information, they signed the consent form by selecting the agree or disagree options in the online recruitment form.

2.4 Testing Procedure

Participants gathered in a laboratory as scheduled to conduct the pilot testing and collect data from their feedback. Generally, the procedure for testing is depicted in Figure 2. Firstly, participants were informed about the general information of the research, objectives, testing stages and duration, and the consent form. Afterwards, the CT concepts and operational definitions were explained using a slideshow presentation completed with a video. The explanation contains an example of a case study about CT implementation in daily activities and core CT skills, such as decomposition, pattern recognition, abstraction, and algorithm design [55]. The emphasis is on these four CT skills: decomposition, pattern recognition, abstraction, and algorithm design [35], [55]. To support it, we informed the participants about how the developed VR game can be used for learning CT. Therefore, it will give them insights into the CT concepts and the skills integrated into the VR game, which enable them to answer questionnaire questions appropriately. Before continuing to the next step, they were confirmed if they understood what we had explained or needed to repeat.

The subsequent explanation is about the VR device, *Oculus Quest 2*, and how to use it. Afterwards, explain the game mechanics of *CT Saber*, covering the game goals, rules, challenges, how to play, and the possible experiences that will be obtained. Then, we explained the questionnaire with all the section parts, objectives, and how to fill it out. Before playing the game, they were confirmed to clarify that they understood. Participants were allowed to play *CT Saber* for 10-15 minutes each. We used 3 VR devices of *Oculus Quest 2*, and one of them was cast on the LCD projector. Hence, their activities in the VR game environment can be monitored, and we can give guidance when they face difficulties in operating the device and the game. We can also look at their actions while playing the game to inspect their behavior. Additionally, we can also see their game achievements to ensure that they accomplished the game goals. Lastly, they fill out the questionnaire to gather feedback after playing the game. Each participant needs at most 10 minutes to finish the distributed questionnaire.

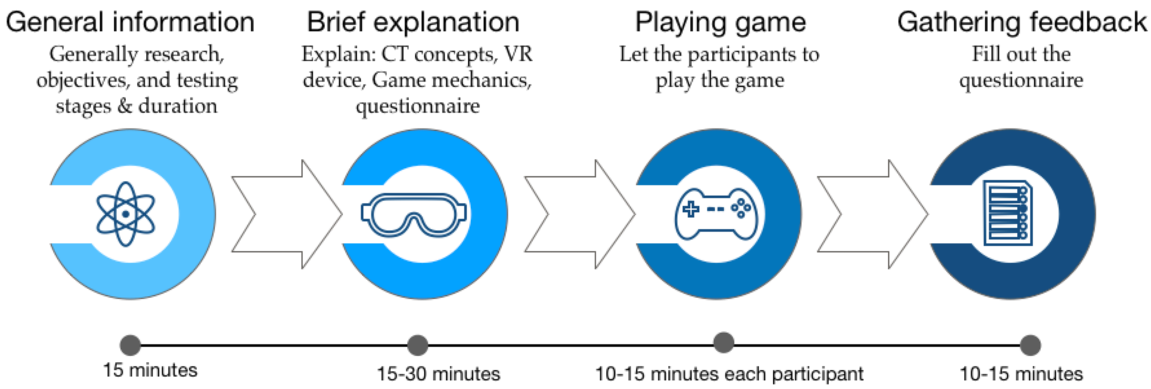


Figure 2. Testing procedure to the real users

2.5 Material Instruments

The instrument used in this pilot study is the USE questionnaire [44], [53], divided into three independent variables (usefulness, ease of use, and ease of learning) and one dependent variable (satisfaction), as depicted in Figure 3. It is strategically chosen to assess the usability of *CT Saber* for several reasons. First, its established validity and reliability make it a robust tool for evaluating key aspects of usability, such as ease of use, satisfaction, and learnability, which are critical for the initial assessment of educational VR games. Second, while acknowledging the significance of broader constructs like user experience, playing experience, flow, and immersion in the context of VR for education, the study aimed to prioritize the foundational aspect of usability. This focus was chosen due to the pilot nature of the study and the necessity to establish a baseline understanding of the game's practical application in educational settings. Future research is encouraged to incorporate additional validated questionnaires that comprehensively assess these broader constructs, to provide a more holistic evaluation of the educational VR game's effectiveness.

Before being used to collect data, the questionnaire is validated by three experts with backgrounds in CT knowledge, learning technology, and English. All the experts have experience of more than five years in their respective areas. Experts with a CT background assessed questions related to CT and the elements, while experts with a background in learning technology assessed the questions related to VR technology for learning.

Meanwhile, English expert assessed the questions adapted from the original version and the translation since the involved participants were using Bahasa Indonesia. All the three experts confirmed that the developed instruments were suitable for the study. However, they have several suggestions related to references, terms or phrases, and abbreviations in the questionnaire. The suggestions are more to the technical aspects of writing.

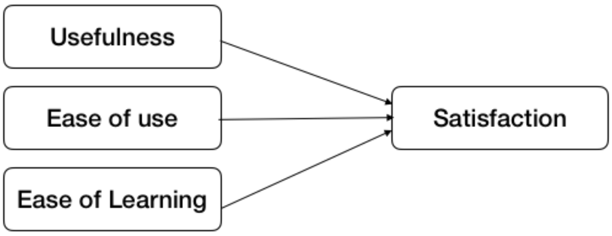


Figure 3. Conceptual framework of USE questionnaire [53], [56]

The questionnaire consists of three parts, they are (1) questions about brief identity like name, age, gender, and their experiences in learning CT, programming, and using VR devices; (2) 31 question items to measure usability that adapted from the USE questionnaire; and (3) one closed-ended question to find out whether participants feel dizzy and two open-ended questions to discover the experiences and comments after playing the VR game. The USE questionnaire to evaluate *CT Saber* is presented in Table 2. The options consist of a 4-point Likert scale that: 1 states "strongly disagree", 2 states "disagree", 3 states "agree", and 4 states "strongly agree". All the questions were constructed in positive wording format.

