Autonomy-supportive Fire Escape Rehearsal in Mobile Virtual Reality

CS4552 Guided Study Final Report

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Introduction

In 2021, the Fire Services Department (FSD) in Hong Kong reported 33,891 fire calls, 23 members lost their lives in fires, 306 members of the public, and eight fire personnel were injured in blazes, and 11,434 persons were rescued from fires.[1] In the long run, reducing future misery requires improving the residents' awareness and safety knowledge in a firing situation.

Decades of global endeavor put forward the training potential of Virtual Environment (VE). It allows rehearsals for inaccessible situations. Inhabiting on pervasive computing platforms, VE for serious purposes penetrated in various application scenarios, across game-based therapy [10, 17, 23, 42]. Derived from VE, also an interaction medium with novel features, Virtual Reality (VR) attracted enormous attention mainly due to its higher level of immersion and multimodal affordance over the typical VE; such promises solicited a considerable size of body putting effort to explore the possibilities of VR for educational and training purposes [25].

[1] FSD website: https://www.info.gov.hk/gia/general/202201/13/P2022011300771.htm?fontSize=1

With the same intention to utilize VR for education, we noticed that most previous design frameworks of serious games emphasize the eventual learning outcome, the educator's intention, but merely take the learner's perspective to improve and enrich their learning experience and motivation. Not to mention that "mainstream forms of gamification – behavior tracking, quantitative progress feedback, reward systems – might thwart rather than support the openness, inconsequentiality, and voluntariness characteristics for play" [13]. Due to their intended learning outcomes, serious games manifest the tension between entertainment and educational purposes [13]. On the one hand, pedagogical nature requires a certain degree of control and instruction that may thwart learners' motivation; on the other hand, allowing autonomy and introducing gamified elements may diverse learners from the intended path and distract them from the learning content [31]. A balanced approach should be found.

Therefore, we want to explore a way of teaching that satisfies learners and educators, which is equivalent to achieving both high motivation and ideal learning outcomes. We utilized serious game elements that contribute to the attractiveness of entertaining games to motivate learners and expect a better knowledge acquisition. The key to this goal may not exist in the appearance of game elements but hide in the implicit game mechanics that satisfy basic psychological needs [38]. A*utonomy* is one important need that partially determines the inner motivation of human beings [44], and whose effect was verified in the game-playing context [45]. Therefore, we want to answer whether introducing autonomy in a VR training game in a balanced manner will bolster both the experience and learning.

We first designed and developed a mobile VR application with balanced autonomy support. A preliminary user study focused on usability issues and perceptions of autonomy-related features. We recruited 8 participants and assessed the usability issues and training experience through a mixed-method approach, combining a post-training questionnaire and semi-structured interviews. Our results first identified various usability problems in the current system and informed further improvement. We also collected qualitative data on the perception of autonomy support in the system. We found that most of our participants prefer autonomy to instruction in such a training scenario, and they found it enjoyable to explore on their own with the help of implicit hints rather than explicit instructions. Our findings could be not only valuable for our development but also inspiring for the improvement of educational serious games. As for now, we did not formally study autonomy in detail, but we can iterate our system design and infer future directions to explore from this preliminary study.

Related Work

This section introduces relevant previous studies that fundamentally supplement the interest and motivation of our study. We begin with a brief account of game-based learning, educational Virtual Environment/Virtual Reality (VE/VR), and related conceptualization as the theoretical base of such practices. Then we introduce the Self-determination Theory

(SDT) as the underlining psychological perspective to investigate the motivational pull of video games and elicit autonomy as a potential catalyst for an enjoyable and effective learning experience. Next, we investigate the dilemma of serious games mechanism in terms of the pedagogical intentions for learning and autonomy support for enjoyment and motivation. In the end, we give a summary of the reviewed literature.

Game-based Learning and Educational VR

Virtual Environment (VE) is gaining enormous popularity for its potential for eliciting future education, training, and simulation. In principle, it supports performing any operations in any scenario, making it suitable for simulating extreme and risky environments that cannot usually be accessed. Such virtual training systems acquaint the trainees with the target environments and develop essential skills aforehand. VE for education and training may be even more vital in the post-pandemic world where remote collaboration and isolation will be prevalent.

Many application areas deployed VE as a part of the training program, suggesting its potential for improving social well-being. As part of the early constructive endeavor, some scholars designed a virtual city according to the special needs of people with learning disabilities [7]. VE can also improve the reaction behavior of people with severe intellectual disabilities [48]. Other applications evidenced VE's capability in supporting learning social interaction and communication skills in users with Asperger's Syndrome [9], adolescents with autism [9, 23], and people with Aphasia [19]. These particular scenarios and needs suit VE simulation where problematic real-world contact is avoided and repetition is encouraged. Apart from therapeutic usages, game-based VE has also been applied to science education [10], persuasive intervention for attitude improvement [17], safety education [15], and many more areas. In general, game-based learning is an umbrella term for serious games, a type of video game that directly provides instructional content to the learners [28]. Serious games are mediums of game-based learning, and most examples above can be regarded as serious games. They essentially convert instructions into the gaming experience to motivate learners. Such experience is further enhanced in Virtual Reality.

