Design and Development of a VR Serious Game for Chemical Laboratory Safety

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Abstract. Virtual reality (VR) technologies are becoming more and more popular, not only as a gaming console, but also as a viable training tool. Especially for health and safety training programmes, VR can be very useful to train people in dangerous environments and situations without imposing real danger on them or others. Chemical laboratories are environments where risks of severe injury or even fatality are always present. For this, we developed a VR serious game, called VR LaboSafe Game, as a tool for laboratory safety training. However, designing a VR serious game is a challenging task. There are many factors to consider for an optimal game design. In this study, we discuss important design considerations and we present the game design of VR LaboSafe Game. Preliminary tests of an early version of the game show usability issues and minor discomforting symptoms for some participants. Nevertheless, participants do agree that VR LaboSafe Game is useful for learning laboratory safety; is more active and responsive in their learning process and makes safety training more engaging.

Keywords: Virtual reality · Laboratory safety · Serious games · Game design

1 Introduction

Training interventions on the topic of Health, Safety and Environment (HSE) are of major importance for any workplace where hazardous chemicals are involved. This holds especially true for chemical laboratories in academia and industry. Insufficient safety training could lead to a lack of safety awareness and at-risk behaviour, which then increases the risk of causing accidents in chemical laboratories [1].

Current safety training interventions are commonly provided using traditional teaching methods, such as classroom lectures, videos and printed safety manuals. However, they are considered as low engaging teaching methods as the trainee is required to passively listen to the instructor [2]. As such, low engagement can lead to boredom and diminished attention to the learning content, thus making the training less effective [3].

Researchers and HSE experts agree that there is a need for learner-centred safety training programmes utilising more engaging learning methods and incorporating competency-based skills development [2].

Since the last decades, simulation technologies such as, immersive virtual reality (VR) and digital games, have been creating great opportunities to improve safety training methods. With these technologies, the trainee can be trained in a realistic representation of the workplace environment, performing realistic tasks with a high degree of interaction [4]. This makes it possible to improve decision-making skills on important safety issues, where mistakes can be made without real-life hazardous consequences. Also, games are widely known for effectively sustaining the engagement and entertainment of the player within the virtual environment [5]. The activity of learning-by-doing and learning from mistakes can make the learning experience more engaging and more memorable.

In this paper, we present the design and development of a serious game using VR technology as a training tool for chemical laboratory safety, called VR LaboSafe Game. At first we describe theoretical design principles that are necessary in order to design an effective VR serious game. Then we discuss the game design of VR LaboSafe Game and the tools used for development. Our ultimate goal is to investigate the learning effectiveness and motivation of this game. However, to ensure optimal conditions for final evaluations, we analysed whether the game has good usability and does not induce severe simulator sickness. This study may be considered useful by other researchers and designers who are also interested in designing and developing VR serious games for health and safety training.

2 Theoretical Design Foundation

Although VR and games are promising novel tools for educational purposes, there are some complications in designing effective learning experiences for such technologies. For example, immersive VR Head-Mounted Display (HMD) devices are known to cause users to feel nauseous while being immersed; this is often called simulator sickness [6]. Moreover, it has been proven that implementing VR experiences can inhibit effective learning by overloading the cognitive processing with overwhelming information [7]. While games can sustain engagement and active involvement of the trainee, researchers have mentioned that implementing game elements does not automatically make the training motivating [8]. It is a more complex interplay between cognitive capabilities and psychological factors of the learner. In general, designing such complex training systems is not easy and requires many factors to be considered in order to maximise its effectiveness. In this section, we discuss several well-researched design principles that can overcome these challenges and examples are given how these are implemented in the VR LaboSafe Game's design.

2.1 Cognitive Instructional Design

According to the cognitive theory of multimedia learning, three types of cognitive processing occur while learning [9]: essential, generative and extraneous cognitive processing. Instructional support should be designed in a way that supports the cognitive processing system so that cognitive load of the learner is efficiently managed in serious games using virtual reality.