Table 2. Question lists adapted from the USE questionnaire [53].

Code	Statements	Code	Statements
	Usefulness		
U1	"CT Saber" helps me be more effective to foster CT skills	U5	"CT Saber" makes learning CT easier to get done
U2	“CT Saber" helps me be more productive to foster CT skills	U6	"CT Saber" saves me time when I play it to foster CT skills
U3	“CT Saber" is useful to foster CT skills	U7	"CT Saber" meets my needs to foster CT skills
U4	“CT Saber" gives me flexible control while playing it to learn CT	U8	"CT Saber" does everything I would expect it to do to foster CT skills
	Ease of use		
EOU1	"CT Saber" is easy to play	EOU7	I can play "CT Saber" without written instructions
EOU2	"CT Saber" is simple to play	EOU8	I don't notice any inconsistencies as I play "CT Saber"
EOU3	"CT Saber" is user friendly	EOU9	I can recover from mistakes quickly
EOU4	Learning CT with "CT Saber" does not require a lot of steps to accomplish	EOU10	I can recover from mistakes easily
EOU5	"CT Saber" is flexible to play	EOU11	I can play "CT Saber" successfully every time
EOU6	Playing "CT Saber" is effortless		

Code	Statements	Code	Statements
	Ease of learning		
EOL	I learned to play "CT Saber" quickly	EOL3	"CT Saber" is easy to learn to play
EOL2	I easily remember how to play "CT Saber"	EOL4	I quickly became skillful playing "CT Saber"
	Satisfaction		
S1	I am satisfied playing "CT Saber"	S5	"CT Saber" is wonderful
S2	I would recommend "CT Saber" to my friend	S6	I feel I need to have "CT Saber" for my own
S3	"CT Saber" is fun to play	S7	This VR game "CT Saber" is pleasant to play
S4	"CT Saber" works the way I want it to function	S8	Both occasional and regular users would like "CT Saber"

3. Final Product

The VR game name in this study is *CT Saber*, a game for learning CT. It was developed using the game engine *Unity* with editor version 2020.2.7f1. The software development kit (SDK) used was *Oculus Integration* version 34.0, released in November 2021, then updated regularly when the notification came up. The last update used before deploying to the actual device of *Oculus Quest 2* was version 40.0, released in May 2022. The SDK and its editor are running on MacOS *High Sierra* version 10.13.6.

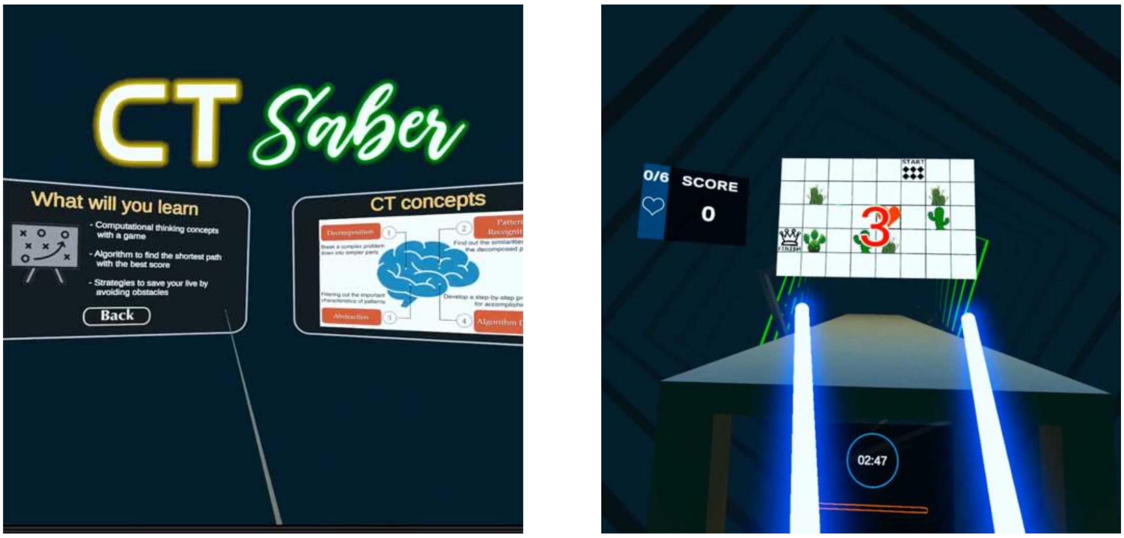
The game mechanics resemble the *Beat Saber*, slashing a cube that flies toward a player. However, the players *of CT Saber* are not only just slashing a cube, but also thinking about the best path that should be taken. The mission is to make the best route from start position to finish and avoid obstacles that appear on the map.

The game has two main scenes: the main menu and the arena. Figure 4(a) depicts the main menu scene when the *CT Saber* game is run. It consists of three menus; they are "*how to*", "*play*", and "*info*". When the "*how to*" menu is selected, the system shows information about how to play the game, quests and obstacles, and game levels, as seen in Figure 4(b). If the player presses the "*info*" menu, the system shows information about what they will learn with this game and general information about CT concepts, as depicted in Figure 5 (a). Testing results of the menu scene conducted by all participants showed that all features were running well.