Virtual Reality (VR) offers an immersive experience. VR is then regarded as a potential educational medium based on the assumption that VR induces a higher degree of immersion, presence, and motivation, thus potentially better learning outcomes. Visual immersion is a factor that associates with the experienced presence in VR. People may feel a higher degree of presence in VR than in reality and in desktop VE [30, 56]. A preliminary study then suggested a moderate relationship between the degree of presence and performance [49]. Besides, learning through immersive VR can be much more motivational for learners than traditional learning through desktop VE [30]. To conclude, a higher degree of presence and perceived motivation can yield better experience and performance than traditional methods. These characteristics make VR ideal for the training medium in our study.

As for specific practices, VR was used in scenarios identical to VE. It was used for complementing existing therapeutic programs for children with Neurodevelopmental Disorders [37, 57]. Beyond that, it was also applied to the professional education context and received positive feedback regarding training efficacy and experience [42]. Other applications share the same interests in using VR as these did. However, experimental results in [58] nuanced the expectation that VR training could be equivalent to or even better than in-person training and video training. However, the cause might stem from the usability and accessibility issues when operated by fresh VR users [25]. There are also studies of successful VR applications in an educational context that dealt with usability issues like [36] and formed constructive design guidelines grounded on empirical studies, targeting usability issues [33].

Most applied VE/VR games for non-entertainment context focus on a specific application scenario, but some parallel work was devoted to drawing the "blueprint" of serious games on a conceptual layer. Early work includes the design and evaluation framework [35] and models to evaluate various aspects [51] and core attributes of serious games [59]. The LM-GM model maps the game mechanics to the corresponding learning mechanics to better serve educational design, but at a point-to-point level, the details remain untouched [2]. Recent studies suggested practical methods for educational serious game design [47] and activity theory-based perspective [8]. Frameworks for specific game genres or game learning goals were also produced [34, 55] to satisfy ad hoc needs. Serious games share some attributes with entertaining games, so linking the game attributes to learning could be informative in designing serious games elements and mechanisms [4]. Besides, voices from industrial game designers gave us more insights from the chamber beyond academia [24], pointing a practical direction in discussing and designing serious games. This body of work greatly informed the design and development of our VR application.

Another concern is the transferability of knowledge "learned" from serious games to reality [6]. This property was measured by various assessment methods that stressed ultimate learning outcomes and scientific rigor of assessment design [1, 3, 5, 32, 40]. As for VR training, knowledge transferability can be achieved through mental models that visualize and simulate familiar situations, those trained in the VR environment, for the analysis of unfamiliar situations those might happen in real-world [26]. This justifies VR's capability of knowledge delivery again.

Serious games' intention of instruction and learning cannot be successful unless the learners have a certain level of motivation for learning in this way. In the next subsection, we introduce Self-Determination Theory (SDT) which has been widely used for explaining human motivations in various contexts to examine the psychological driving force of video games and the revealed implications of serious games design.

Motivational Pull of Games and Autonomy

Self-Determination Theory (SDT) emphasizes the importance of three fundamental needs of human beings – *competence*, *autonomy*, and *relatedness*, and they are the determinants of human motivation [44]. People will act with a sense of full endorsement and volition if these needs are satisfied, whilst they will be demotivated if the needs are thwarted [11]. SDT was applied to explain the motivational pull of video games [43, 45]. In the game context, autonomy and competence are in relation to "game enjoyment, preferences, and changes in well-being pre- to post-play"; game controls and the sense of presence or immersion are also in relation to autonomy and competence [45]. The descriptive and predictive function of SDT in the game context was well-evidenced by countless instances [38, 43, 46, 52, 53]. Needs satisfaction contributes to the immersive experience, which amplifies the effect of virtual content on the players [41]. Given the successful entertaining games, serious games could benefit from incorporating the need-satisfaction perspective to motivate learners and achieve better learning outcomes.

Among the three needs satisfied by many video games, *autonomy* received relatively more attention [12, 50]. It is reasonable even merely based on the subjective feeling that a person will be more motivated if he/she wants to do something intrinsic to his/her mind and not from any extrinsic requirement. Serious games, however, have more extrinsic requirements than entertaining games do. In order to utilize serious games as an enjoyable and motivational way of learning, we need to incorporate the attributes that make games enjoyable, especially *autonomy*. In real-life and interpersonal situations, autonomy can be best achieved through non-controlling language, acknowledging perspective and feelings, providing rationales, and nurturing motivational resources [50]. We expect a similar mechanism applies to the virtual and human-computer situations as presented in our work.

However, it is neither good to be fully instructional or even commanding, nor to provide absolute autonomy----both cannot induce optimal learning performance [14]. We must strike a balance.

Tensions Between Instruction and Autonomy

A learner in VR might be laden with cognitive tasks with mere guidance while might have fewer cognitive tasks when clear instructions are presented [27]. Minimally guided learning is less effective and less efficient than guided learning [27]. An immersive game experience might require too many cognitive resources - people must devote entirely to the virtual environment and observe the unreal artifacts – thus being distracted from the learning content. Besides, without instructions, learners might draw the wrong conclusions and construct unrelated knowledge diverse from the educator's intention [31]. Guaranteed learning outcomes require effective delivery of knowledge through instructions.

