IMMERSIVE VIRTUAL REALITY TRAINING TO ENHANCE PROCEDURAL KNOWLEDGE RETENTION

by

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To my family, my advising committee and my friends

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ABSTRACT

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Immersive virtual reality (VR) technology has brought many new opportunities for training researchers and students. In the immersive VR environment, trainees can practice tasks which are similar to what they will perform in a physical environment. By repeating the training, trainees will finally get themselves familiar with concepts and operations related to a specific device. Virtual reality technology has several advantages for training researchers or students, such as reducing the cost, increasing the flexibility of the training, as well as protecting the trainees from any potential risk. However, learning from the VR scenario should meet several requirements: first, trainees should indeed learn the expected learning objectives from the virtual training; second, trainees should be able to transfer the knowledge which trainees gained from virtual training to physical scenario; third, trainees should remember these skills well enough compared with the traditional training method. In the traditional training environment, trainees usually follow verbal instructions (lecture) or visual instructions (video tutorial, job manual) as certain training methods. For this research study, we not only tested how much procedural knowledge the trainees could learn from the VR training compared with traditional media training (video plus instruction manual), we also specifically focused on how well the knowledge could retain in a certain amount of time. The finding of this study shows that VR training can help trainees learn procedural knowledge, and also shows that VR training can help enhance procedural knowledge retention in terms of recall error. However, we did not find any significant difference in recall time between VR training group and traditional media training group.

CHAPTER 1. INTRODUCTION

This chapter provides an overview of the study. In particular, this chapter includes a general discussion about the research background and introduces the significance of the study, statement of purpose, and research question. This chapter also defines the scope of the study and key terms related to the study.

1.1 Background

Since the 1960s, the term virtual reality (VR) has been used to describe a wide range of technology, including both hardware and software. In this article, VR is specifically referred to a virtual environment where users can either step into or look into from outside. Researchers typically will name the former VR as immersive VR because users are surrounded by the virtual environment; while naming the later VR as non-immersive VR because users typically look into the virtual environment through 2D desktop monitors (Jensen, & Konradsen, 2018). Immersive VR technology has emerged rapidly due to the improved computational power of personal computers, and reduced expense of VR goggles such as HTC Vive or Oculus Rift. This provides a great opportunity to enable training and learning in the virtual environment. According to Carlson, Peters, Gilbert, Vance, and Luse (2015), traditional training related to procedural work in a factory setting is expensive because trainees need to be trained in a real-world assembly line, which will decrease the productivity of the factory and increase accident rate for novice trainees. They also concluded that introducing VR training can mitigate safety issues and increase training efficiency. Many 3D VR simulators (desktop version, like serious game) have been developed to help students from medical background to prepare for either decontamination process or performing cataract surgery (Lam, Sundaraj, &Sulaiman, 2013; Smith, Farra, Ulrich, Hodgson, Nicely, & Matcham,2016), and their experiments both suggested the great potential to incorporate VR training into traditional training.

Procedural skill consists of procedural knowledge and technical skills (Ganier, Hoareau, &Tisseau, 2014). Procedural knowledge can be defined as knowledge that guides how to perform a particular procedure, it’s a high level of abstraction; while technical skill is the execution of a specific manual procedure. When people want to enhance their procedural skills, practical experience is critical. VR brings a great opportunity for people to explore things with their body moving around and perform tasks by interacting with virtual objects, which suggests that VR can be a valuable tool for procedural knowledge learning.

Training and learning in the VR environment can be at least as effective as training received in the real environment, as suggested by Smith et al.'s (2016) and Ganier et al.'s (2014) study. Carlson et al.'s (2015) study suggested participants trained in VR environment improved their assembly task performance after a long-term period. They also concluded that the colors of the puzzle pieces in VR environment may provide visual hints, which implied that VR training results can be affected by other factors, carefully designed VR training tool might be more effective compared with traditional training material.

Although Smith et al.'s (2016) work suggested that training result from VR environment can be as effective as traditional methods and have potential advantages when it comes to the knowledge retention part, their experiment was not conducted in an immersive VR environment. Instead, their participants can only receive the training via a desktop simulator, which did not involve too much body movement and immersive feeling of the emergency room. Few studies have been conducted to test the procedural knowledge retention from training in immersive VR environment. This study will examine whether immersive VR training can enhance long-term procedural knowledge retention.

1.2 Significance

Procedural learning involves tasks related to motor, verbal, or cognitive procedures (Beaunieux, Hubert, Witkowski, Pitel, Rossi, Danion, & Eustache, 2006). Testing on procedural learning should involve a comparison between motor, verbal or other cognitive training methods. Therefore, this study will compare procedural learning from VR training (kinesthetic, verbal and visual) and traditional media training (verbal and visual).

As we discussed in section 1.1, many researchers have uncovered the value of VR training related to procedural learning. However, the learning retention from virtual environment training is still unclear, Smith et al. (2016) performed their cognitive test related to decontamination training and found that the subjects learned in the virtual environment did not have a significant knowledge decay after 5-month periods. Their study, however, did not focus on the comparison between different learning methods and their study did not involve the immersive VR training.

This study focused on the differences in procedural knowledge retention between immersive VR training and traditional media training (video plus instruction manual). Understanding the distinction helps us decode whether immersive VR can be considered as an effective training tool for procedural learning. The findings of this study also contribute to other experiment design related to procedural learning.

1.3 Statement of Purpose

Recently, many researchers have done a great amount of work related to training procedural knowledge in the virtual environment. Smith et al. (2016) and Ganier et al. (2014) have tested the effectiveness of VR training related to procedural learning, and they concluded the VR training for the procedural study could be at least as effective as traditional training. However, few studies have focused on the comparison of procedural knowledge learning retention between immersive VR training and traditional media training. This study conducted an experiment and found out the procedural knowledge gained in the immersive VR training lasted longer than the traditional training. The finding of this study can provide guidance for all kinds of procedural learning.

1.4 Research Questions and Hypotheses

This study is designed to answer the following two questions:

1) Compared with traditional training (group 1: video + instruction manual), can VR training (group2) enhance the long-term procedural knowledge retention?
2) What is the difference in knowledge retention between the two training modes?
3) What are the potential factors which make people like or dislike the training method (VR training or traditional training)?

According to the research questions, we propose the following hypotheses:

1) There is a significant difference between the two training groups in terms of recall accuracy from the first and second test respectively. (group1 vs. group2 in accuracy)

2) There is a significant difference between the two training groups in terms of recall time from first and second test respectively. (group1 vs. group2 in recall time)
3) VR training can enhance procedural knowledge retention after approximately two weeks, compared with traditional training. (group1 vs. group2 in later accuracy minus former accuracy / group1 vs. group2 in later recall time minus former recall time)

For the first two hypotheses, we test whether VR training and traditional training can have a significant difference in procedural learning. For the last hypotheses, we answer the question of whether VR training can enhance procedural knowledge retention. If this hypothesis were supported, we know that VR training can enhance procedural knowledge retention compared with traditional training.

1.5 Assumptions

This study compares immersive VR training and traditional media training. The following assumptions are made:

1. Participants utilize the given training time to memorize the whole procedure as much as possible;
2. While the training contexts are different, both training materials are clear and intuitive for participants from both groups.

1.6 Limitations

The limitations of this study include:

1. Participants were not able to operate on physical CP3 device during the test. They were tested by sorting the cards which represent different operations on the experiment devices.
2. Participants in this study are all students from Purdue University.
3. The number of participants is not sufficiently large.
4. The warm-up time for the VR training group is not sufficient. We have seen some reviews from our VR training group that they need more time in order to be more familiar with the device and interaction.

5. We need to provide a more detailed explanation of each operation for both training groups. Some participants feel they cannot fully understand the meaning of the operation during the training.

1.7 Delimitations

This study will acknowledge the following delimitations:

1. This study relies on current commercial VR devices - HTC VIVE, and does not focus on other user input device, which means the user uses VIVE controller to interact with objects during the procedural training;
2. This study does not focus on procedural knowledge transfer from the VR environment to a physical lab environment;
3. This study does not involve participants with the structural biology background, because they may have prior CP3 training or prior experience with the CP3 device.

1.8 Definitions of Key Terms

Virtual Reality: Virtual environment where users can either step into or look into from outside. (Jensen, & Konradsen, 2018)

Immersive Virtual Reality: Users can step into the virtual environment and be surrounded by a virtual environment. Typically, users need to wear a goggle in immersive virtual reality. (Jensen, & Konradsen, 2018)

Procedural learning: Learning tasks involving a motor, verbal or cognitive procedure. (Beaunieux, et al., 2006)

Verbal learning: Learning by written or spoken explanation. (Coffield, et al., 2004)

Visual learning: Learning through visual representations. (Coffield, et al., 2004)

Virtual environment: A 3-D virtual environment can be defined as an environment that ‘capitalizes upon natural aspects of human perception by extending visual information in three spatial dimensions’, ‘may supplement this information with other stimuli and temporal changes’ and ‘enables the user to interact with the displayed data’. (Wann & Mon-Williams, 1996, p. 833)

1.9 Summary

This chapter gave an introduction to the background and motivation of the whole study. This chapter also discussed the scope and contribution of the study. In the next chapter, previous research work related to the study is introduced.

CHAPTER 2. LITERATURE REVIEW

Procedural learning has become an important topic for a long time period, and procedural learning tasks typically involve learning a specific task step by step. However, when the task becomes more and more complex, more human cognition load and efforts are needed during procedural learning. Traditional training methods for procedural learning involve training by the instructor, watching videos, reading a job instruction manual or a combination of all. Recently, immersive virtual reality training has become a great supplement method for learning procedural knowledge. Evaluation of how effective procedural training in the virtual environment and how long the knowledge can last has become an important research topic. This section discusses the procedural skills, training, long-term memory, learning effectiveness and knowledge retention related to virtual reality.