(a) (b)

Figure 4. (a) Main menu of the game, (b) Screen in "*How to*" menu.

The second scene is the game arena. Figure 5 (b) displays the arena when the player enters it and selected the "*Play*" button. The player will see a map in front and a scoreboard on the side. The map is provided in the grid tiles hanging above the floor with white colors. Each tile can randomly emerge icons: cactuses and rocks to indicate obstacles, start and finish flags to indicate the route's beginning and last positions and a heart icon to make a double score. The start icon is located at the top two grids, and the finish icon is located at the bottom two grids. The icon positions of start, finish, and heart on the map are always generated differently in each game and level. Meanwhile, the obstacle icons have constant locations on each level, but each level has a different map, and this game has six levels. Therefore, every single player will have different start and finish positions that determine the route that will be made. These are other features available in the game, and each player undergoes different experiences.

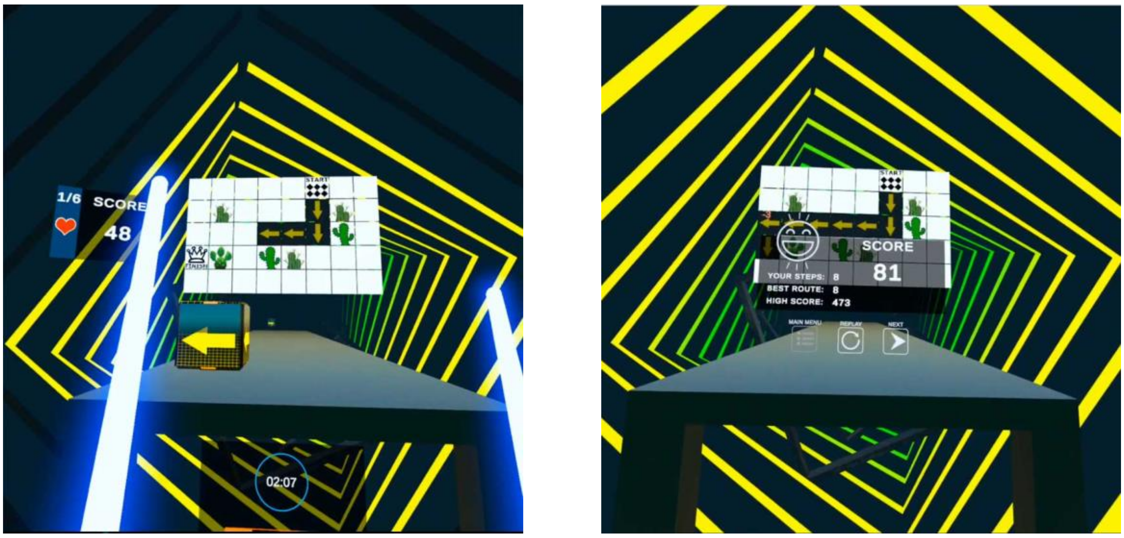


(a) (b)

Figure 5. (a) Screen in Info menu, (b) Game arena for playing the game.

Before the player starts to play, a countdown is run from number 3 to number 1 to indicate that the game will be started soon. Hence, the player can prepare himself, thinking and planning the route that will be made. As mentioned, the mission is to define the best route from the start position lead to the finish. The route can be constructed by slashing a cube that has arrow direction with lightsabers. The challenge is that players must think about creating the best route and avoiding obstacles. Even they will also be thinking about how to get a heart icon to double the score displayed on the left side of the map. They must also notice the timer since the game will be over if the time is up and the route is not created. These are other features provided in the developed VR game.

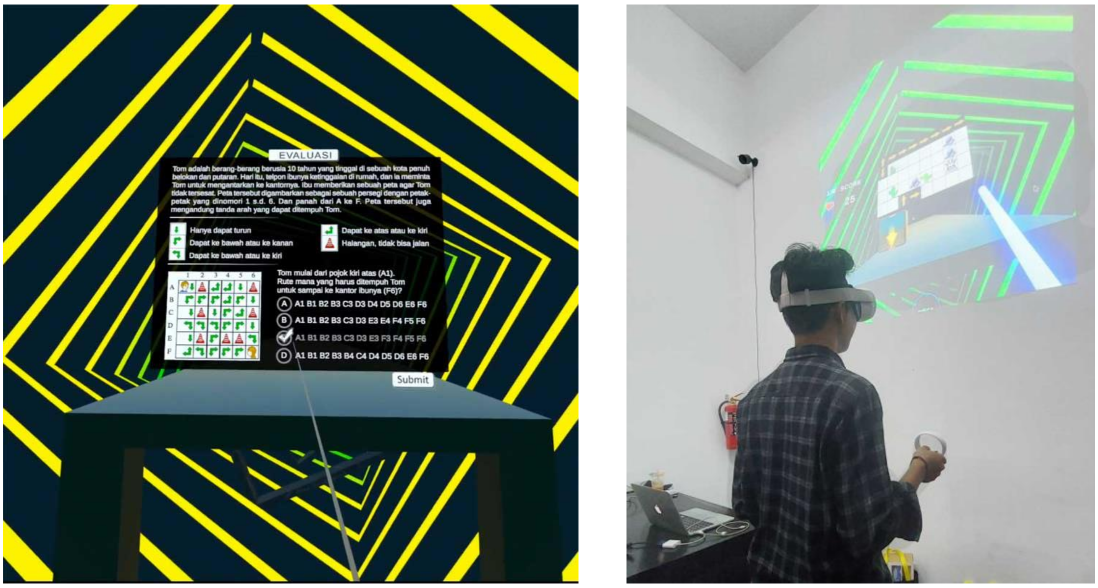
The game system shows a pop-up menu when the player accomplishes the mission, as seen in Figure 6 (b). The pop-up menu contains a recapitulation of the obtained score at this level, the number of steps, the best route amount, and the highest score that has ever been obtained. A smile icon is displayed to indicate happiness when completing the game. Meanwhile, a sad icon is displayed if the player fails to accomplish a mission. The pop-up menu also contains three active buttons; they are (1) the Main menu button for going back to the main menu, (2) the Replay button to replay the game at the same level, and (3) the Next button to continue the next level with different obstacles and map. However, if the players fail to accomplish the mission, the Next button will not appear. It indicates that the player should complete the challenge at this level before continuing to the next level. These are other available features in this developed game. Based on the testing results conducted by the participants, these features were also running well.