Nevertheless, intended instructional content could be problematic. Evidence suggested that introducing pedagogical agents in educational VR impacted the learning efficacy of scientific facts [39]. This adverse effect might be due to the distraction caused by the presence and acting of the humanoid agents in the scene. Meanwhile, being fully instructional may thwart the learner's motivation and experience, and this is more worth considering for serious games since they usually lack autonomy as the core of enjoyment [13]. Autonomy-supportive serious games can effectively deliver knowledge and offer an enjoyable experience if they succeed in providing flexibility in choosing a preferred learning style [29, 60] and timely feedback that bolsters reflection activities [16]. A possible direction for future design is providing implicit scaffolding to support "partial autonomy," which performed better than no-autonomy and full-autonomy [14]. In conclusion, we argue that leveraging autonomy and other needs satisfaction properly can improve the experience and achieve pedagogical goals. This study is one step towards it.

Summary

Educational Virtual Environment (VE) and Virtual Reality (VR) have been widely adopted for various scenarios, especially for simulation and rehearsal of special environments or situations. Such practices were complemented by design, implementation, and evaluation frameworks for serious games, which provided regulations and directions. However, learners' motivation in serious games needs more stress as it closely relates to experience and learning efficacy. Autonomy is a determinant of motivation that receives more attention but one that may conflict with pedagogical instructions. More empirical studies on organic incorporation between instructions and autonomy support are in demand to serve both educators and learners optimally.

System Modeling and Structure

We designed and developed a mobile VR application prototype to simulate building fire events and thus provide a virtual rehearsal environment through which the trainees will learn essential fire safety knowledge and procedures when escaping from buildings on fire. This section introduces our VR application prototype, its rationale, technology, implementation, and concepts. To ground our system design on previous studies, we first summarize the implications revealed in literature and how they informed our design to establish the bridge between them. Then we describe details regarding the hardware apparatus and software implementation and elements or content for achieving an autonomy-support serious game, along with discussions on how our design tried to realize the implications stated.

Rationales From Literature

Given the related practices, frameworks, and theories for educational VE/VR applications, our mobile VR application prototype was implemented with design elements based on the literature review. Serious games design frameworks were the start point and scaffolds. The heat discussions regarding game attributes that constitute the learning settings informed us about the elemental level and conceptual level design. Some of the attributes are intuitive and evidenced to be effective in entertaining games, but others need adjustments when transferring to serious games specifically. For example, a game needs a clear goal for players to pursue before presenting the enormous details of the game elements. Failing to conform to that will probably destroy the players' motivation and get them lost. The goals can be part of the game world's fantasy or mystery, which is a game attribute and is therefore preferable to be involved. However, since we did not intend to create a fictional world full of fantasy, these attributes were eliminated eventually. Similar reasoning applied to the other points in [2, 4] in our decision process. Popularly mentioned attributes were examined and carefully selected for fitting the goals of this application.

From the practices and thoughts of educational VE/VR applications, we obtained and adopted suggestions towards designing a baseline serious game that can be comfortably deployed to the application scenario, namely fire escape rehearsal. But it is never enough until pedagogical content is effective and distributed in a preferred manner. Trainees need to be motivated psychologically. But the design should balance being instructional and autonomous because instructions or commands could thwart their motivation whilst the opposite could thwart the education. There are many ways of autonomy support, but they are supposed to be chosen only if they are not likely to cause frustration or deviation. We adopted some lightweight but effective devices to support self-reported perceived autonomy; they are using non-controlling language, acknowledging perspective and feelings, and providing rationales [50]. Another layer of autonomy support in our design got inspiration from the attempt of providing flexibility [29, 60]. Our design supports flexibility by allowing the trainees to get trained either by following clear instructions or by autonomous exploration and implicit hints so that different preferences or learning styles can be well accommodated. Additionally, we utilized the players' strategy of "trial and error" [20-22] that enables them to explore the training environment and system independently, i.e., with higher degree of freedom in deciding the place to go and object to interact with.

Technology

We chose Google Cardboard (DSCVR Headset) as the target VR device for this preliminary study because of feasibility concerns. Google Cardboard is equipped with two lenses through which the users view the rendered images to obtain an immersive VR experience. There is a conductive button on the upper-right corner through which all interactions with objects in the virtual scenes are performed. This application prototype was developed with Unity 3D in the version of 2019.1.14f1 for PC with the Android support modules and Google VR SDK for Unity installed. The main scene building model was captured by a Matterport 3D scanning equipment and exported to vertices and textures for use in Unity.

Design

Scene This application consists of four scenes, among which two are scenes for experience, and the other two are for UI display. The scenes are labeled as Menu, Loading, Main, and Hint, respectively. The Menu scene is the start place of the application, where two UI buttons are displayed horizontally in front of the users. The START button directs to the Loading scene while the EXIT button functions as the exit point. The Loading scene displays a loading progress bar with text percentages. Users can freely observe the environment by head movement in both the two UI scenes. The Loading scene navigates automatically to the Main scene once it completes loading. The Main scene is a simulated environment for practicing and teaching fire escape knowledge and procedures. The simulated building has three floors, but only one floor has a corridor and an inner view of an apartment unit. At the start, the player will be placed in the unit's bedroom, looking at the unit door. The unit is connected with the corridor, and the corridor is connected with the staircase that goes to the ground floor. If at any moment, the player fails a task, he or she will be transferred to the last scene, the Hint scene. The Hint scene displays the hint text for the player and two objects as triggers for autonomous mode or instructional mode, respectively (introduced in *Balanced Autonomy* below).