Manage essential processing. Essential cognitive processing refers to cognitive processing in the working memory that is needed to mentally select the visual and verbal information from the learning content. Providing pre-training sessions about key concepts of the learning content and familiarisation of the technological medium prior to the learning experience can manage the intrinsic cognitive load of the learner [9]. Another method is by dividing tasks to learn a complex skill or knowledge into smaller sections and sequencing it from simple to difficult according to the expertise growth of the learner [9]. In the VR LaboSafe Game, a VR tutorial is provided before starting the game levels. These game levels are sequenced to correspond to a specific subskill.

Reduce extraneous processing. Extraneous cognitive processing refers to cognitive processing that does not support the learning objective. In the case of VR environments and games, excessive extraneous processing is highly probable because high amounts of distracting details are displayed to the learner [7]. Some techniques are: highlighting elements, that are relevant to the learning material, with attention-drawing cues [9] and eliminating redundant information that is not necessary for achieving the learning objectives [9]. In the VR LaboSafe Game, important information is indicated with a prominent colour or a distinct shape. On the other hand, information that is not needed yet in the early game levels is made invisible.

Foster generative processing. Generative cognitive processing refers to cognitive processing aimed at comprehension by organizing and integrating the content into knowledge. Several techniques have been researched that provide guidance to the learner to enhance deep learning of the learning content, such as scaffolding the learning content by providing instructional support for novice learners in the beginning, but fades away as the learner gains more skill and expertise [9]. Another technique is by bringing a sufficiently high variability in learning tasks throughout the whole training experience [9]. In the VR LaboSafe Game, we designed the game levels such that hints are provided when the player is struggling. For more experienced players, these hints are not immediately shown, but can be requested when needed. To implement variability, each game level has different objectives with randomised content appearing at random locations in the virtual environment.

2.2 Motivational Game Design

Although the novelty and increased sense of presence of VR technology can be inherently motivating, the interactivity of the player with the virtual environment is also very important for sustained engagement [4]. To achieve this high level of engagement, the serious game design should support the motivational needs of the player. Game elements that are based on the self-determination theory (SDT) of Ryan and Deci (2002) can sustain the intrinsic motivation of the player by supporting the psychological needs of autonomy, competence and relatedness.

Autonomy. The ability to feel in control of one's behaviour and goals is one of the elements of SDT. A flexible game design that allows players to make their own choices creates a more meaningful and motivating experience [10]. Moreover, allowing players to explore and have a sense of control over the environment, sparks their interest and curiosity of the virtual space [11]. In the VR LaboSafe Game, safe or dangerous situations can appear depending on the players' decisions. They can choose how to interact with objects and can freely move in the virtual environment.

Competence. Another element of SDT is the feeling of confidence over one's mastery to overcome new challenging tasks effectively. Providing a challenge scaffolding that tailors the level of difficulty to be not too easy nor too hard for the players, can boost their confidence in their abilities [12]. This also means that such game design allows a graceful failure of these challenges making it a part of the learning experience to enhance the players' ability to overcome them the next time [13]. In the VR LaboSafe Game, this is related to the scaffolding structure of the game levels as mentioned before. When the players fail, they receive feedback on what they did wrong and how to do better next time.

Relatedness. The third psychological need involved in the SDT is the feeling of being socially connected with others. Although not all games can afford multiple players, this satisfaction feeling can also be achieved by meaningful interactions with non-player characters (NPCs) in the game [14]. Especially with VR technology, a realistic social presence can be simulated. In the VR LaboSafe Game, a virtual character follows the player as a guiding companion. Moreover, there are virtual co-workers whom the player will need to keep safe.

2.3 Virtual Reality Considerations

VR HMDs allow users to be visually closed off from the real-world surroundings, enhancing the sense of presence in a virtual environment. However, users might become disoriented and develop symptoms of feeling nauseous when visual actions inside the device do not match with the actual physical movement of the human body [15]. Research has been done to search for solutions to prevent or minimise this simulator sickness. Improving the immersion of the user by using adequate hardware and interactive design considerations seems to reduce these symptoms [6].