(a) (b)

Figure 6. (a) A route created by the player by slashing the flying cube, (b) Game accomplished.

Among the six levels available in the game, two quizzes are adapted from *Bebras Challenge*. They can be met in level 2 and level 4 after accomplishing the game. The challenge is used to measure the CT skills of the players. Figure 7 (a) shows a challenge containing a description, clues, questions, and options the player can choose. Once the player selects the option, the submit button can be pressed to answer the challenge. The game system will confirm the answer by showing a pop-up menu before the answer is really sent. Therefore, the player can check it back or continue the submission. These are other features available in this *CT Saber*. All the features were tested by the participants while conducting the pilot testing. Figure 7 (b) shows a participant who is playing the *CT Saber* using *Oculus Quest 2* equipped with two controllers. The game environment is cast to a projector screen so others outside the environment can see the player's activities.



(a) (b)

Figure 7. (a) Quiz adapted from *Bebras Challenge*, (b) The participant playing *CT Saber*.

Generally, the game features for testing can be summarized into 15 parts and categorized into three scenes, as shown in Table 3. Among the 3 VR devices all 36 participants were using, all the available features successfully ran when the action was triggered. Therefore, feedback and participant responses can be collected using the questionnaire that has been developed.

Table 3. Test results among 3 VR devices used by 36 participants

No.	Scenes	Game features	Results	
			Devices	Participants
1	Opening	Warning pop up menu	3/3	36/36
2	Main menu	How to menu	3/3	36/36
3		Info menu	3/3	36/36
4		Play menu	3/3	36/36
5	Game arena	Creating a grid map	3/3	36/36
6		Making a random obstacles and heart icon in the grid map	3/3	36/36
7		Creating a scoreboard to display information of scores and heart icons obtained	3/3	36/36
8		Running countdown from number 3 to 1 before game is started	3/3	36/36
9		Generating cubes with random arrow direction	3/3	36/36
10		Creating a direction in the grid map based on the arrow in the cube slashed by the player	3/3	36/36
11		Adding a score when the cube is slashed and timer is not over	3/3	36/36
12		Giving a double score when the player hitting a heart icon	3/3	36/36
13		Running game over when the player is slashing an obstacle	3/3	36/36
14		Showing up recap when the game is over or accomplished	3/3	36/36
15		Continue to the next level when the game is accomplished	3/3	36/36

4. Results

To evaluate the usability of the developed VR game, a pilot testing was conducted involving 36 computer science students as the participants. They were asked to play the CT Saber game to test all of the functionality and features. They were allowed to explore all of the scenes provided in the game, starting from the warning menu, entering the main menu, and playing the actual game in the scene arena. The warning menu appears firstly to inform the users about potential adverse effects while playing the game, namely motion sickness or dizziness. They can report when they undergo it, stop playing, and quit the game to avoid the worst impact. The good thing is, there is no participant who stop to play and leave the experiment.

All the participants completed all levels provided in the game, which means that the game and its environment are safe, and the experiment can be carried out with more participants. However, one participant stated that he felt little dizzy when filling out the questionnaire distributed in the last section, even though his dizziness did not interfere with the game he was playing.

4.1 Reliability and Validity Testing

The collected data is analyzed using SPSS Statistics software version 23. Figure 8 shows the reliability testing and indicates a robust internal consistency across the measures of the USE questionnaire, which encompasses four dimensions: Usefulness (U), Ease of Use (EOU), Ease of Learning (EOL), and Satisfaction (S). Each item within these dimensions, coded as U1, U2, ..., EOU1, EOU2, ..., EOL1, EOL2, ..., S1, S2, ..., was subjected to Pearson correlation to assess inter-item consistency. The results show high correlation coefficients, well above the critical value of 0.329 for a significance level of 0.05, suggesting that the items are coherent and reliably measure the constructs of interest. For instance, items within the Usefulness construct (U1-U8) are correlated to ensure that they collectively represent the construct, with similar processes applied to the EOU, EOL, and Satisfaction constructs. Specifically, the Satisfaction items (S1-S8) were correlated with the Satisfaction construct, affirming that participants' responses consistently reflected their satisfaction with the VR learning game. These high coefficients thus confirm the questionnaire's reliability in capturing users' perceptions of the usability aspects of the VR learning environment, underscoring the instrument's validity for further analysis of user satisfaction in the context of VR for educational purposes.