2.1 Procedural Skills and Training

Procedural skills typically involve a sequence of actions which will be carried out by participants (Goode, Salmon, & Lenné, 2013). These actions can be automatized after participants receive some practice. Ganier et al. (2014) distinguished the procedural skills between two different levels, and these two levels are procedural knowledge and technical skills. Ganier et al. (2014) concluded that technical skills are "motor activities required to execute the manual task". For example, pressing the power button to turn on the computer. Technical skills more emphasize on the actual actions to complete one task; while procedural knowledge can be defined as "knowing the steps required to perform a particular procedure at a higher level of abstraction". For example, when driving a car, we know the first step is to start the car, then release the hand brake, etc., even we do not actually perform the real operations. The main difference between technical skill and procedural is the latter one focuses on all the abstract steps of the whole procedure, the former one is the actual motor actions to complete a specific step. In this study, we will focus on testing procedural knowledge retention instead of testing technical skill retention.

According to Adams, Klowden, and Hannaford (2001), human training can be related to cognitive, perceptual and motor aspects. When users receive traditional training, such as training by following the instructions or completing each task manually in the physical environment, their mistakes will be corrected and notified, their motor skills such as handling, orienting or connecting physical pieces are typically involved. Users will finally develop their own strategies after the training section (Carlson, Peters, Gilbert, Vance, & Luse, 2015). Fitts (1964) proposed a three-stage skill acquisition process, these three stages are cognitive, associative, and autonomous stages. The cognitive stage is the initial step where users have the general idea how a system or a procedure works; the associative stage is a further step where users try to catch and correct their mistakes during the cognitive stage; the autonomous stage is where users show improvement gradually. A three-stage model is good enough for this study because this study requires the participants to go through the training material multiple times, participants will form an overview first, and then improve their understanding by repeating the same procedure until they can fully understand the meaning behind each step.

When learning procedural knowledge, practical experience is important (Anderson, 1982). Users need to receive repetitive training in order to reach the autonomous stage, and finally improve their skill level. Lam, Sundaraj, and Sulaiman (2013) designed their VR training tool in order to provide "repetitive training on the main procedures of phacoemulsification surgery", and Smith et al. (2016) also proposed that VR simulator could be beneficial for training medical students because VR enables repetitive training at a low cost and free the students from a hazardous environment. They also mentioned that through repetitive training, students could build their long-term procedural knowledge related to the decontamination process.

2.2 Long-term and Short-term Memory

When we talk about knowledge retention, we need to know the meaning of short-term memory, long-term memory, and the relationships between them. Cowan (2008) gave a great explanation about these two terms and their different characteristics.

Cowan (2008) concluded that two important features of short-term memory are temporal decay and chunk capacity limit. Temporal decay means that short-term memory usually decays in a relatively short time period, although the perish time varies in different situations. The delay effects were said to be related to delays from the previous trials (Cowan, 2008). Keppel and Underwood (1962) concluded from their experiment that within the first few trials, the delay has a slight impact on the final result. Baddeley and Scott (1971) found that the test decay effect existed within the first 5 seconds, while the decay was not obvious when tested in longer delays. However, their conclusion was not solid enough for covering all the firm ground of the short-term decay effect. Cowan (2008) found that decay of short-term memory may not be gradual, it might be some sort of collapse at a specific point, which is case dependent.

According to Cowan (2008), chunk capacity limit of short-term memory means the limited amount of memory that can hold a small number of items in memory in a very accessible state temporarily. Typically, a memory span is approximately seven items for each adult, and each item does not necessarily mean they are completely separated. If the number of items smaller than the capacity limit, these items will remain in the short-term memory until they are replaced by new items. The limited amount of storage makes short-term memory a valuable resource for maintaining instant knowledge input, as a result of this, utilizing the short-term memory in a more efficient way was discovered. Miller (1956) pointed out that multiple items can be combined and synthesized into a larger, meaningful unit, and this strategy will utilize the limited chunk of memory better.

Cowan (2008) concluded that long-term memory is a knowledge pool for storing all the previous information or events, almost every normal person will have their unique long-term memories, although long-term memory may not be flawless or complete. In contrast to short-term memory, long-term memory typically has large memory capacity and long duration. There is retrieval progress when we need to recall the item stored in the long-term memory, this retrieval progress will increase the cognitive load. Baddeley and Warrington's (1970) experiment showed that in immediate recall of the last few serial positions of the list from the amnesic individuals was preserved well. However, when they were tested after a relatively long time period, these individuals encountered a deficit at all serial positions, which showed the short-term memory perished after some time period (Glanzer & Cunitz,1966). These data also suggested that short-term memory and long-term memory will have separate storage space, and training procedural knowledge should transfer the learning result from short-term memory space to long-term memory space.

Another important concept related to this study is declarative non-declarative memory. According to Faruji (2012), memory can be classified as declarative and non-declarative, the former one is mainly responsible for storing facts and events, and the later one, on the other hand, supports "habit learning or simple condition". We can see that non-declarative memory is more related to technical skills (actual actions to complete a task) and declarative memory is more related to procedural knowledge (know the steps about how to perform one task). Procedural memory is one type of the non-declarative memory, which is firmly related to performance, cognitive and motor skills, in other words, it is a memory for how things are done (Smith et al., 2016). Dörnyei (2009) concluded that procedural memories are routine ability and less subjective to decay compared to declarative memory, which shows the main goal for successful procedural training is to build up the long-term procedural memory (non-declarative memory), and this goal can be achieved by repetitive training.

Another aspect we are interested in is how long long-term memory will last before it perishes. Students will forget whatever they have learned related to basic science knowledge in school, typically after a short time period after the exam (Tyler, 1930). Lang, Wei, Xu, Zhao, & Yu (2018) replicated the experiment and tested the Ebbinghaus Forgetting Curve, which models the decline of memory retention against time. Their findings suggested humans generally forget about 75% of knowledge (declarative memory) they have learned after one week. As we have seen before, that procedural memory is less subjective to decay (Dörnyei, 2009), so we choose two weeks as the time interval for testing procedural knowledge retention.

2.3 Learning Style: Kinesthetic Learning, Verbal Learning, and Visual Learning

When we discuss any type of learning, a very important concept could be learning style. According to Rolfe and Cheek (2012), learning styles can be defined as the special characteristics which affect how the user learns knowledge. In their article, Rolfe and Cheek (2012) also introduced the modality style theory, which categorized learning styles into four main types: visual/verbal, visual/non-verbal, tactile/kinesthetic and auditory/verbal learning styles. In our study, we compared the VR training with traditional training and focused on the kinesthetic learning style and visual/verbal learning style.

Kinesthetic learning is learning by doing, users with this learning style prefer practicing and being physically active rather than watching a video or reading books during the learning process. Users also benefit from physical demonstration about a concept or a procedure. Visual learning users typically prefer reading instructions or watching tutorial video during the learning process;

while verbal learning users prefer to listening to instructions in the spoken language during learning. Theoretically, users will have different learning performance when given different sense modality of stimuli (Cassidy & Eachus, 2000), to be more specific, how users absorb and retain knowledge depends on whether the information is presented in their preferred learning styles (Zapalska & Dabb, 2002). For example, if a user prefers the visual learning style, her/his performance will be much better when given pictures, videos or charts and diagrams as main learning materials than verbal instructions. As a result, identifying the learning style of users will be beneficial for both trainees and instructors because trainees can learn better if provided suitable learning method, while instructors can tailor their class or training section to better accommodate trainees.

Presenting information to learners by multiple learning modalities could increase their learning performance, no matter what their own learning style is (Rolfe & Cheek, 2012). For traditional training, users often receive visual and verbal learning, for example, nursing skills are often taught in a lecture model and students receive their demonstration from the instructors (Smith et al., 2016). However, immersive VR training could provide trainees with a chance to include kinesthetic learning modality. When users are trying to complete each task in a virtual environment, they need to perform the task with hands-on experience. Chang, Yeboah, Doucette, Clifton, Nitsch, Welsh, and Mazalek (2017) stated in their paper that kinesthetic system is not a passive system that only receives inputs from the cognitive system, but they are intricately related to each other. In other words, cognitive progress would affect bodily states and actions, while bodily states and actions in the environment can shape the cognitive progress. This provides evidence that kinesthetic training will influence the training outcomes. We hypothesize that with an extra kinesthetic learning modality, carefully designed immersive VR training could boost the trainees' final learning performance compared to the traditional training.

Descarreaux, Dugas, Lalanne, Vincellete, and Normand (2006) designed their experiment to test whether augmented feedback related to various kinetic parameters would finally contribute to medical students' performance in spinal manipulation therapy. Their study was a comparative study which divided the fourth-year medical students into two groups, one of the groups received the traditional training method like receiving instructions from instructor, while another group of students received augmented feedback training using an instrumented manikin. The result showed that participants from feedback training group significantly reduced their peak force variability and increased their preload force, which highlighted the merits of practicing with an instrumented manikin or other supplement equipment. The result suggested the kinetic training could increase the retention of motor skills for chiropractic students.

Féry and Morizot (2000) conducted an experiment to test what influence the kinesthetic and visual image could cast on motor skills. In their experiment, they provided all participants (no experience) with tennis serve training, and two main independent variables are: 1) kinesthetic image vs. visual image training; 2) with mental practice vs. without mental practice. They divided the participants into four different training groups: 1) kinesthetic training with mental practice; 2) kinesthetic training without mental practice; 3) visual representation training with mental practice; 4) visual representation training without mental practice. Their findings suggested that kinesthetic training was better than visual representation training in terms of speed scores and form performances, however, this benefit only existed when the learners had the time and opportunity to rehearse the training process in their mind before the test.