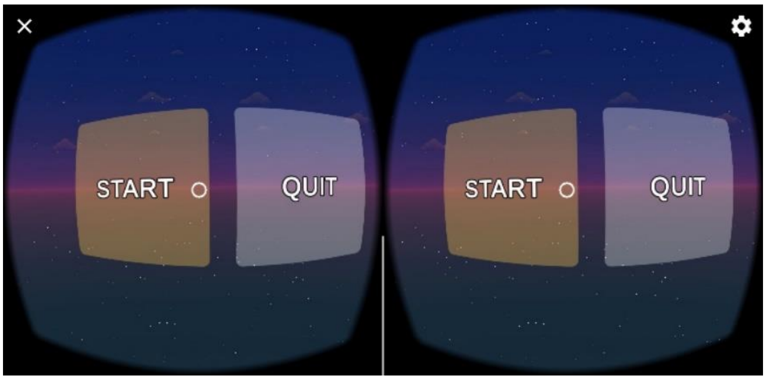

Figure 1 Menu Scene

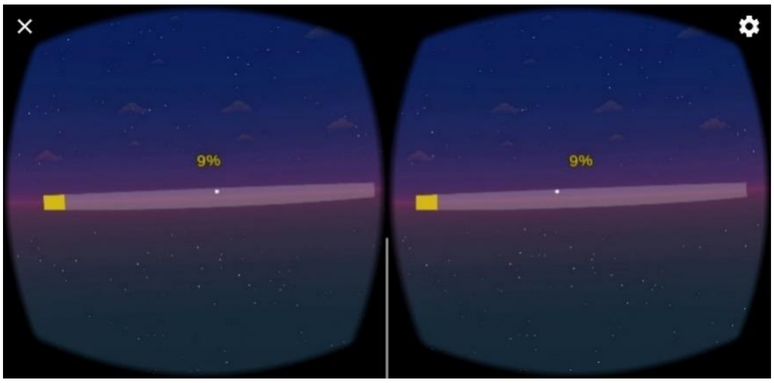

Figure 2 Loading Scene

Figure 3 Main Scene

Figure 4 Hint Scene

Interaction All interactions are initiated by clicking anywhere on the phone screen, which is "mechanically equivalent" to pressing the button on the Cardboard. VR locomotion is a heat research topic, and there are novel solutions for mobile VR locomotion as well like [54]. However, we adopted a simple and basic way of moving in the scene to concentrate on our research questions. Precisely, the trainees move their characters by clicking the floor or walls in the scene. A circular indicator fixed in the center of the screen specifies the targeted point. The shortest path from the point where the character is standing to the destination will be calculated on the baked navigation mesh using the A* algorithm[2], which Unity implemented. Therefore, the character will follow the navigation path to the destination assigned but at high speed to mimic the effect of teleport. Key virtual objects in the scene related to the tasks (introduced in *Tasks* below) are interactable. Actions include picking objects and using the equipment. The indicator circle will turn red if the distance from the player to the object is far than the interaction allows. It will turn green if a reachable destination is set and enlarged to

[2] Unity Manual: https://docs.unity3d.com/Manual/nav-InnerWorkings.html

be to circular ring when it is hovering on an interactable object.

Figure 5 Indicator (normal)

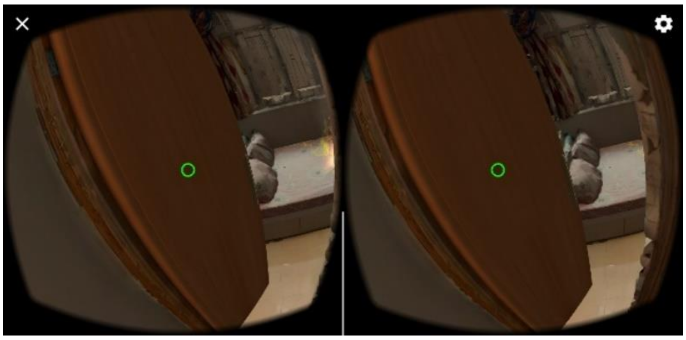

Figure 6 Indicator (interactable)

Balanced Autonomy As mentioned before, the training content is provided in two ways, aggregated together to strike a balance. The first way is autonomous trial & error, while the second way is simply instruction. We introduce the two ways via a presumed typical train flow from a trainee's perspective.

In the beginning, the trainee needs to explore the virtual environment and try to complete tasks through independent exploration. The autonomous way is the default setting that the trainees will experience from the first time they enter the Main scene. If our assumption is valid, the trainees will try to move outwards and probably make mistakes regarding fire safety, such as failing to take the required items when leaving and going through a corridor full of heavy smoke without protection. We set several test colliders in the scene, where the trainees will be subjected to tests on certain conditions about fire safety (introduced in *Tasks* later). If the trainee fails a test, his/her locomotion will be ceased immediately, with the screen turning black gradually, and he/she will be transferred to the *Hint* scene, where he/she will read hints about the circumstance and possible actions to take to satisfy this test condition.