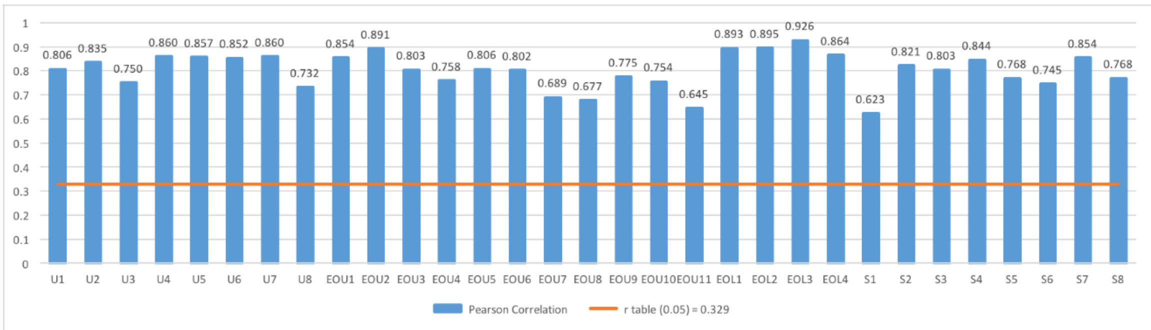


Figure 8. Validity testing results

Table 4 shows the reliability test results of all variables based on the framework depicted in Figure 3. It can be seen that all of the construct items (usefulness, ease of use, ease of learning, and satisfaction) are reliable based on *Cronbach'*s alpha score, which is higher than 0.7 [44], [57]. Even, the reliability test score of all variables is more than 0.90 which refers to the perfect reliability. Therefore, it can be concluded that all the construct variables are acceptable.

Table 4. Reliability test results

No.	Variables	Cronbach's alpha	N of Items
1	Usefulness	0.930	8
2	Ease of Use	0.931	11
3	Ease of Learning	0.915	4
4	Satisfaction	0.900	8

4.2 Usability Measurement Score

One way to describe the result of usability measurement is by the mean score of each variable used [56], [58]. Table 5 provides the mean score of each variable: usefulness, ease of use, ease of learning, and satisfaction, namely 3.20, 3.20, 3.37, and 3.14, respectively, on a four-point Likert scale. The classification of mean scores into acceptable or unacceptable categories follows a dichotomous approach, reflecting the directionality of participants' responses. Scores that lean towards the higher end of the Likert scale, specifically 'agree' (3) or 'strongly agree' (4), indicate a favorable evaluation of the VR system's aspects and are thus deemed acceptable. Conversely, lower scores representing 'disagree' (2) or 'strongly disagree' (1) suggest that the system does not meet user expectations, categorizing the evaluation as unacceptable. This binary interpretation, as applied by [59], streamlines the Likert scale into a 'binomial data' format by classifying scores into acceptance or rejection categories based on participant consensus. In this vein, our study's Likert-derived mean scores for 'Usefulness', 'Ease of Use', 'Ease of Learning', and 'Satisfaction' correspond to the percentages of 80.12, 79.92, 84.20, and 78.56, respectively, on a standardized 0-100 scale. According to the threshold defined by [60], a score above 50 is considered satisfactory; thus, our findings, which exceed this benchmark, affirm the system's usability across all measured dimensions.

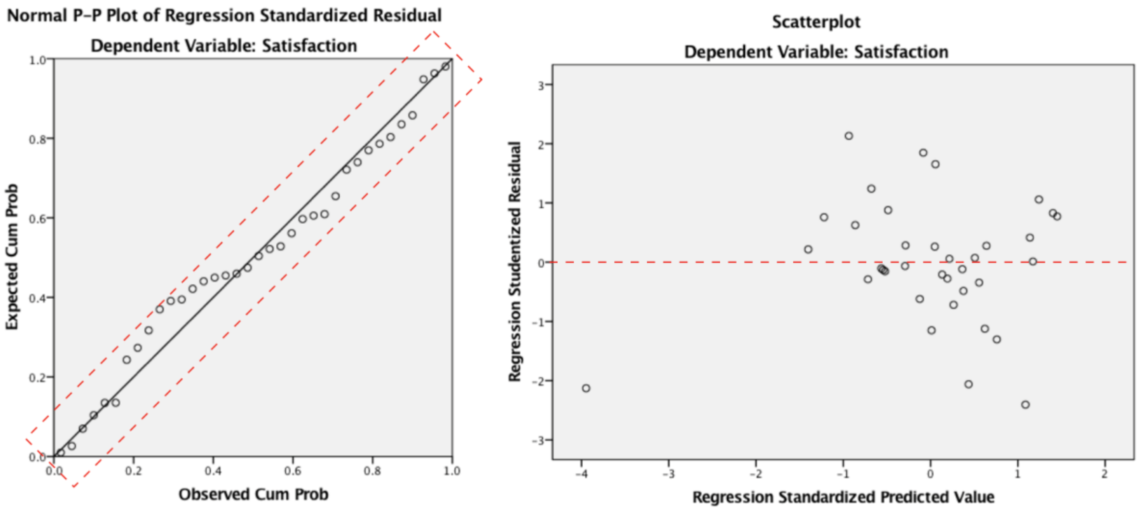
Table 5. Mean score and 0-100 score

No.	Variables	Mean score	0-100 score
1	Usefulness	3.20	80.12
2	Ease of Use	3.20	79.92
3	Ease of Learning	3.37	84.20
4	Satisfaction	3.14	78.56

4.3 Multiple Linear Regression

Analysis of the relationship between two or more independent variables and a single dependent variable, as depicted in Figure 3, was carried out using multiple linear regression testing. This model should meet normality assumptions and be free from classical multicollinearity, heteroscedasticity, and autocorrelation assumptions. Figure 9 (a) depicts the results of the normality test to show the data distribution. It can be seen that the points of the data follow a straight line, so it indicates that the residual is a normal distribution. Multicollinearity test results are shown in Table 6. Multicollinearity is not found when the tolerance data of each independent variable is more significant than 0.1 and the variable inflation factor (VIF) is below 10. It can be shown that the tolerance score of all independent variables is more significant than 0.1, and the VIF score is below 10. Therefore, all independent variables are free of multicollinearity, or no correlation exists among each variable.