Learning with motor feedback can give participants' the real experience of how the accuracy of a specific action and may contribute to procedural memory. Immersive VR training provides trainees with a great opportunity that they can learn the whole procedural with hands-on experience. This might contribute to learning procedural knowledge and finally contribute to knowledge retention after receiving the immersive VR training.

2.4 Procedural Training in Virtual Reality

In the past few years, VR training and education has received great attention from researchers. VR training can decrease the training cost, especially considering the case that some traditional training will involve many experienced workers during the training or decrease the productivity due to the shutdown of devices (Carlson et al., 2015). Another situation is when we train new learners to operate on scientific devices, these devices are easily damaged due to the inexperienced operations, and typically the devices are very expensive. Some of the operations, such as pulling liquid nitrogen to a specific container, if not skillfully carried out, can cause damage to trainees. VR training provides a simulation environment which can reduce the training cost and guarantee the trainees' safety. VR training can also serve as an important training tool for training health care professional with inadequate skills in dealing with decontamination from disaster events (Smith et al., 2016). In Smith et al.'s (2016) experiment, they simulate the disaster scenario and let 108 participants (nurse students) do the decontamination job on a virtual manikin. It is almost impossible to carry out traditional training under disaster situations, so VR can bring some new opportunities for training under hazard situations.

Researchers really care about what trainees can gain from the training, whether the skill gained is good enough compared to the traditional training and what potential factors that may affect final training results. Moreno and Mayer (2002) carried out an experiment which aimed at comparing training in head-mounted display (HMD) VR environment and training using traditional display under different instructive modes (providing narration, text and both of the two). In their experiment, the botany students were divided into three groups, and the students in each group received different training modes: desktop display training (D), head-mounted display (HMD) training while sitting and head-mounted display training while walking. They also presented the explanation under both narrations (N), text (T) or both (NT) within D and W condition. Their findings suggested that trainees scored higher on knowledge retention, transfer and programming rating in N conditions than T conditions, while the training environment (both D and HMD) did not affect the knowledge retention and transfer, although trainees felt more presence in HMD environment. Carlson et al.'s (2015) experiment suggested that different settings between the physical environment and virtual environment may affect knowledge retention related to assembly task. They first assigned the participants into an either virtual or physical training group, the task for each group was to assemble a wooden burr puzzle. The participants could try as many times as possible during the training period (with 20 minutes of limited training time). After the training, participants were tested using physical puzzles and retested again after two weeks. They found that the participants from the physical training environment performed better when they were immediately tested after the training, however, the participants from the VR training group improved their test assembly time after two weeks. The result suggested different settings of the testing assembly task affected the final result (in their case, the difference is color).

Despite the potential benefits the VR training can be, researchers also care about the training transfer rate from the VR training. The knowledge gained in the VR training environment should be able to transfer to a physical environment. Ganier et al. (2014) showed in their study that a maintenance procedure work could be learned in the virtual environment as well as in the real-world training environment. In their experiment, 42 adults were divided into 3 equally sized groups:

VR training group, conventional training group, and control group (no training, just job instruction). They measured the successful rate, time and number of guidance from the instructor when the learners performed the final test, the result showed that learners trained from VR training and physical training had similar performance, which indicated that training in a virtual environment could be transferred to a real-world setting. Lam et al. (2013) presented a VR training method to help medical students be more familiar with cataract surgery. Their cataract surgery system contains the interactive module for the whole procedure of the surgery and an assessment system to evaluate the performance of the students. By repeating the whole training process, the proficiency of students was increased. These results indicate that VR training could be beneficial for gaining cognitive skills (Jensen et al., 2018) related to procedural learning.

Dalgarno and Lee (2010) reviewed different characteristics and learning affordances of the different 3D virtual environment. They concluded that learning benefits from the 3D virtual environment could help enhance the spatial knowledge representation, increase learning motivation or establish collaborative learning between learners. Dalgarno and Lee (2010) also proposed a road map which could be considered as a guide for designing and developing the virtual environment training process. Fowler (2015) pointed out that Dalgarno and Lee's (2010) work focused mainly on technical perspective and extended Dalgarno and Lee's (2010) road map to a more pedagogical perspective: different learning stages should correspond to different 3D virtual environment settings. When it comes to design virtual environment training, we need to break down the major task into smaller components, and specifically design each component based on the functionality and objective of that trivial task, for example, if we are designing a task which requires the participants to grab a pen, and put it to the pen case, we need to consider things like how to provide instructions to the participants during this step and what the virtual hand gesture will look like when participants grab the pen.

When the question comes to under which situations VR training can really help learners to learn better, Jensen and Konradsen (2018) showed that under the learning situations like "learning cognitive skills related to spatial and visual knowledge understanding, or psychomotor skills related to head movement, or affective skills related to controlling your emotional response to difficult situations", we can see that learners can benefit from immersive VR environment to learn spatial and perceptual skills, and finally improve their procedural learning performance.

2.5 Summary

This literature review summarized the four different aspects related to procedural learning in the virtual environment. We started from defining the procedural skill and training. Understanding the relationship between procedural knowledge and training is critical to design our experiment. Long-term memory is a special memory type that is responsible for storing most skills, events, and knowledge. Implementing the VR training in a repetitive way can help trainees better build their long-term procedural memory. Researchers have already shown that training in VR environment can be as effective as training in a real scenario when the training content is related to spatial or perceptual skills. However, few studies addressed the problem that whether VR training can enhance long term procedural knowledge retention. In this study, we addressed this problem and also tested what could be the difference in the training outcomes from both training groups. Finally, researchers have shown the advantages of VR training and potential of procedural learning in VR. Some obvious advantages include the lower cost for training, easy to do repetitive training and easy to simulate dangerous situations.

CHAPTER 3. METHODOLOGY

This chapter discusses the methodology of this study. We start from the research framework, then participants and sample method, and finally the procedure of this study.

3.1 Research Framework

The Purdue CryoVR project is funded by the National Institute of Health (NIH). The goal of the project is to design a VR training tool to help novice users familiar with the operations related to cryogenic electron microscopy (cryoEM) through a safer and easier way. The equipment involved in cryoEM includes plunge-freezing instrument such as CP3 or Vitrobot and the Cryo-electron microscope. We introduced the VR training tool to the regular training section to solve two major problems: the first one is that in traditional training, inexperienced user may potentially damage the expensive device during the training section; another one is that we want to mitigate the equipment usage time required by regular training, occupying the equipment longer means decreasing the productivity of Purdue structural biology lab. This study is based on the CryoVR project. In this study, we specifically focused on procedural knowledge retention between VR training and video plus instruction manual training.

CP3 is designed for preparing the cryogenic specimen. After cryogenic samples are obtained, the samples can be observed in an electron microscope to identify the structure of the virus. Our experiment focused on procedural learning related to CP3. We choose CP3 module as learning material because learning how to use CP3 involves long sequential operations, which is ideal for testing procedure knowledge retention. Another important fact is that training how to use CP3 can be compressed within 20 minutes for both training groups (VR or video). In this study, we utilized the CP3 VR training tool which was developed for the Purdue CryoVR project as the VR training material. In this training tool, trainees need to follow the instructions given by the tool and complete each step with their hands. Operations with the device in this immersive VR training environment are similar to operations in the real lab settings. For example, if a participant needs to add liquid nitrogen to the workstation in the VR environment, he/she has to grab the nitrogen tank first, then remove the cap from the tank, and pour out some liquid nitrogen to the workstation.

Having the training tool ready provides a good opportunity for us to test the procedural knowledge retention between immersive VR training and traditional training (video + instruction manual). Screenshots of our training simulator, the training video, and the instruction manual are presented from the left to right in Figure 3.1.

Figure 3.1 VR Training Context and Video Training Context

3.1.1 Research Questions

My research questions are as follows: (1) Compared with traditional training (video + instruction manual), can virtual reality training enhance the long-term procedural knowledge retention? (2) What is the difference in knowledge retention between the two training modes? (3) What are the potential factors which make people like or dislike the training method (VR training or traditional training)?

3.1.2 Independent Variables

Based on this research question, the main independent variable is:

Training mode:

The training modes include the training by immersive VR training tool and by watching the demonstrating video plus reading the instruction manual.

In a VR training environment, participants wear a head-mounted display (HMD) device to fully immerse themselves in the virtual environment. Then the tool simulates the whole procedure related to CP3. Participants need to follow the instructions provided by the tool, complete each step with their hands (similar to operating CP3 device in a real lab environment) (Figure 3.2). Currently, our VR training tool provides two types of instructions, the first one is by text, several short sentences which describe the objective and guidance of current step are displayed in the VR room; the second one is by narrations, the tool plays sound description of the task at the same time. The training tool also highlights the target virtual object to indicate the participant to interact with it, and the whole procedure does not move forward until the participant has finished that step. In Figure 3.3, a participant is trying to pour liquid nitrogen from the nitrogen dewar to workstation. Our VR training tool highlights the workstation with the yellow silhouette and a red marker to indicate the participant to perform the task.