The hint given to the trainee is in the form of a paragraph displayed on the hint panel. The text content consists of two parts, a description of the circumstance and a piece of suggestion regarding possible actions to be taken, respectively. The circumstance description acts as an inducer towards context-awareness through which the trainees realize the situation around them and enhance their impression. In the meantime, the description is narrated in the second-person point of view, initiating perspective-taking in the language layer. Also, the action suggestion is given in the form of "Have you forgotten to …?". The suggestion is implicit, which means no explicit or specific solution is directly presented; on the contrary, the trainees need additional mental effort to figure out the hinted solution independently and pass the task test. The words used eliminates controlling language to avoid unnecessary impediments to autonomy. Afterward, the trainees are given either continuing self-exploring or receiving instructions. The former option reloads the Main scene and follows the same flow described earlier; the latter option reloads the Main scene, but the instruction for *this* task is provided *in* the scene. The instruction is displayed on a world-coordinated UI panel in the scene environment in the same form as a paragraph text. Different from hints, a specific, explicit, and clear instruction in terms of what needs to be done in the current situation and the reason why doing it composes the text. Being aware of the instruction, the trainees can complete this task and proceed to the next task by autonomous trial & error again. The loop runs until all tasks are correctly completed in a single turn, and the training process should end afterward. In a nutshell, autonomy and instruction are aggregated in an organic, flexible, and balanced manner.

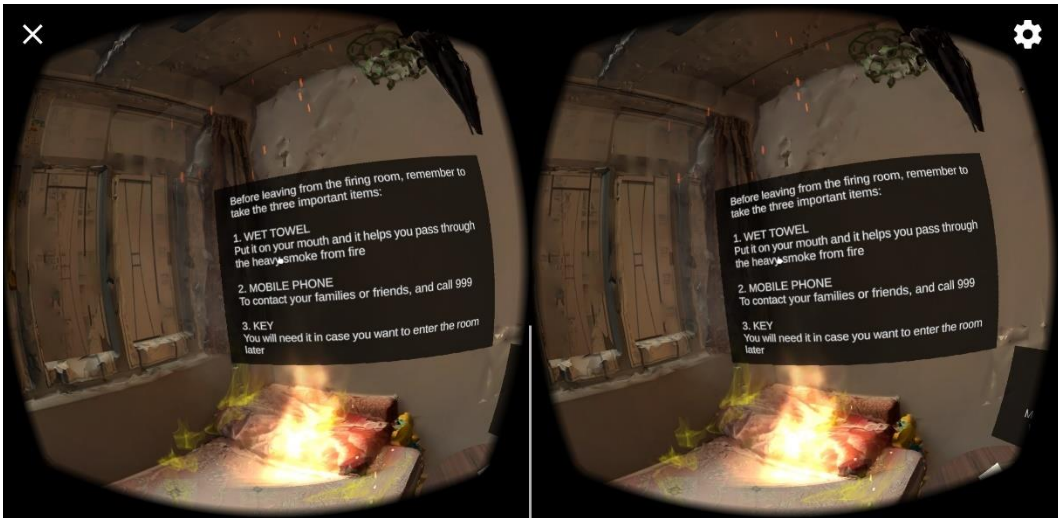

Figure 7 Instruction

Tasks The pedagogical goal of this application prototype is to deliver fire escape knowledge to the trainees through a sequence of educational content. We achieve that via four distinct tasks and convey several essential points regarding fire safety in such emergencies to the users. The tasks were extracted from all tasks specified by fire safety experts in the City University of Hong Kong and based on the needs for essential demonstration and usability testing. To align with the research goals, only a portion of tasks were selected and subjected to minor modifications. Here we briefly describe the four tasks respectively.

1. *Task One* – Pick essential items when leaving

   According to the fire escape instruction set by FSD, three key items should be taken when escaping – a mobile phone, keys, and a wet towel.[3] The test trigger colliders are placed in presumed places that are relevant to the items, such as in the middle of the corridor for the wet towel test. The trainee's items are recorded for testing, and at most, three items can be taken at once.

2. *Task Two* – Close the doors

   When leaving the firing room, the bedroom door and apartment unit door should be closed to prevent fire and smoke from spreading and reduce loss in case of fire.

3. *Task Three* – Alert the neighbors

   A person is supposed to tell everyone in the unit to leave immediately. In our case, the trainee needs to knock on two neighbors' unit doors to alert them.

4. *Task Four* – Use the fire extinguisher

   A person should pick up a fire extinguisher to put out the fire in the necessary and controllable situations. In our case, for simplicity, a portable fire extinguisher is used.

[3] FSD website: https://www.hkfsd.gov.hk/eng/education/brochures/

Preliminary User Test (Method)

This preliminary user test adopted a mix-methods approach and aims to understand the underlying usability issues of using our mobile VR application and further inform the next iterative design phase. We conducted training sessions for each of the participants and each of them filled a questionnaire and attended an interview after his/her session. Here we introduce the participants, apparatus, and procedure in detail.