Immersion. While there are different definitions of immersion in literature, one of the definitions is the technical capability of a system where the user perceives a virtual environment through natural sensorimotor contingencies [16]. This means that VR HMDs with more advanced technological features can provide a high level of immersion and reduce symptoms of simulator sickness. Some technological characteristics that can affect simulator sickness are: visual performance, spatial audio and motion tracking quality [6]. The VR LaboSafe Game uses the Oculus Quest 2, which provides high-quality performance and comfort by allowing free movement untethered to a computer.

Interactivity. The term interactivity refers to the interaction between the user and the virtual environment, allowing the user to influence the environment in real-time [17]. VR technology is able to bring a high level of interactivity with natural and intuitive user interactions. This improves the immersion and reduces simulator sickness [18]. Moreover, allowing users to freely move in the virtual environment by means of teleportation also prevents symptoms of nausea [19]. In the VR LaboSafe Game, players are able to intuitively interact with virtual objects, such as grabbing, throwing, pinching, etc. Moreover, they can teleport to different locations in the virtual environment.

3 VR LaboSafe Game Design

We developed VR LaboSafe Game, which is a serious game that utilises immersive virtual reality to train the safety awareness and safety behaviour in chemical laboratories. The genre of the game is a single player simulation game with a problem solving characteristic. A realistically accurate laboratory environment is simulated with task-based activities that are related to laboratory activities in real-life (see Fig. 1). In general, the game is divided in several modes and levels with three specific objectives: risk spotting, risk minimisation and performing safe experimental procedures. The goal is to complete these objectives as safe as possible without causing accidents and losing health points. In this section, we reveal more information on the learning objectives, level design and development of the VR LaboSafe Game.

3.1 Health and Safety Learning Objectives

The main learning objective of the game is to improve the player's decision-making skills in context of laboratory safety by practicing safety awareness and safety behaviour. The target audience of the game can be anyone who frequently works in a chemical laboratory, including students, researchers and lab technicians. These learning objectives are derived from the RAMP principles of laboratory safety skills [20] and the dynamic human decision-making model of Endsley [21]. Safety awareness is the constant consciousness of the state of safety in the surrounding environment and consists of the subskills hazard identification and risk assessment. Safety behaviour, in this case, refers to the practical application of safety measures in the workplace. After completing the VR LaboSafe Game, the player is able to recognise hazards that are present in the chemical laboratory, assess the risks and apply safety measures to minimise risks in the chemical laboratory, and demonstrate safe procedural skills of laboratory procedures.

3.2 Level Design

The VR LaboSafe Game has three different game modes: tutorial, training and evaluation mode.

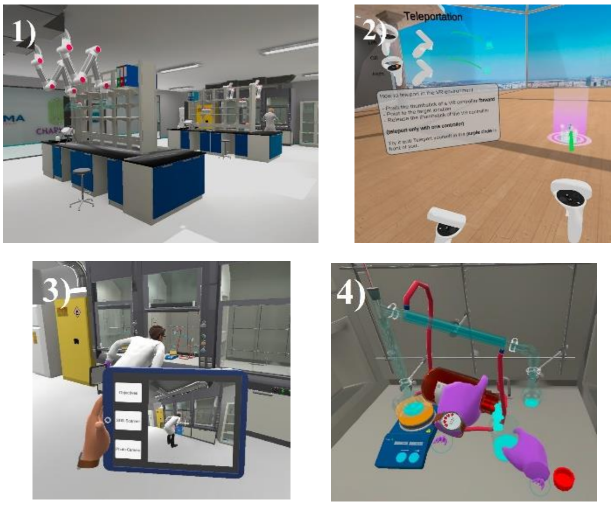

Fig. 1. In-game screenshots of VR LaboSafe Game: 1) the virtual laboratory environment; 2) tutorial of teleportation; 3) risk spotting mission; and 4) safe experimental procedure mission.