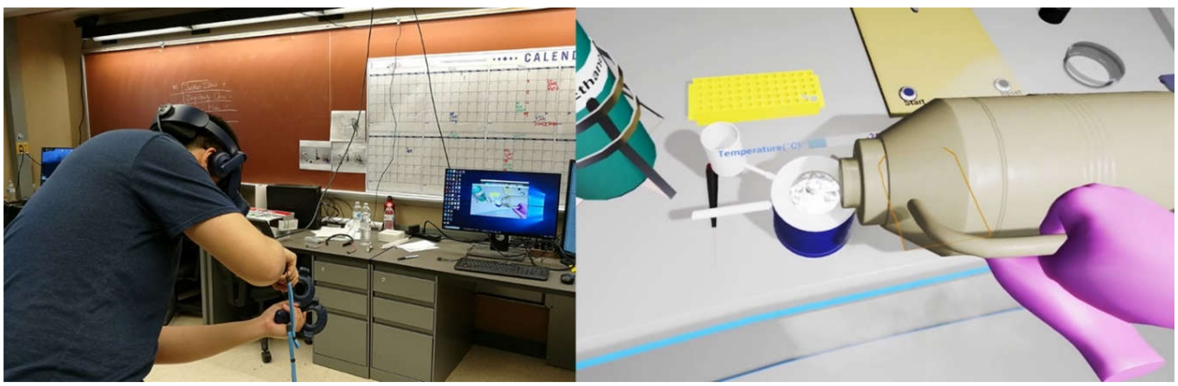


Figure 3.2 A participant receives the training through VR

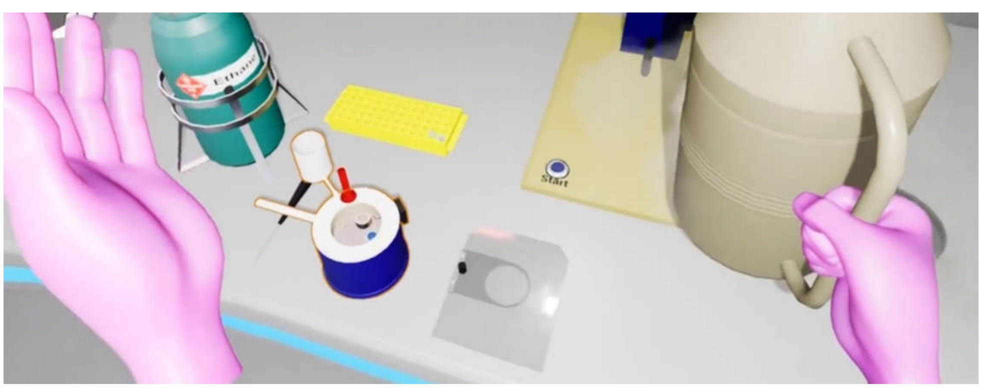


Figure 3.3 Markers in VR training

In the video training group, participants watch a training video which is recorded by an expert in a real-world scenario (third person view). The expert demonstrates the whole procedure by operating the actual CP3 device in a lab environment, at the same time, she also dictates the meaning of each step and critical points about each operation. Participants from video training group also receive an instruction manual. This instruction manual describes all the steps related to how to operate the CP3 with descriptions and images. Participants can refer to the instruction manual during the training without any limitations (Figure 3.4).

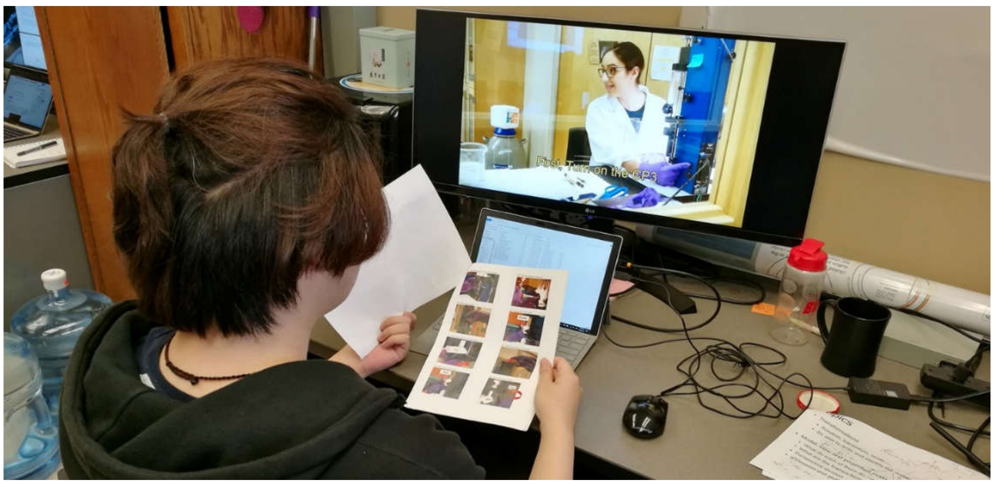


Figure 3.4 A participant receives the training through video plus instruction manual

When preparing training materials for both training groups, we divided the whole procedure into 23 sequential steps in advance. Each step represents one critical operation. We implicitly grouped our training materials (both VR training tool and training video) into an approximately similar number of steps to make it easier for participants to follow the training. However, we never explicitly told the participants to pay attention to these steps. The main objective for all participants is to understand and memorize the whole procedure of how to operate the CP3 device.

3.1.3 Control Variables

The main control variables are as follows:

1) Training time:

Each training mode has the same amount of training time, which is 20 minutes. In this study, we explicitly chose 20 minutes as the testing time for two reasons. The first reason is that the whole training time of our training material is approximately 6 – 8 minutes long (in video training group, the video is about 6 minutes long, if the participant refers to instruction manual, it might take a little bit more time; in VR group, complete the whole procedure once typically takes 6 – 8 minutes to complete). The second one is that the maximum estimate attention span for a healthy teenager or adult is 20 minutes (David Cornish & Dukette, 2009). In this study, even if we provide much longer time, participants might not be able to totally focus on the training material, especially for the video training group, and 20 minutes is long enough for participants to go through the training materials 2 - 3 times. During the training, the participant can freely explore the procedure by themselves. For example, in the video training group, the participant can freely choose to play the video multiple times or jump to any specific point of the video and watch that step. They can also refer to the instruction manual when needed.

2) Interval time period (the gap between two tests):

During the research study, participants are tested twice. One test will be carried out immediately when they finish the training, another test will be carried out after approximately two weeks after the training. The average time interval for the video training group is 13 days, with a standard deviation to be 1.15 days, and the range is between 11 to 14 days; while the mean time interval for VR training group is 13.36 days, with standard deviation to be 1.12 days, and the range is between 12 to 16 days. We chose two weeks as the interval time period (gap) because two weeks are long enough to test the long-term memory retention (Lang et al., 2018).

3) Test section:

We developed an online sorting game to test whether participants can remember the whole procedure. Participants from both training groups took the same test after the training. In this online sorting game, we presented 23 cards through a website which represent 23 major operations related to CP3. At the very beginning, all the cards are shuffled randomly. Then the participants need to drag and move each card to the corresponding position to rebuild the right sequence. During the testing, their final sequence and the total time they spent on sorting were recorded (Figure 3.5).

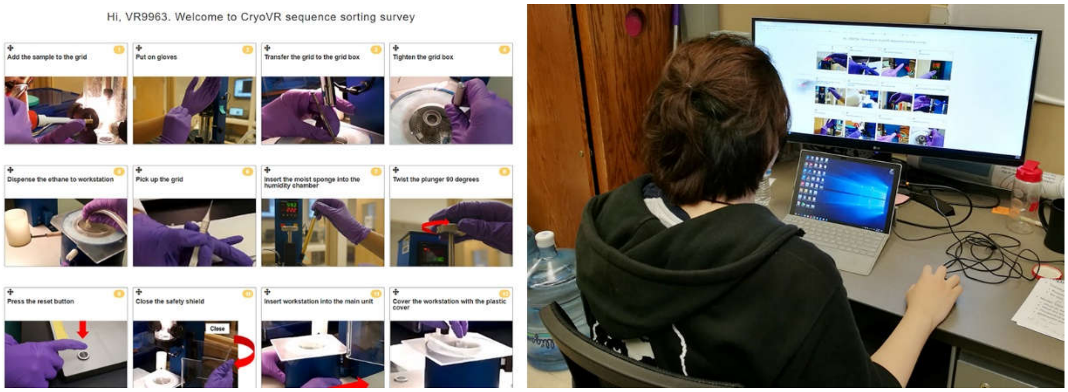


Figure 3.5 Testing Section

3.1.4 Dependent Variables

The main dependent variables are as follows:

1) Recall errors

This measures how many errors the participants made when they recall the whole procedure. During the testing section, the final sequence of each participant was recorded. We utilized the Levenshtein distance comparison algorithm (Wagner and Fischer, 1974) to calculate the string distance between the participants' sequence and our correct sequence. We considered the calculated value as errors.

The general idea of the algorithm is as follows: in this algorithm, we define 3 operations: insertion, deletion and replacement of a character in the given string S. In order to calculate the difference between the given sequence (S) and our target sequence (T), we need to apply the 3 operations to S in order to transfer it to T. During the transformation, we calculate the minimum number of operations we need to apply to S, and using this number as the distance (errors) between the two strings. The formula for calculating Levenshtein distance is given below (Figure 3.6):

$$\mathrm{lev}_{a,b}(i,j) = \begin{cases} \max(i,j) & \text{if } \min(i,j) = 0, \\ \min \begin{cases} \mathrm{lev}_{a,b}(i-1,j) + 1 \\ \mathrm{lev}_{a,b}(i,j-1) + 1 \\ \mathrm{lev}_{a,b}(i-1,j-1) + 1_{(T_i \neq S_j)} \end{cases} & \text{otherwise.} \end{cases}$$

Figure 3.6 Formula of calculating Levenshtein distance

In this formula, i and j represent the current length of the remaining string. Let's suppose i represents the current remaining length of target string T, and j represents the length of given string S. Then we will have the following conditions:

1) If one of the lengths is 0, which means during the operation of the two strings (insert/delete/replace 1 character in the string), at some point, one of the strings reaches the beginning (we start from the very end of the string), then the total error will be max(i, j), meaning we need to insert max(i, j) numbers of characters in the empty string in order to match another string. Then the total number of errors should be max(i, j).
2) Another situation is whether we insert 1 character from given string S (lev(i-1, j) + 1), delete 1 character from S (lev(i, j-1) + 1) or replace 1 character from S (lev(i-1, j-1) +1($T_i \neq S_j$)). If T_i equals S_j, we do not need to perform any operation, and can safely move forward i and j; Otherwise, we always increase the total number of error by 1 if we have to perform one of the 3 operations. Since we are calculating the errors recursively for all the remaining string, we need to find the minimum of all 3 possible outcomes. That is to say, considering we are at position i and j, what will be the minimum possible errors we can get after we try all the 3 possible operations. In the end, we will get the minimum total number of errors to transform given string S to target string T.