Participants

We recruited eight participants from our personal network in the total, all of whom are students at the City University of Hong Kong; two are Ph.D. students, while the rest are undergraduates. Participants consisted of four females and four males and came from various academic backgrounds, including business, social science, science, and engineering. All of them reported limited VR experience and knowledge in the form of short trials on Head-Mounted-Display (HMD) with controllers, VR movies, and games. Reports on daily playing video games vary across the participants from almost not playing at all to more than 10 hours per week. But most participants (6 out of 8) confirmed experience playing video games either in the past or present. Participants acknowledged and received a 50HKD coupon as a reward once after completion.

Apparatus

The VR application was played on one single mobile phone (Samsung G9600 S9) attached to one single Google Cardboard Headset (DSCVR Headset) for all participants. The study was conducted in a lab environment where interference was avoided. The participants played the application in the standing gesture. The screen was recorded by the testing mobile phone for analysis. Meanwhile, another camera set aside from the participants recorded the training process and conversations.

Procedure

Pre-Training The researcher first introduced the test and evaluation process and told to ask questions to the researcher in case of any doubt. The participants then read and were assigned a consent form regarding this study. Next, the researcher introduced the simulated scenario in the application and the goal the participants needed to accomplish (learn the fire safety knowledge and escape from the firing building). The researcher also stressed that there is no need to hurry and only regard it as a new learning experience that is also good for their well-being, and we would not assess their technological savvy or fire safety knowledge by any means as this is merely a study that tests whether the application makes the users feel comfortable. Then the participants tried using the Google Cardboard Headset, understood how it was attached to the mobile phone, and was orally instructed regarding the basic functionalities of the device and application. When the participants had no more questions, the sessions proceeded to the actual training.

In-Training The participants were informed to ask questions or seek help from the researcher in case of necessity. The researcher also encouraged them to "think aloud" during the sessions and gave examples to explain what it means if the participants did not know that. The researcher kept silent most of the time but offered help when the participants asked questions.

Post-Training The participants completed a questionnaire after the training sessions, assessing multiple usability concerns. The researcher then conducted semi-structured interviews to obtain comprehensive accounts of their user experience and system design drawbacks. The questions focused on usability issues and features related to autonomy support. Some questionnaire scales were aggregated in the processing stage to foster more holistic understandings and then undertook two-tailed t-tests on the significant difference from the middle scale points (3 in a 5-scale item). Interview data were coded by two iterations and analyzed by the author individually.

Measures

The questionnaire set three subtopics that focus on fundamental usability issues, task load, and autonomy support. Part of the measures about fundamental usability issues are extracted from previous works and adapted to our goals, while we proposed the other part for assets specific interactions. We adopted Nasa-Task Load Index (NASA-TLX) to estimate the perceived workload while training [18]. For simplicity, we scaled the indices to the range of 1 to 5 and kept the subscales rather than calculating the weighted average that has been in debate and requires comparison to a baseline that is ambiguous and not universal to every case. Based on [46] and our modifications, the rest of the questions assess how autonomy and related features were perceived by the trainees, which could inform us of the current state and future directions for improvement.

Results and Discussion

We report the user study results through questionnaire statistics and thematic analysis for the transcript codes. Discussions are followed as well. All student's *t*-tests in the following had a degree of freedom of 7.

Usability

Elemental Usability Table 1 summarizes usability scales at the element level, one that focuses on fundamental and common concerns in such a VR training program. *Interaction* and *Reading* assess how easy it is to interact with virtual objects and move and read the text in the scenes. Significant differences in the middle score were found in *Interaction* (p=0.008) and *Reading* (p=0.0012). No significant difference was found in *Learning* (p=0.676) which assesses the easiness of learning operations such as interacting and moving. A significant difference was found in the perceived naturalness of VR FOV (Field of View) (p=0.0066). *Discomfort* measures the degree of perceived dizziness and nausea after training with five scores as the minimum level and one as the maximum level, and no significant difference was found with the middle score of 3 (p=0.0112).

Scale	***M***	***SD***	***p***
Interaction	4.375	1.06	0.0080
Reading	4.375	0.74	0.0012
Learning	4	1.31	0.0676
FOV	4.125	0.83	0.0066
Discomfort	4.25	1.04	0.0112

Table 1 Elemental Usability scales

Two participants mentioned the easiness of operating the device because they only needed to press one button on the Cardboard for all interactions. Although did not mentioned by any participants during the interviews, the inaccuracy in selecting a destination was identified by watching through the screen recordings. When the trainee tries to set a destination that is relatively far from where he/she is standing, it could be difficult to point to the intended position from this distance. Very easy, it would move either farther or too closely. Additionally, it was an inconvenience to move back – a trainee had first to turn around and move forward.

The participants frequently acknowledged issues around reading in the scene. Usually, reading text on a world-coordinated panel is not problematic if the scene is spacious that has enough space for placing a text panel right in the front of the field of view. But several participants complained that a text panel was placed in the narrow corridor in our main scene because they found it hard to notice the panel put on the left side wall when crossing through the corridor. Some of them also expressed the inconvenience reading text in the scene when most of the text panels did not appear in the direct front of their view, but instead required them to look at the text from one side or with an angle. "*Perhaps because space is relatively* *small, sometimes I feel that it is difficult for me to find a way to read the text from the front, often inclined, but my body will not be willing to do a great rotation.*" Other minor problems with text reading were also identified.