Figure 9 (b) shows the scatterplot of residual data from the heteroscedasticity test. It can be noticed that the residuals have no specific pattern and are randomly scattered above and below 0 on the y-axis. The *Breusch-Pagan* test was conducted to confirm it, and the results are provided in Table 6, column '*Breusch-Pagan's Sig.*'. All the scores of *Breusch-Pagan's Sig.* are more than 0.05 (p >0.05). Therefore, it can be stated that there is no heteroscedasticity in the regression model, and it meets the criteria of the classical assumption test.



(a) (b)

Figure 9. (a) Normality test data plot, (b) Heteroscedasticity test scatterplot.

Multiple linear regression tests can be performed once the normality test and classical assumptions are met. Table 6 displays the test results of multiple linear regression, which show the *Sig*. value of each variable, namely usefulness (p = 0.001), ease of use (p = 0.190), and ease of learning (p = 0.371). The detailed analysis of the coefficients clearly shows that usefulness presents as the only significant influence on satisfaction. The *standardized coefficients*, or *Beta* values, highlight the relative strength of each predictor in the model, with usefulness exhibiting the strongest relationship with Satisfaction (*Beta* = 0.499). Based on the *F* test shown in Table 7, it can be stated that together, the three independent variables (*usefulness*, *ease of use*, and *ease of learning*) significantly influence the dependent variable (*satisfaction*) due to the *Sig*. value being less than 0.05 ($p < 0.05$).

Table 6. Test results of multicollinearity and multiple linear regression.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			Breusch-Pagan's	Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Sig.	Tolerance	VIF
1	(Constant)	5.361	3.045		1.761	.088	.381		
	Usefulness	.434	.123	.499	3.520	.001	.656	.645	1.550
	Ease of Use	.159	.119	.252	1.338	.190	.681	.366	2.733
	Ease of Learning	.227	.250	.147	.907	.371	.864	.491	2.035

a. Dependent Variable: Satisfaction

Table 7. Results of *F* test.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	365.932	3	121.977	17.433	.000[b]
	Residual	132.938	19	6.997		
	Total	498.870	22			

a. Dependent Variable: Satisfaction
b. Predictors: (Constant), Ease of Learning, Usefulness, Ease of Use

4.4 Open-ended Feedback of Participants

In the last section of the questionnaire, participants were prompted with open-ended questions to elicit user feedback regarding their engagement with the CT Saber game. These questions were: "*Describe a unique (interesting) experience you had while playing the CT Saber game*" and "*Provide comments regarding the activities of playing & learning CT that you did through the CT Saber game*". This qualitative approach allowed participants to express their perspectives and insights, offering a nuanced understanding of the game's impact on learning computational thinking. These open-ended questions are instrumental in capturing the richness of the user experience, going beyond quantitative metrics to reveal personal narratives and subjective responses that could offer valuable directions for future refinements of the educational tool. Table 8 shows several experiences and comments written by the participants.

Data gathered from participants indicates that the use of the VR game, specifically CT Saber, provides a distinctive and engaging experience that not only fosters the development of CT but also presents an interactive and enjoyable way of learning. Many participants highlighted the game's realism, although some experienced challenges with visual clarity, potentially due to technical issues or limitations of the VR device.

The game's use of a sword to navigate mathematical challenges and solve problems within a dynamic environment illustrates how gameplay elements can be integrated into learning activities. These challenges are designed to reflect questions found in standard tests like UTBK, requiring critical thinking and problem-solving strategies from the players. A significant aspect of this game is its ability to immerse players in a deep thinking process, often necessitating time to contemplate and arrive at the correct solution.

Table 8. Experiences and comments written by the participants

No.	Question No. 1: Describe a unique (interesting) experience you had while playing the CT Saber game	Question No. 2: Provide comments regarding the activities of playing & learning CT that you did through the CT Saber game
1	*The game looks realistic, although the display is a bit blurry*	*Learning is solving problems, such as in the UTBK test, there are questions that take a long time to think about the answer. For games, you can solve the fastest way to the finish*
2	*I feel that I am playing while learning in a more real way*	*CT saber is a good solution to foster computational thinking in lay people*
3	*A unique experience in the form of playing with swords to complete a step to the finish line. After completing this there is also a challenge that is similar but more mathematical*	*In terms of activity, it may be similar to Beat Saber in its use, where it is more flexible in operation, and the blocks that can be hit are not too far from the player. Meanwhile, from studying CT, we have to be able to think quickly to select which ones to hit and which way to go.*
4	*Can experience playing games realistically*	*It's fun and it's better to add several other complementary features to increase the level.*
5	*Because I have nearsightedness, the picture is a little unclear*	*The activities or activities of the game are good and interesting. Makes players more interactive and able to think critically*
6	*Very unique game, great for introducing VR to students*	*A fun game to try and learn to hone critical thinking*
7	*The stick vibrated when it touched*	*It's fun and very interactive*
8	*I can feel as if I have entered the game.*	*Cool, unique, and very satisfying*

Participants also noted that CT Saber serves as an effective solution for nurturing computational thinking, especially among individuals new to the concept. Activities requiring participants to think critically and interact with elements in the game have the potential to enhance their ability to understand and apply computational thinking principles in various scenarios.