For my study, the given string S and target string T will always have the same length, which is 23. Then in general, we only need to consider two possible operations, which is swapping and replacement. Swapping actually is 1 deletion plus 1 insertion. We define the total number of error for 1 swap is 1, which means each insertion or deletion is 0.5 error. For example, if the correct sequence is "ABCDEF", we have a sequence like "BCDEFA", the algorithm will consider this as we have 1 error ('A' swapped from beginning to the end, while another subset of the string "BCDEF" is still correct); if we swap 2 characters with each other, we will consider this situation as 2 errors because we need to do 2 replacements or 2 swaps. For example, if our sequence is "AFCDEB", then we have to replace 'F' with 'B', then replace 'B' with 'F', so we will have 2 errors.

We use this algorithm to scan the sequences from participants and calculate the minimum operations (swap/replace) to transform the given sequence (participant's sequence) to our defined correct sequence ("ABCDEFGHIJKLMNOPQRSTUVW"). In this study, we only defined one correct sequence because, during the training section, our training material only demonstrated one specific sequence to all participants. It is true that some of the operations can be swapped in reality, however, we considered these swaps as invalid since we did not tell the participants that there are other valid sequences. They were expected to remember the sequence that they had learned during the training.

The errors were calculated for the first and second test independently.

2) Recall time

Recall time measures how much time the participants spent recalling the whole procedure. The recall time is also recorded for both tests. A sample data format can be found below. We will record the participant's ID, testing time, the final sequence, and the date for testing (Figure 3.7).

VE7711	458.71	["A","B","D","R","E","G","F","K","Q","J","O","L","M","N","P","C","S","I","H","T","U","V","W"]	4/26/2019 1:30p.m.
VR5570	512.715	["A","B","C","E","F","G","L","K","P","D","O","M","I","Q","H","T","U","N","J","V","S","R","W"]	4/26/2019 12:00 p.m.
VR5237	632.671	["A","B","D","C","E","G","F","K","H","T","N","U","J","I","P","L","M","O","Q","S","V","R","W"]	5/1/2019 4:30p.m.

Figure 3.7 Sample Data

After the second test, all participants filled in a short online survey. This survey includes their basic demographic information, subjective feedbacks for our training system and their strategies for memorizing each step. These data are used as a supplement explanation in the data analysis section.

3.2 Equipment and Environment Settings

Our research study is set up in the open lab environment. For VR training group, we install our training tool in a high-end desktop computer with i7 processor and GTX1080Ti graphics card.

We chose HTC VIVE as our VR goggle since HTC VIVE provides decent user experience and is compatible with our training tool. For VE training group, we just play the video on a computer with a big display screen. The instruction manual will be color printed as supplement material for video training participants (Figure 3.1).

3.3 Participants and Sample Method

Participants were all from Purdue University, they are all university students with various academic backgrounds. Since preparing the cryogenic specimen on CP3 device is more related to scientific research, most of its target users are students or researchers. We chose university students as participants could be a balance between procedural learning and CP3 context.

We recruited a total number of 27 participants (19 males and 8 females) during the study. All participants are from Purdue University, and their academic background varies significantly. All of them have no experience directly related to CP3 or Cryo-EM. Among all the participants, 55.56% of participants are among the 21-25 age group. Almost all participants' age is between 15 and 35 years old.

We randomly assigned participants to either the VR training group or video training group by using a random number generator. This generator generated a random ID for each participant, approximately half of the ID has the prefix "VR", and another half has the prefix "VE", these two prefixes represent the training groups this participant will be in. The ID also contains 4 randomly generated digits as an identifier. Once the ID has been generated for the participant, the ID number was used throughout the whole training and testing section. In the end, 14 participants (2 females, 12 males) were assigned to the VR training group while 13 participants (6 females, 7 males) in the video training group. Although all the participants were randomly assigned to different training groups, we notice that there is a bias of gender distribution in the VR training group. We discuss the potential impact in Chapter 5.

3.4 Procedure

Each participant first signed in the consent form, after that, he/she was given a short introduction about the general research background. In this section, we told the participant what is CP3 device, what problem we are going to solve (research question) and why we conduct this study.

Then participants were assigned to either VR training group or video training group by the random number generator. For participants in video training group, we provided the instruction manual, and told them that they have plenty time to go through the training video multiple times and they can refer to instruction manual during the training; for VR training group, we first provided a 1-minute video to demonstrate how to use HTC VIVE controllers and how to interact with virtual objects. Then we provided a 3-minute warm-up training. In this warm-up training, participants were teleported to a second VR level. This VR level is the same as the actual training level but has no instructions, guidance or restrictions. Participants needed to interact with most of the virtual objects in order to be familiar with the operations. These operations include grabbing, rotating, pulling, opening and closing a specific device. They would not receive any information related to the procedure.

Then participants received the actual training within 20 minutes. The major difference between training groups is that in VR training, participants have hands-on experience. For example, participants first need to grab a pipette, and suck the sample and transfer the sample to the grid through VIVE controllers (Figure 3.8). During the training section, participants can freely interact with the given training material and develop their own strategies to memorize the procedure.

Figure 3.8 Participants can interact with objects without limitation during the warm-up

After the training section, all participants received an immediate test. Participants needed to sort the cards on our website. Their final sequences and total time were recorded when they click the submit button.

Participants retook the same test after approximately two weeks. After the second test, all participants filled in a short online survey. We also asked the participants whether they want to try another training method. This option is voluntary. For those who tried another training method, we asked them to vote for their preferred training method in our online survey.

3.5 Summary

This study is a quantitative study which aims at finding the long-term procedural knowledge retention rate between two different training modes. This chapter provides an introduction to the research framework. We described the different variables, participant samples, and a detailed experiment procedure.

CHAPTER 4. RESULTS

This chapter presents the results of the study. In the first section, we present a brief summary of the data we collected. Then we analyze the data based on our proposed hypotheses. We also include some subjective feedbacks from our online survey to help identify the potential explanation about our data.

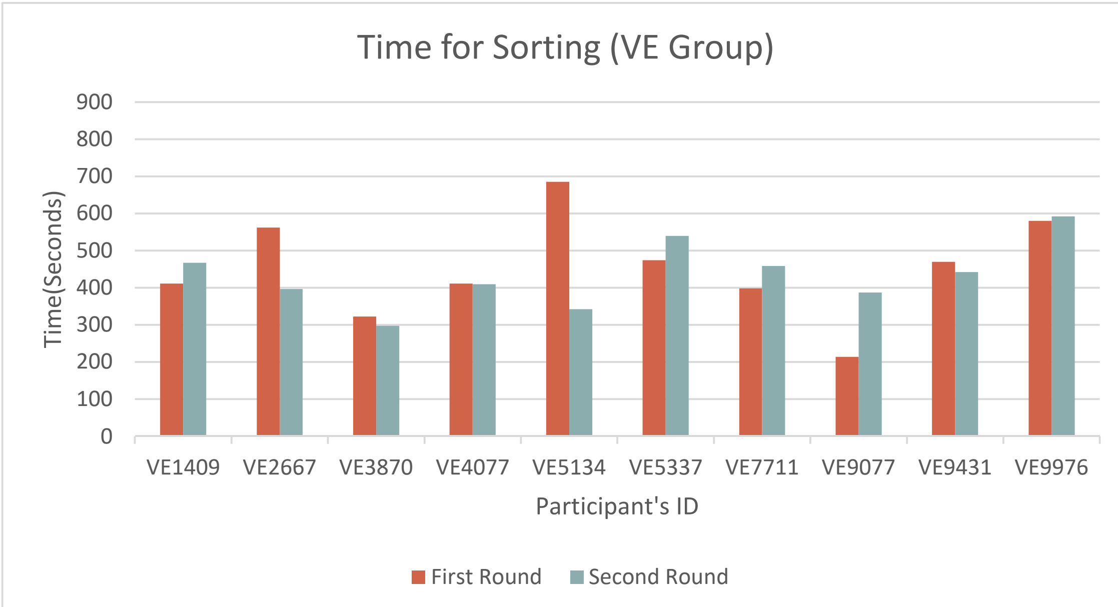
4.1 Data Representation

In this research study, we collected 27 data in total. We dropped several participant's data due to the following reasons:

1) The participant spent too much time sorting the sequence. We noticed one of the participants from the VR group spent almost three times more time sorting the sequence, even though his accuracy is not bad, we considered this data as an outlier;
2) Participants came for a second test after 16 days. We considered data from these participants as outliers because the gap between the two tests was approximately 13 days;
3) Participants performed even better in the second test.

In general, we dropped 6 records and got 21 valid data (11 from the VR group and 10 from Video group) in the end. The following 2 figures (Figure 4.1, Figure 4.2) provide an overview of the distribution of the recall time and errors respectively. From the table, we can see that recall time between both training groups is similar, while the errors are quite different. As for the errors between two test, the number of errors from the video training group during the second test increases significantly compared with the first test, while the number of errors from VR group increases much slower compared with video training group. We provide a detailed statistical analysis in the next section.