Tutorial mode. This mode has the purpose to get the player familiarised with the controls and interactions of the game (see Fig. 1). Especially for beginners who are new to VR, tutorial sessions are recommended prior to using the game to its full extent [4]. In this way, the player could be able to handle the controls more easily during the learning experience, thus reducing cognitive load, which leads to performing the tasks more effectively [22]. The tutorial, that we developed, includes instructions for interacting with Graphical User Interfaces (GUI) in the 3D environment, teleporting in the environment, grabbing objects, using a virtual tablet touch UI, taking pictures, and displaying Safety Data Sheet (SDS) documents of chemicals. For each instruction we incorporated small minigame tasks related to the VR interaction. With these minigames, the player can practice and improve their skills of interacting and handling in VR.

Training mode. This mode has the purpose to train the player's skills of laboratory safety in an interactive and engaging way. There are three distinct game levels with different tasks: 1) Risk Spotting; 2) Risk Minimisation; and 3) Safe Experiment. In the first game level the player needs to search and find a certain number of risks that appear in the virtual laboratory (see Fig. 1). The player takes a picture of this risk and answers questions related to its hazards and consequences. This game level is completed when all risks are found. The second game level is an extension of the first game level in a way that the player not only needs to spot risks in the lab but also needs to correctly eliminate or minimise these risks. In the third game level, the player needs to complete a chemical experimental procedure with the necessary safety measures (see Fig. 1). Unsafe and dangerous decisions of the player can result in an accident with a reduction of health points.

Evaluation mode. The evaluation mode is where the safety awareness skills and safety behaviour of the player are taken to the test. The different objectives, that are also found in the training levels, are combined into one game level where the choices of the player can influence the scenario of the level. For example, the player needs to spot safety risks in the beginning of the level before performing an experimental procedure. When crucial safety risks are not recognised and eliminated, these risks can cause an accident during the chemical experiment procedure. The in-game assessment of the player's decisions and actions can evaluate the player's competence in laboratory safety.

3.3 Development

For the development of the VR LaboSafe Game, we selected inexpensive and easy-to-use development software and VR hardware.

Software. We used the Unity3D game engine to develop the VR LaboSafe Game. Unity3D is a widely used game engine that is based on C# programming language and has a free licensing option. It offers a lot of advanced options to develop the game with high quality, while also offering an abundance of support. With Unity's XR Interaction Toolkit, ready-to-use solutions are provided to implement VR interactions easily. In addition, we used the free-to-use 3D modelling software Blender in order to make 3D models for the game. Other 3D models are bought or downloaded for free online.

Hardware. We selected the Oculus Quest 2 as VR HMD for this game due to its affordance to move freely while providing high performances. This device does not require a cable connection to a computer, allows six degrees of freedom (6DOF) tracking and provides a resolution of 1832x1920 per eye. This device's comfort and high-quality performance can reduce the symptoms of simulator sickness.

4 Evaluation

In order to eventually perform evaluations on the learning effectiveness and motivation of using the VR LaboSafe Game, we must ensure that its usability should be optimal and the severity of simulator sickness should be minimal. Therefore, we have conducted preliminary tests with an early version of the VR LaboSafe Game in order to examine the usability, simulator sickness and feedback from laboratory technicians. The tested version contained only the first game level of Risk spotting and tutorial levels with textual step-by-step instructions without a pedagogical agent.

4.1 Participants and Methodology

We recruited 10 participants (5 female, 5 male, age 20-30) who were assigned as interns or students at a research centre of the chemical company Arkema in France. Only 3 participants said they had prior experience with a VR HMD. During the testing sessions, they played an early version of the VR LaboSafe Game for a duration of approximately 40 minutes continuously with no one dropping out before the end. Because of the COVID-19 sanitary measures, the participants wore a face mask and the VR HMD, the Oculus Quest 2, was disinfected before each use. In order to analyse the usability and simulator sickness, we used the questionnaires System Usability Scale (SUS) [23] and Simulator Sickness Questionnaire (SSQ) [24] after playing the game. Additional questions were added on the usefulness of the game, their perceived learning and intention to use. Although most of the participants were French, they stated that they had no issues playing the game and replying to questionnaires in English.