As for learning, the way of performing pointing and moving could be too implicit for some participants at the beginning as they were not sure or familiar with it. This suggests the necessity of pilot instructions for trainees who have little knowledge about VR and games. One possible way could be setting up a pilot playground where basic interactions are explicitly explained and practiced before the trainees enter the main scene. Meanwhile, learning the rules was in need of instructions as well. In our setting, only three items can be taken away when leaving the bedroom, and almost all the trainees were unaware of or unclear about the rules. This coincides with the *Learning* scale, which had a middle level of learning difficulty. Such a result may be that the system provided little information on the rules, so the possible solution could be providing rule-acknowledging in some forms and adding the function of placing items back and retaking.

Several inconsistency problems were also reported. For instance, the inconsistency with people's intuition to treat small-size text panels as clickable buttons rather than the object on the side. Also, the trainees would treat objects with special appearances as interactable objects. They suggest the need for revision on the aspect of intuitive use.

Task Load Table 2 summarizes the self-reported scales of the Nasa-Task Load Index (NASA-

TLX). No significant differences were found between the mean scores and the middle score in mental demand (p=0.0479), physical demand (p=0.7318), temporal demand (p=0.1970), effort (p=0.0112), and frustration (p=0.4015). While a significant difference was found between the mean performance score (perceived success in accomplishing the goals) and the middle score (p=0.0016). It is revealed that middle-level mental, physical, and temporal demand was required by the training, which could be acceptable for youngsters but not for middle-aged or elders as the latter is likely to be less familiar with VR or games.

Scale	***M***	***SD***	***p***
Mental Demand	3.75	0.89	0.0479
Physical Demand	2.875	0.99	0.7318
Temporal Demand	3.375	0.74	0.1970
Effort	3.625	0.52	0.0112
Performance	4.25	0.71	0.0016
Frustration	2.625	1.19	0.4015

Table 2 Task Load scales

The result of physical effort is partly because the Cardboard device requires the trainee to lift and hold all the time, which incurs sore hands. Another source of physical demand could be the dizziness caused by VR. The degree of dizziness was reported by all participants, but the degrees vary. With reference to the common sources of motion sickness in mobile VR and reports from the participants, we proposed the following major factors that had contributed to dizziness and nausea.

- The low positional accuracy of mobile phone sensor
- Visual lag / low FPS

- Low texture resolution of the model
- Teleport locomotion without visual clues

The first three factors are due to the hardware capability of mobile devices and the 3D scanner. The fourth factor is the missing of an important feature – a visual clue. In the current system, a pointer is used to indicate destination so that a user needs to frequently bow the head and look up to observe the environment and then bow the head again and again. Such behavior was found among all our participants and self-reported by some of them. In many cases, abrupt teleportation to a far position, corner, or a narrow space could cause temporal loss of sense of space and navigation, dizziness, and nausea – "*When I made a relatively large displacement at once, I would suddenly feel nauseated. And for example, when I clicked the wall, the view was very close, and I suddenly felt nauseated. From a place where you could see a lot of things all at once, maybe the perspective changed too quickly.*", "*This teleportation will make you suddenly not know where you are.*" An out-of-shell solution shows a trace of parabola starting from the point of a VR hand controller, either left or right. It may assist the user in maintaining a sense of space and predicting the upcoming view changes. Apparently, such clues are not native to mobile VR without controllers, so there is a need to explore ways of providing a similar visual clue without controllers; but this is out of the scope of this study.

Participants characterized the impression of the training as "*realistic*", "*panic*", "*urgency*", "*immersive*", and "*engaged*". The realistic representation may contribute to the sense of immersion and engagement. Participants mentioned that the sound effect, visual special effects, and realistic models caused a high sense of immersion. In the meantime, the narrow space, dim environment, and sound and visual effects, all the components of such an emergency scenario incurred a sense of panic, nervousness, and urgency. Two of them also explicitly mentioned psychological pressure as the byproduct of the realistic environment. The pressure was even enlarged by experimental conditions and lack of introduction to the operations and tasks, which amplified their sense of uncertainty and un-confidence. It, therefore, raised the concern regarding potential negative effects caused by a high degree of immersion and a high mental requirement that could be common in VR applications. It would need more trials before the experience and a longer transition time for the users to gradually familiarize themselves with all the aspects of VR.

Autonomy

Table 3 summarizes the test results of autonomy-related scales. *Making sense hints* measures the easiness of understanding and reasoning from the implicit hints provided after every time the trainee missed a task. *Autonomy* measures the level of perceived autonomy provided by the system in the sense that trainees had free trials and exploration. *Flexibility* measures the degree to which trainees were free to choose between autonomous exploration and explicit instructions and guidance. *Engagement* and *Motivation* from hints measure how much the implicit hints improved trainees' perceived engagement with the training process and motivation to continue. *Enjoyment* assesses the overall fun and interest in playing with the training application. Results for all the above scales showed significant differences between the means and the middle score. At the same time, no significant difference was found for

Difficulty (*p*=0.0676) which assesses the perceived overall difficulty of completing the tasks.