A) Recall Time from Video Training Group



B) Recall Time from VR Training Group

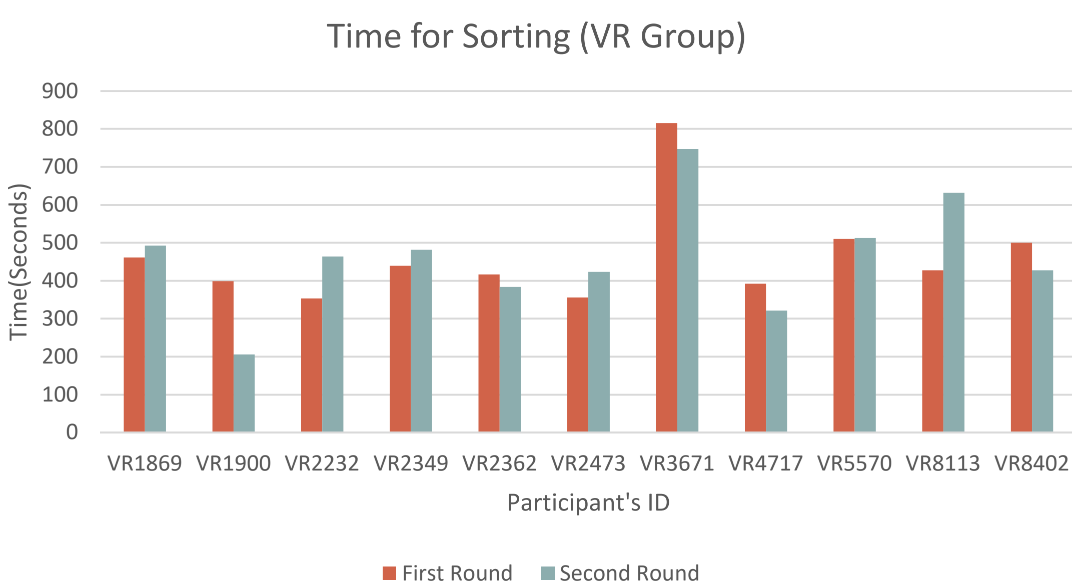
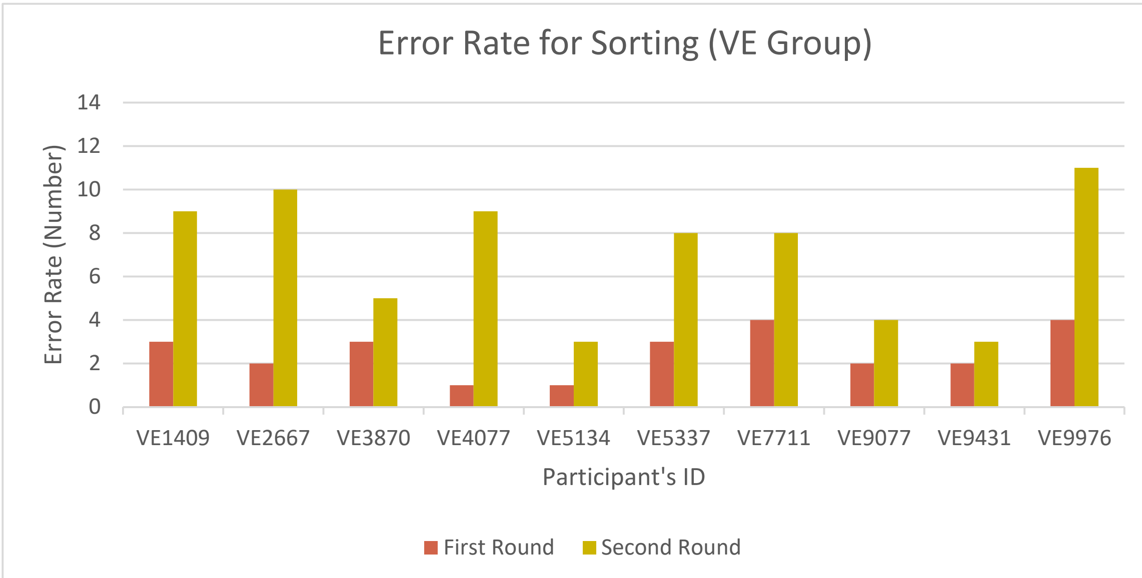


Figure 4.1 Recall Time

A) Recall Errors from Video Training Group



B) Recall Errors from VR Training Group

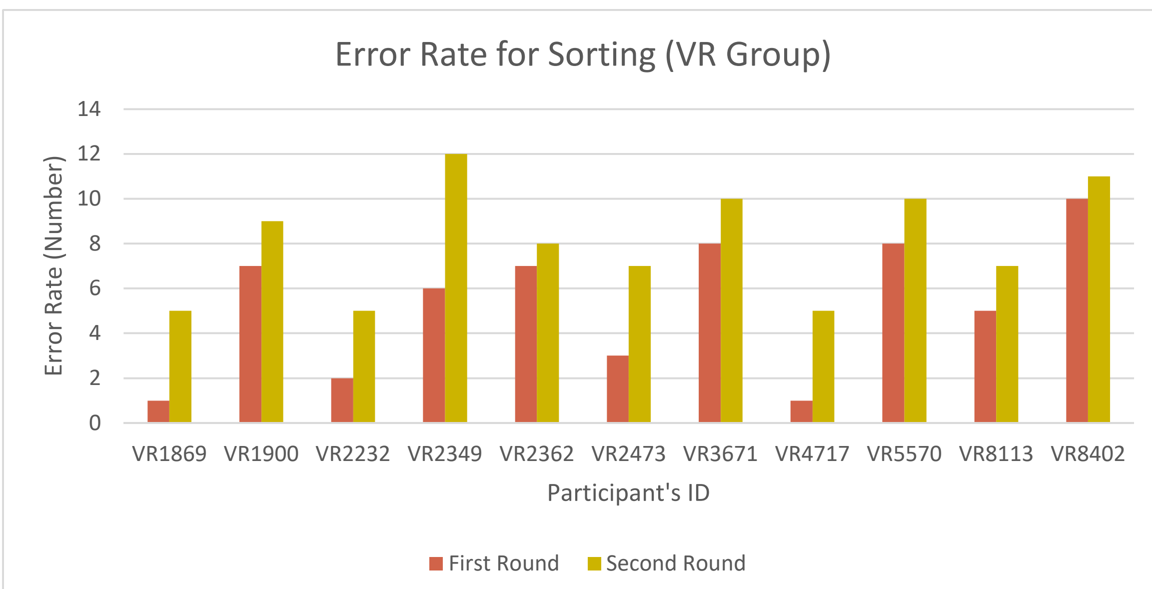


Figure 4.2 Recall Errors

4.2 Statistical Analysis

In this section, we provide a detailed statistical analysis of our data. We analyzed the data based on our proposed hypotheses through independent samples t-test, with alpha value to be 0.1.

1) Recall time:

We first tested the hypothesis that there is a significant difference in recall time between two training groups.

The mean and standard deviation of testing time can be found in table 4.2. The average recall time from video group for the first-round test is 452.80 seconds, the standard deviation is 134.81 seconds, while the corresponding recall time for VR group is 461.12 seconds, the standard deviation is 128.07 seconds. As for the second-round test, participants from the video group spent 433.32 seconds, with standard deviation to be 87.64 seconds, while participants from the VR group spent 462.94 seconds, with standard deviation to be 144.40 seconds. In general, participants from the video training group spent less time compared to the participants from the VR training group for both tests.

Table 4.1 Means and STD of Recall Time

	First Round		**Second Round**	
Recall time (s) \ Training mode	Video Group	VR Group	Video Group	VR Group
Mean	452.80	461.12	433.32	462.94
Standard deviation	134.81	128.07	87.64	144.40
Range	213.54 - 685.55	353.81-815.39	297.50 - 592.19	205.70 - 747.44
T Value	-0.14		-0.56	
P value	0.44		0.29	

Even though the data indicate that recall time for video training group is better than the VR training group, however, there is no statistically significant difference in recall time between video training group and VR training group for both first test (p-value = 0.44 > 0.1) and second test (p-value = 0.29 > 0.1). These results indicate that participants tend to finish the sorting within a specific given time period, regardless of how many steps they can still remember.

2) Recall errors

Now we test the hypothesis there is a significant difference of recall errors between two training groups.

The first thing we want to evaluate is the base error from our online sorting platform. Since for each participant, these cards were randomly shuffled at the beginning of the test. We want to know the average error from the initial random sequence. If the average error is similar to what the participant's average error, then we know that participants generally forget everything during the second test, which indicates that VR training is not better than video training in knowledge retention. In order to evaluate the base error rate, we carried out 5 independent tests. We randomly shuffled the 23 steps 500, 1000, 5000, 10000 and 20000 times, whenever we shuffled the sequence, we calculated a new recall error. In the end, we calculate the average error for each test and the average errors are 16.03, 16.08, 16.09, 16.10 and 16.09. In this study, we will consider the average error to be 16.

The mean and standard deviation of recall errors is presented in table 4.2. For the first round testing, the average recall errors for video training group is 2.5, with a standard deviation of 1.08; while for VR training group, the average recall errors are 5.27, with a standard deviation of 3.1. From the data, participants from the video training group perform significantly better than participants from the VR training group (p-value = 0.0074 < 0.1) in the first round test. For the second round test, the average recall errors for video training group increases to 7.0, with a standard deviation of 2.98; while for VR training group, the mean is 8.09 and the standard deviation of 2.51 respectively. In the second round test, there is no significant difference between the training groups (p-value = 0.18 > 0.1).