4.2 Results and Discussion

Results of the SUS and SSQ scores are presented per participant in Fig. 2. The SUS questionnaire contains 10-items on a 1 (strongly disagree) to 5 (strongly agree) Likert scale. The calculated SUS score can range from 0 to 100, wherein values of above 68 are desirable in order to present a good usability [23]. The SSQ contains 16-items on a 0 (none) to 4 (severe) Likert scale [24]. The calculated SSQ scores are rather not a quantitative measure, but can be used to compare simulator sickness between users or other comparisons. The SUS scores measured in these tests vary widely from 40.00 to 72.50 with an overall mean score of 58.25 among the 10 participants. The best scoring item states that VR LaboSafe Game is 'well integrated', whereas the worst scoring item states that the participants 'would need the support of a technical person'. In terms of simulator sickness, 5 participants scored an SSQ score below 20 and only reported zero to two symptoms, while the other 5 participants scored higher SSQ scores. The most frequently reported (6/10) symptoms are 'eye strain' and 'blurred vision', but also 'general discomfort' and 'difficulty focusing' (5/10).

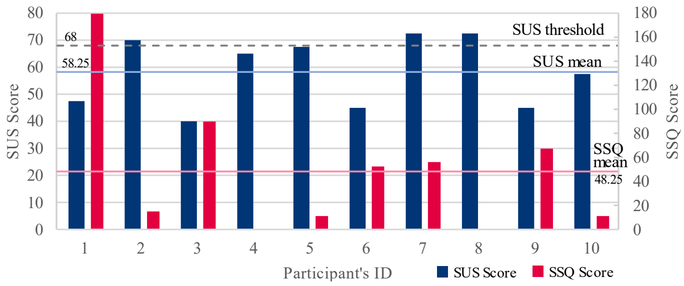

Fig. 2. System Usability Scale (SUS) (blue) and Simulator Sickness Questionnaire (SSQ) (red) scores per participant

The varying SUS scores show that the usability of VR LaboSafe Game should be improved in a way that supports the users better. Indeed, we have observed some participants having issues with controlling the VR interactions more confidently, especially for people using VR for the first time. This could be caused by the abundance of visual and textual instructions in another language resulting in a high impact on the cognitive load of the user. Thus, improved versions of the VR LaboSafe Game should replace most textual information with spoken instructions via a pedagogical agent and add more comprehensible animations demonstrating the VR controls [9].

Despite no one dropping out and symptoms of simulator sickness were not apparent from our observations, some participants have experienced mild symptoms of visual discomfort according to the SSQ results. This could be explained by the relatively long duration of 40 minutes continuous VR experience. Prolonged duration of visual exposure to a digital screen can cause ocular sickness symptoms, such as eye strain and headaches [25]. Therefore, it is important for the future use of VR LaboSafe Game to allow frequent breaks of a few minutes, especially for first-time VR users in order to minimise discomforting symptoms.

Nevertheless, participants still agree that VR LaboSafe Game is useful for learning laboratory safety; is more active and responsive in their learning process; makes safety training more engaging; and that they would like to participate in other training programmes using VR LaboSafe Game.

5 Conclusion

We designed and developed a serious game using VR technology as a training tool for chemical laboratory safety, called VR LaboSafe Game. This VR serious game could improve training programmes for chemical lab safety in order to make them more engaging and to deliver realistic dangerous experiences without real danger. The game design contains an elaborate level design in order to prepare laboratory technicians to be aware of risks in the lab and make decisions to deal with these risks in a safe manner. Because designing such serious game is not an easy task, we also presented design principles on how to implement elements to efficiently manage the cognitive load of learners, to intrinsically motivate them and how to minimise the severity of simulator sickness due to the use of VR. Although the sample size is rather small, the evaluation of an early version of VR LaboSafe Game shows a first indication that there are usability issues and minor symptomatic discomfort for some participants. Improvements of the VR LaboSafe Game should be focused on reducing textual information and allowing short breaks while playing. Despite these issues, participants still agree on the usefulness, active learning and the intention to play the VR LaboSafe Game more frequently.

For the future work of this research, we will investigate the added value of motivation and the learning effectiveness by using VR LaboSafe Game as a tool for chemical laboratory safety training. Moreover, we will examine this added value on populations with different age and experience, including laboratory employees in the chemical industry and students in academia.

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