Despite some participants expressing satisfaction with a fulfilling and visually comfortable gaming experience, others pointed out potential areas for improvement. For instance, the addition of complementary features to increase the level of difficulty and variety of activities, as well as enhancements to audiovisual elements, could further support immersion in the game. This feedback indicates room for further innovation and adjustments in the game design to facilitate effective learning.

5. Discussion

This study aims to develop a VR game for learning CT and evaluate its usability. The developed VR game is named *CT Saber*, inspired by one of the most successful VR games on the *Oculus* platform, *Beat Saber*. All the designed game features successfully ran on three devices of *Oculus Quest 2*. It means that all the functional game is running well according to the game mechanics that have been design. The USE Questionnaire framework was adapted to evaluate usability, and a pilot test was conducted with computer science students. Variables measured are usefulness, ease of use, ease of learning, and satisfaction.

The results showed that the adapted USE Questionnaire was a valid and reliable instrument for evaluating the developed VR game, *CT Saber*. This is evidenced by the validity test, which confirmed that each item within the questionnaire met the criteria. Additionally, the reliability indices for all variables encompassed by the questionnaire surpassed the established baseline.

These results are congruent with numerous scholarly inquiries aimed at appraising the usability of pedagogical applications [53], [56], [61].

The development of this CT Saber VR game was included within the software engineering framework, so it is necessary to ensure that all game functions run smoothly and without errors. Errors checking was conducted based on the developed features as described in Table 3. The systematic examination of the game features demonstrates that each functionality performed optimally when tested by 36 participants in the three distinct *Oculus Quest 2* devices. This comprehensive validation is a testament to the robustness of the game's architecture, wherein all incorporated features were observed to operate seamlessly, affirming the game's operational integrity. The absence of functional discrepancies during these trials underscores the meticulous development process and the reliability of *CT Saber* as a viable educational tool within a virtual reality environment.

Quantitative assessments were conducted utilizing the Likert-scale-based USE Questionnaire to appraise the usability of the CT Saber VR game. Data analysis revealed that each variable secured a substantial rating. Hariyanto et al. (2020) [56] stated that the evaluation can be seen from binary rationale [62], the "binomial data" method [63], and the conventional academic grading system [60]. Based on these, the results were categorized as accepted due to the mean scores of all variables more than 3. The aggregate score across the four assessed usability dimensions attained a commendable 80.70 out of a potential 100, surpassing the established usability benchmark [60]. This indicates that the CT Saber VR game met and exceeded the threshold for acceptable usability, reflecting user satisfaction with the overall interactive educational experience provided by CT Saber.

Furthermore, a multiple linear regression analysis was conducted to explore the interrelationships among the variables included in the survey. All model assumptions met the standard prerequisite criteria before the regression test was performed. Based on the F-test results show that simultaneously, all independent variables (usefulness, ease of use, and ease of learning) significantly influence the dependent variable (satisfaction). This suggests that these three facets are interrelated and have a substantial and simultaneous impact on how satisfied users feel about their experience.

In terms of usability, this signifies that the dimensions defined in the USE Questionnaire effectively predict and explain the variance in user satisfaction. The high mean square value relative to the residual mean square further reinforces the explanatory power of the regression model. This implies that a significant proportion of the total variability in satisfaction scores can be attributed to variations in the independent variables, confirming the aptitude of these usability constructs for capturing user satisfaction in educational VR applications.

However, when dissecting the individual contributions of the independent variables, it emerges that only usefulness significantly influences satisfaction when evaluated partially. Meanwhile, ease of use and ease of learning aspects do not show significance. This finding indicates that the functional utility of the VR game CT Saber is paramount in the users' evaluative process, underscoring usefulness as the cornerstone upon which user satisfaction is built.

One of the reasons why usefulness may outshine other factors is its impact on satisfaction can be attributed to the novelty of VR technology in educational environments. Users place a premium on the practical benefits of novel technology as they navigate the initial learning curve to secondary considerations until the fundamental utility criterion is satisfied. It is also plausible that once a user deems the VR helpful tool, they are more willing to invest effort in overcoming any usability challenges. This could explain the diminished perceived impact of ease of use and ease of learning on overall satisfaction.

To enhance the usability of VR games that feature embodied interactions similar to *Beat Saber*, several key design recommendations can be made based on the development and evaluation of *CT Saber*. Firstly, intuitive controls and immediate feedback are paramount [64].

This can be achieved through the use of haptic feedback and clear visual cues that guide player actions and provide instant confirmation of their success or errors [65]. Clear objectives and a well-defined progression path are also essential. Players should understand their goals at all times, and the game should offer a smooth difficulty curve that allows them to build skills progressively. Additionally, ensuring an immersive and engaging environment through high-quality visuals, spatial audio, and realistic interactions can significantly enhance user experience [66], [67]. Finally, accessibility and comfort must be prioritized by including adjustable settings for visual and control preferences, thereby accommodating a wider range of player needs and reducing potential discomfort during extended play sessions.