These results indicate that both training materials can help participants learn how to operate the CP3 device. For both training groups, their average errors (video: 2.5, VR: 5.27) are significantly better than the base errors (16.0) in the first test, this is even true for the second test (video: 7.0, VR: 8.09). We can see that participants can indeed transfer what they have learned in the training section to the testing section. These results also indicate that well-organized video training might be more helpful for short term memory. After a long time period, video training group tend to forget more steps compared with VR training group. Our data also shows that the

VR group performs significantly worse than the video group. The reason may be that most participants from the VR training group have little experience using the VR device. Among the 14 participants from the VR training group, only 1 participant reported that he/she is an experienced VR user (have tried more than 20 VR demos or games), 2 participants reported that he/she has some experience with VR (more than 5 but less than 20 VR demos or games). Lacking the experience makes it difficult for the participant to go through the whole procedure more than twice within the 20 minutes training time. In general, the video training group, participants can easily watch the video 3 times. Some participants from the VR group leave the feedbacks like we need more time to get familiar with VR devices or we find it difficult to interact with the virtual objects. These challenges slow down the whole training process and potentially break the integrity of the procedure, finally affect the testing results.

Table 4.2 Means and STD of Recall Errors

	First Round		**Second Round**	
Recall errors \ Training mode	Video Group	VR Group	Video Group	VR Group
Mean	2.5	5.27	7.0	8.09
Standard deviation	1.08	3.10	2.98	2.51
Range	1 - 4	1 - 10	3 - 11	5 - 12
T Value	-2.68		-0.91	
P value	0.0074		0.18	

3) Time and error difference between the two tests

The last hypothesis we tested is whether the difference of time (DoT) and the difference of errors (DoE) between the two tests are significant. Here the difference of time (errors respectively) is the recall time (errors) from the second test minus the time (errors) from the first test.

We present the mean and standard deviation of DoT and DoE in table 4.3. The mean of DoT from the video training group is -19.48 seconds, with standard deviation 143.01 seconds; for VR training group, the mean is 1.82 seconds and the standard deviation is 107.05 seconds. The negative mean value represents that in the second test, video training groups spent less time on sorting. However, there is no significant difference in DoT between video and VR training groups (p-value = 0.35 > 0.1). The mean of DoE from the video training group is 4.5, with standard deviation to be 2.68, while the mean from the VR training group is 2.82, and the standard deviation is 1.54. Our data shows that the VR group forget much fewer steps in the second test compared with the video group (p = 0.045 < 0.1).

This result indicates that VR training can help enhance the long term retention in term of recall errors, however, the DoT doesn't show any significant difference. Even though video training group performs better in both the first and second test, the VR training group actually shows the participants forget fewer steps after approximately two weeks.

Table 4.3 Means and STD of DoT and DoE

	The difference of Time (DoT)		**The difference of Error (DoE)**	
Training mode	Video Group	VR Group	Video Group	VR Group
Mean	-19.48	1.82	4.5	2.82
Standard deviation	143.01	107.05	2.68	1.54
Range	-343.03 - 173.72	-193.62 – 203.87	1 - 8	1 - 6
T Value	-0.39		1.79	
P value	0.35		0.045	

4.3 Feedbacks from Online Survey

In this section, we present several important feedbacks from our participants. Their feedbacks serve as a potential explanation about our data and help us summarize several important rules that can be used to guide the design of future VR training. We also present the preference of participants who have tried both training methods.

We collected a total of 26 valid surveys after the second test (one participant from the VR group mistakenly fill in the survey designed for video group). Just as we've mentioned before, among 13 participants from the VR group, only 3 of them reported they have some experience using VR training demos or games, less experience with VR might be a great hinder affecting the performance of VR training group. Another problem that participants from the VR group pointed out is that VR training lacked the detailed context. People could easily follow the instructions during the VR training but still felt confused about the reason why they needed to do this (Figure 4.3). This could be another factor which makes the VR training result worse.

There are less explanation about the reason why I did this in each step, it may be difficult to establish the connection between each step.

I am not familiar with the terms related to the tools. I spend some time to understand them. Plus, I do not know what is the machine for and what is the meaning of each step, which makes those steps nonsense.

- The narration speed is little fast for me. - While I followed the training procedure, I did not realize what is purpose of this chemical experiment and each step. I think that if I learn the purpose of the chemical experiment and basic terminology, I might well memorize each step.

Figure 4.3 Some Comments from VR Training Group

Despite that people reported that they had difficulties using the device or had difficulties to understand the overall context, when we asked whether the VR training is effective for learning CP3 device, 69% of the VR participants voted a score of 9 and 10 for VR training. According to Net Promoter Score, participants who give a score 9 or 10 are classified as promoters, which means these participants are highly likely to make positive referrals to other people (Reichheld, & Markey, 2011). Then we concluded that most participants considered that the VR training is more effective (Figure 4.4).

Figure 4.4 Most VR participants think VR training is effective

In the video training group, many participants thought the training video is clear and narrations are descriptive, however, some participants pointed out that video might lack small and significant steps and the instruction manual was oversimplified about the whole procedure. When we asked them to vote for the effectiveness of video training. Only 29% of the video participants voted the video to be effective (Figure 4.5).

Figure 4.5 Only a few participants from video group think video training is effective

After the second test, 24 participants tried both of the training method (VR training participant watched the video or vice versa). They also voted for their preference for the training methods. From the data,19 participants prefer VR training to Video training (Figure 4.6). The main reasons why they prefer VR training are as follows:

1) VR training provides hands-on experience;
2) Training in a virtual environment makes trainees stay focused on what they are doing;
3) VR training provides step by step guidance, which can make trainees easier to follow with his/her own pace;

The main reasons that participants dislike VR training are as follows:

1) VR training lacks detailed context. Participants felt they could easily follow the step by step guidance during the training, however, they still could not totally understand the meaning behind the scene. We need to provide a clear overview of the training and much detailed description of each step in the future;
2) Participants need more time to get themselves familiar with operations in the VR environment;
3) VR environment simplifies the equipment (3D models are simplified compared with the real device) and makes testing more challenging.

We have 5 participants voted for video training due to the following reasons:

1) The training video has a real lab environment and physical devices, which brings more technical details during the training;
2) The instruction manual can provide further information at one's own leisure.

The main reasons that the participants dislike video training are as follows:

1) The instruction manual is oversimplified and it seems not to align with the training video.
2) Video training lacks a detailed context. This might be a similar problem as VR training, participants think it might be better if we provide a more detailed explanation about the meaning of each step.

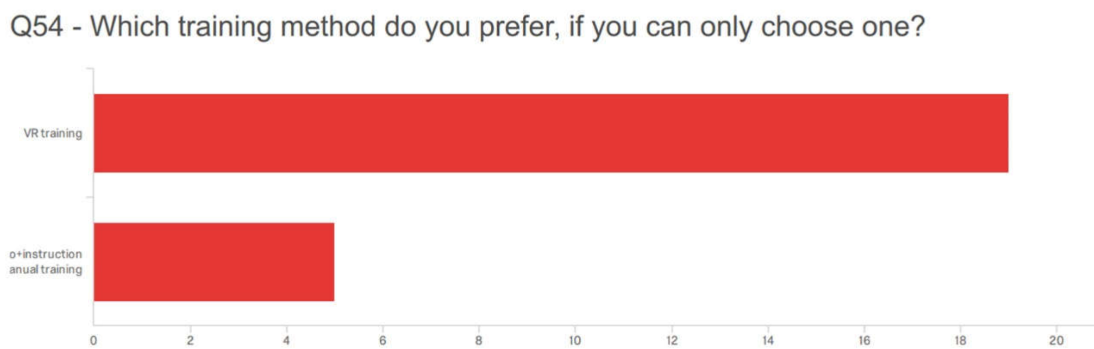


Figure 4.6 Participants who tried both training methods preferred VR training

Even though most people think that VR training is more effective in our online survey, we can see that in the first-round test, participants from the video training group still performs significantly better than VR training participants. People show great interest in VR training maybe because it involves new technologies. However, as indicated by the survey, people still prefer learning through VR to learning through video plus instruction manual.

4.4 Summary

In this chapter, we present the data and analyze the data in detail. We can see people show great interest in VR training and VR training can enhance the procedural knowledge retention compared with video training in terms of errors, however, there is no significant difference in terms of recall time.

CHAPTER 5. DISCUSSION AND CONCLUSIONS

In this chapter, we present a general discussion about the results and form our conclusions. We also present the contributions of this research study, limitations and future work.

5.1 Discussion

In this study, we tested whether VR training can enhance long-term procedural knowledge retention compared with the traditional training method. According to our research questions, we proposed 3 hypotheses:

The first hypothesis we proposed is that there is a significant difference in recall time between VR training group and video training group. We initially assume that participants from the VR training group can finish the sorting earlier, given they can remember the operations more clearly. However, the result turns out to be no significant difference in recall time from both tests. The potential reason for this is the total amount of cards the participant can sort is 23, for most participants, no matter how many operations they remember, tend to finish the sorting within a given time period. In our 21 participants' records, 16 participants complete the sorting within 500 seconds. In the second test, the data indicates that they tend to finish the sorting even faster compared to the first test. Participants might rely more on guessing in the second test. Whenever participants could not remember some steps, they might make a quick guess and this reduced the overall testing time for both training groups.

The second hypothesis is that there is a significant difference in recall errors between the two training groups. Initially, we assume that participants in the VR training group will perform better than participants in the video training group. The data indicates the opposite situation. Even though in both tests, the VR group performs worse than video training group, we can still clearly see that VR techniques can be applied to train participants on how to learn procedure knowledge. Just as Ganier et al.'s (2014) paper suggested, what people learned in the virtual environment can be transferred to another context. The data also shows that in the second-round test, there is no significant difference in recall errors between the two groups. This indicates that participants from video training group forget more steps compared with participants from VR training group, which also means VR training can help to retain more procedural knowledge after a relatively long time period (approximately 2 weeks in this study).