Scale	***M***	***SD***	***p***
Making sense hints	4.125	0.81	0.0072
Autonomy	4.5	0.53	<0.0001
Flexibility	4.25	0.71	0.0016
Engagement from hints	4.3125	0.79	0.0023
Motivation from hints	4.5	0.53	<0.0001
Enjoyment	4.375	0.52	<0.001
Difficulty	2	1.31	0.0676

Table 3 Autonomy-related scales

All participants could understand why the hint text appeared every time they failed on a task. They agreed that the language used in both hints and instructions was in a non-controlling voice, making one of them explicitly say it "*feels very comfortable*". One participant thought some text was still too long and suggested using more concise and clear text. Another participant did not notice that the hints are helper text for the tasks, but once acknowledged, she found the hints very useful. Moreover, she could obtain much information from the hints -- "*That prompt tells me exactly what to do. I get more (information) directly from that.*" However, two participants encountered difficulties in reasoning. They could clearly understand the literal meaning of the hints but could not know what specific things to do and where to do the things. Because the hints were not appeared in the same space with where the task should be performed, the participants might need additional mental efforts to find the specific location and objects – "*Even you know you should knock the door, but you don't know where to knock.*" Some participants suggested using simultaneous feedback in the autonomous exploration process, in which at each location that a task should be performed, an option for receiving instructions is given to users. This could be helpful because it links the locations and the hints and increases the degree of flexibility. But it may thwart the learning effect benefiting from autonomous trial and error, as the participant pointed out – "*Displaying the hints simultaneously during the explore instead of reappearing when they die again may reduce some fatigue, but I don't know. This may be a tradeoff. If all have instructions, he may always click instructions, and he may not get this process of internalizing knowledge.*" It is clear that the tension between autonomy and instruction needs deeper inspection in the future.

As for autonomy, despite one participant who chose the instructions all the time during the whole process, all the others chose self-exploration for some time. And the reason for this one participant always choosing instruction was that she already figured out the solution from the hints so choosing either this or that simply made no difference. 7 participants reported being willing to do the first try and explore by themselves instead of receiving instructions from the start. Words from different participants are shown below. It can be identified that self-exploration and hands-on experience rather than passively receiving instructions could be potentially more impressive and thus result in a better knowledge acquisition.

- "*Don't like giving me all clear guidance. This is more interesting, and I prefer this mechanism of self-exploration.*"
- "*I didn't choose the instruction when I first played the game, I'd love to try it myself and find a solution.*"
- "*I've never been someone who likes to read manuals.*"
- "*Experience many times, and step-by-step you know where you need to improve. If each step clearly*

tells what to do, I may not remember clearly, and I feel that the impression will be shallower."

- "*I prefer the current one because if it is like the other one, I think that for me personally, I may not remember it very well. I just go through the whole process, and I don't really remember what I did, because it feels like that it puts knowledge in your head. I may not be very comfortable with this way.*"

When asked under what condition they would choose to receive explicit instructions from the system, seven participants stated a condition characterized as "exhaustion". "*I will definitely try it myself first, unless I have no way to go. I will try until I can't do it at all before I go for the instructions.*", "*The freshness has not yet passed, I will not want to go to the instructions.*" Also, we found the inclination may have a potential relationship with their gaming experience because we spotted three participants who prefer self-exploration in video games showed similar preference -- "*Don't have too many directions or a very clear route you need to follow.*" All these coincide with the high score of *Autonomy* and closely related *Motivation from hints*, which conforms with the SDT theory. Nevertheless, autonomous trials still require goal-acknowledging but are not necessarily explicit. This is one of the drawbacks identified of the current system where only a general goal of "escaping" was provided, but apparently more clues and assistance are needed.

All the participants valued the realistic simulation of the fire events and seven of them admitted getting new knowledge about fire safety; some mentioned the connections between failures in the training and degree of an impression on the knowledge. They also reported their perceived difference between doing fire escape rehearsal in the real-world and doing in our VR system. Some further pointed out the higher degree of immersion and engagement in

VR than in real-world settings:

"*When you follow the group, you won't necessarily learn anything about closing the door, grabbing a towel, or bell for the fire. This thing can be very intuitive and very immersive to tell you that everyone is gone, you are the only one, and you need to do this. So, it is a very good way of education. The responsibility rests entirely on you, you need to make your own choices and consider the consequences of every action.*"

In a real-world fire escape rehearsal, one person bears little mental effort because following the group can always guarantee the "success," whilst in the VR simulation, originally diffused responsibility is regained back to the person so that he/she will devote more mental effort and thus experience in a more immersive and engaging manner. This implies the potential higher knowledge transferability than its real-world counterparts.

Conclusion

We developed a mobile VR application that simulates fire escape rehearsal. Essential fire safety knowledge was incorporated into several tasks in an autonomy-supportive manner, drawing from the need to balance autonomy and pedagogical instructions to achieve high motivation and ideal learning outcomes. We conducted a preliminary user study using mixed-method on eight participants to identify usability issues and test the effects of the autonomy-supportive features. The results informed us of underlying usability issues of the mobile VR system and the promising potential of autonomy in serious games in general. The identified issues will be considered in future iterative development. Also, our approach to balance autonomy and instruction and the results could join the more significant discussion of improving serious games education.

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