These suggestions are supported by comparative analyses with other VR saber games, such as *Fruit Ninja* VR version and *Synth Riders*. *Fruit Ninja*, which requires players to slice fruits with precise hand movements, emphasizes the importance of intuitive controls and immediate feedback, similar to *Beat Saber*. *Synth Riders*, on the other hand, focuses on freestyle hand movements synchronized with musical beats, highlighting the significance of clear objectives and immersive environments. Both games demonstrate how usability can be enhanced through balanced challenges and engaging gameplay, reinforcing the findings from *CT Saber*'s usability testing. By integrating these design elements, VR games can offer more effective and enjoyable experiences, extending beyond the single focus of evaluating the CT Saber test to a broader application in educational and entertainment contexts.

The empirical evidence gathered from user comments provides substantial support for the primacy of usefulness in shaping user satisfaction with the VR game *CT Saber*. Participant feedback consistently highlights the practical value and applicability of the game in facilitating CT, reflecting a direct correlation with the quantitative findings that underscore usefulness as a critical determinant of satisfaction. Users expressed a sense of achievement and engagement when the game successfully bridged the gap between virtual activities and the acquisition of computational skills, affirming the practical benefits of the game's design.

The qualitative data from open-ended responses reveal that when users perceive the game to be beneficial for learning, particularly in developing and applying computational strategies, their satisfaction levels are notably higher. It can be seen from the feedback provided by participants, who frequently stated in the comments that the interactive and engaging nature of the CT Saber game helped them better understand and apply CT concepts. For instance, many participants noted that the game's tasks, such as finding the best route, directly mirrored problem-solving activities they encountered in their academic studies. This alignment between the game's challenges and real-world applications made the learning experience more relevant and practical, thereby enhancing their overall satisfaction. Additionally, participants appreciated the immediate feedback and rewards within the game, which reinforced their learning and contributed to a sense of accomplishment and engagement. These aspects highlight the importance of perceived educational value in determining user satisfaction with educational VR games.

6. Conclusion and Limitations

Based on the results and discussion, it can be concluded that the developed VR game *CT Saber* meets the usability criteria as evident from the tripartite assessment conducted. Firstly, the mean scores of the four usability variables (*usefulness*, *ease of use*, *ease of learning*, and *satisfaction*) stood at an average of 3.23. Using a dichotomous approach to the 4-point Likert scale, these scores lean towards the acceptable category, indicating a favorable user perception. Secondly, the multiple linear regression analysis using the USE Questionnaire framework demonstrated that, simultaneously, all independent variables (*usefulness*, *ease of use*, and *ease of learning*) significantly influence the dependent variable of *satisfaction*. However, a closer inspection reveals that, partially, only the aspect of usefulness exerts a significant influence on satisfaction. This underscores the paramount importance of perceived utility in users' overall satisfaction with the VR experience. Thirdly, the responses to open-ended questions from participants echoed this sentiment, with feedback overwhelmingly supporting the utility of *CT Saber* in providing an engaging and effective learning experience. Together, these assessments suggest that the developed VR game *CT Saber* shows the principles of usability, which is pivotal for educational technology acceptance and efficacy.

This study has underscored several key principles for enhancing the usability of VR learning games, particularly those with embodied interactions like *CT Saber*. One significant lesson learned is the critical role of intuitive controls and immediate feedback in maintaining user engagement and facilitating effective learning. For instance, *Fruit Ninja* VR, which also relies on precise hand movements, highlights the importance of responsive controls and clear visual feedback. Similarly, *Synth Riders* emphasizes the need for immersive environments and rhythmic interaction to keep players engaged. However, *CT Saber* stands out by seamlessly combining educational content with gameplay mechanics that directly reinforce CT skills. This targeted approach to learning makes *CT Saber* a valuable tool for educational purposes beyond the general entertainment focus seen in *Fruit Ninja* VR and *Synth Riders*. It is essential to ensure that VR learning games have intuitive controls, clear objectives, and immersive environments. These elements collectively enhance the educational impact and user satisfaction, providing a robust framework for the development of future VR educational tools.

While this study provides valuable insights into the usability of the *CT Saber* VR game for learning CT, several limitations should be acknowledged. Firstly, the sample size was relatively small and consisted predominantly of computer science students, which may limit the generalizability of the findings to a broader population. Future studies should involve a more diverse group of participants to enhance the external validity of the results. Secondly, although the usability of the game was thoroughly evaluated using the USE Questionnaire framework, cognitive load assessment was not included in this study. Given that embodied/reality-based interaction in VR can significantly affect mental workload, future research should integrate cognitive load measurement better to understand its impact on learning efficiency in CT [68]. This consideration is particularly important for optimizing the educational effectiveness of VR games like *CT Saber*.

Finally, the study duration was limited, restricting the depth of participant interaction with the game. Extending the study period in future research could provide more comprehensive insights into the long-term usability and learning outcomes of the game. Although the promise of VR gaming for CT learning is evident, the depth of its impact has yet to be thoroughly explored. Our future research plans include an investigation into the longer-term educational impacts of VR gaming on CT abilities, with a particular focus on factors associated with VR's strengths in immersion and presence. These unique attributes of VR technology could significantly enhance the learning process, and understanding their effects is essential for optimizing VR's instructional potential. Addressing these limitations in subsequent studies will help refine the design and implementation of VR-based educational tools, contributing to their overall efficacy and adoption.

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Conflicts of interest

No potential conflict of interest was reported by the author(s).

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