Then we have the third hypothesis that VR training can enhance long term procedural knowledge retention in terms of the difference of recall time and difference of recall error. Our data do not show any significant difference in terms of DoT. This might be the same reason as we discussed before: participants tend to finish the test within some time-bound, regardless of how many steps they have forgotten. Our data also shows that VR training is significantly better in terms of DoE, which provide evidence that VR training can help enhance long-term procedural knowledge retention.

In this study, we focused on testing procedural knowledge retention. To be more specific, we focused on testing whether participants can still be able to remember the procedural sequence in the second test. The best way to carry out the test might be to put the participants into the real physical environment and let them replicate the whole procedure with their hand. This could help us evaluate whether VR training can help enhance the procedural memory (non-declarative memory), which in the end help participants to recall more steps after a relatively long term period (2 weeks). In our current study, we only let the participants sort the cards, which not only provides too many visual hints (we only have 23 cards) but also hard to evaluate how significant the procedural memory will be when recalling the procedural knowledge. When participants sort the card, they rely more on declarative memory which they have learned during the training. We can only infer that VR provides hands-on experience, which might help participants form the procedural memory related to CP3 operations, and in the end, help them forget fewer steps in the second test. Lacking the physical presence in the real environment is one of the limitations of this study.

Another interesting observation from this study is that most people feel VR training is promising and they prefer receiving training in VR environment. Although people's preference may be because of the novel technology, we can foresee this attraction can be useful in a future training section. If the training method is defined as below: participants can try the demo as many times as they want until they feel confident to take the test. People are more likely to stay focused on VR for a much longer time and are willing to try the demo more times compared with watching a video or reading a manual. This will eventually help them learn better. Actually, the typical lab training will involve repetitive training for multiple times, VR training might help break the barrier that trainees may feel bored easily when receiving traditional training multiple times.

From the study, if we want to improve the VR training, we need to follow several rules: 1) make the objective clear and easy to follow; 2) provide sufficient context for trainees, like why we need to do this, what is the consequence if we do this; 3) before having participants try the actual training, implement a warm-up mode to get people familiar with VR devices and learn how to interact with the virtual objects. With these rules, we can potentially improve the procedural learning experience in VR and boost the performance of trainees. Our data suggested that a well-tailored VR training tool can be a great supplement training method for procedural learning. By incorporating VR training into traditional training, we can not only reduce the training cost but increase the procedural learning outcomes.

5.2 Conclusions

In this study, we conclude that VR training can help enhance procedural knowledge retention in terms of DoE. However, the effectiveness of VR training also depends on many other factors, such as whether the training objective is clear enough, whether participants are familiar with VR operations or whether the interactions during the training is natural enough. These factors are critical and should be considered in future VR training design. We do not find any significant difference in recall time between VR training group and traditional training group. People, in general, show more interest to receive VR training and prefer having hands-on experience through the training.

5.3 Contributions

From the previous literature review, we know that many researchers have tested whether immersive VR can be applied to learn procedure knowledge and what factors may affect the immersive VR training outcome (Smith et al., 2016; Ganier et al., 2014; Lam et al., 2013). First of all, our data shows that VR training can indeed help people gain procedural knowledge after the training, this conclusion is similar to Ganier et al.'s (2014) study. Despite a lot of research has been carried out, few studies have addressed the procedural learning retention in VR training context. This study fills the gap and proves that VR training can help enhance procedural learning retention. This conclusion implies that VR training, at least in a procedural learning context, can be a promising training method and should be incorporated into the traditional training procedure. Let along that VR training is much cheaper and sometimes even safer compared with traditional training.

Our data also shows that the effectiveness of VR training also depends on many other factors. In our two tests, VR training group actually performs worse than Video training groups. When we analyze the reason behind it, we summarize several important key points from our data and participants' feedback. These points aim at improving the VR training outcome and can serve as the guidance for future VR training development.

5.4 Limitations and Future Work

We will discuss several limitations of the current research study. The first limitation is that the total number of participants is not sufficiently large. Currently, we only have a total number of 21 valid participant's data (11 for the VR group, 10 for video group). In order to make our conclusion more reliable, more participants are needed.

The second limitation is that during the training, we did not provide sufficient warm-up time for participants from the VR training group. We notice that during the VR training, participants feel confused about some operations and can get stuck there for some time. This may decrease the overall performance of the participants. If participants get stuck in one operation for a relatively long time, then it will be difficult for them to understand the overall procedure.

According to the feedback from our participants, we should provide a more detailed explanation of each step for both training groups. Participants not only expect to know how to perform the specific operation, but they also want to know why they need to do this and what will happen if they make mistakes.

As we have mentioned in the discussion section, we only tested the procedural knowledge retention by sorting cards. However, we can have many other options, such as answering the multiple choice questions and interacting with 3D printed physical devices, to evaluate procedural learning. We leave the other testing methods for our future studies.

We also noticed that in VR training group, among the 14 participants, we only have 2 female participants. Considering the fact that typically females play fewer video games, our results may not accurately reflect the general trend of all population samples due to the biased gender distribution.

The last limitation of current work is that we only test the procedural knowledge by sorting cards. It might be better if participants can operate on premade physical models (not necessary to be the real device). This testing will show whether participants can really understand the whole procedure and show whether VR training can help form long term procedural memory.

In this study, we tested whether VR training can enhance long-term procedural knowledge compared with traditional training. In the future, a natural problem is that how can we improve knowledge retention rate by modifying the VR training context. For example, we may design different VR training methods for all users, and test which methods help enhance the long term knowledge retention. These training methods may include: 1) Guided training + testing vs. only guided training; 2) Guided training with gaps between two pieces of training vs. Only guided training. Another natural problem is to include a mixed training (video + VR) method and test whether the mixed approach can help improve the participants' training outcomes. Since some participants leave feedback like if they were given the video training first, then given the VR training, they will learn much better. We can evaluate this statement by incorporating a new training method in future study.

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APPENDIX A. FEEDBACK FROM ONLINE SURVEY

Section 1: Thank you for participating in this study. In the following section, we ask that you help us by providing basic demographic information. Your information will only be used to analyze the data and will not be distributed.

1. Please enter your test ID (e.g. VR1234): _______
2. Gender:
    a. Male
    b. Female
    c. Other: _____
    d. Prefer not to answer
3. Age group:
    a. 15 or younger
    b. 15 to 20 years old
    c. 21 to 25 years old
    d. 26 to 30 years old
    e. 31 to 35 years old
    f. 36 to 40 years old
    g. 41 to 45 years old
    h. 45 or order
4. Ethnicity: _________
5. Experience with CryoEM:
    a. None
    b. Less than 6 months
    c. Less than 1 year
    d. Less than 3 years
    e. 3+ years
6. What is your education background? (e.g. mechanical engineering, structural biological, social media, etc.) : _____
7. Did you receive VR training or video + instruction manual training?

a. VR training
b. Video + Instruction manual training

Section 2: The following questions related to your experience with our training methodology and training tools. Your feedback is important to us for further improving our training system.

- The following questions are designed for VR CP3 Module trainees:

1. How much video game experience do you have?
    a. I am an experienced game player, I frequently play almost all sorts of games including console game, mobile game, etc.;
    b. I am an experienced game player, but most games I played are mobile games;
    c. I am not an experienced game player, I just sometimes play some casual games for fun or play some video games with friends;
    d. I seldom play video games. If I have a choice, video games will never be the top choice for entertainment;
    e. I almost never play video games
2. How much VR experience do you have?
    a. I am a VR lover, I have tried more than 20 VR games or technique demos;
    b. I have some experience, I have played more than 5 VR games or technique demos (less than 20 though);
    c. I have only experienced less than 5 VR demos or games, but I have tried VR before;
    d. I have never tried any VR demos or games
3. According to your past experience, do you think that VR training is helpful to enhance hands-on learning?
    a. Yes, I think VR is useful.
    b. Probably yes
    c. Might or might not
    d. Probably not
    e. Definitely not

4. Did you experience any difficulty when receiving the procedural training in VR environment?
5. Were you able to follow the training procedure in the VR environment?
    a. Definitely yes.
    b. Yes
    c. Yes, but with some difficulty
    d. Not really
    e. Could not follow at all
6. What will be the main factor that might hinder you from following the training procedure?
7. Did you try to memorize each step when you were using the CP3 VR Training Module?
    a. Definitely yes
    b. Yes
    c. Yes, but with some difficulty
    d. Not really
    e. No
8. Could you please briefly describe your strategy for learning and memorizing the steps in the CP3 VR Training Module if for the above question your answer is Yes?
9. On a scale from 0-10, could you rank the training effectiveness of our CP3 VR Training Module? ____
10. If possible, please provide a brief review of the VR training system. Suggestions are extremely important.

- The following questions are designed for Video trainers:

1. Did you experience any difficulty during the training while watching the video and reading the instruction manual?
    a. Definitely yes
    b. Yes
    c. Not really

d. No difficulty

2. What difficulties did you face when reading the instruction manual and/or watching the training video? (e.g. the content is not clear)
3. Do you understand the training procedure demonstrated in the video?
   a. Yes
   b. Not really
   c. No
4. If the above question, your answer is No, which part really confuses you?
5. Please briefly describe your strategy for learning and memorizing the steps while watching the training video and/or reading the instruction manual:
6. On a scale from 0-10, could you rank the training effectiveness of video + instruction manual training? ____
7. If possible, please provide a brief review of the video training and instruction manual system. Suggestions are extremely important.

Section 3: If you tried another training method this time, please fill in the questions below.

1. Which training method do you prefer, if you can only choose one?
   a. VR training
   b. Video + Instruction manual training
2. Could you tell us why you made the choice for the above question? You may discuss some advantages that one training method benefits you or you may provide some disadvantages for other training methods.

APPENDIX B. CONSCENT FORM

Purdue IRB Protocol #: 1804020455 - Expires: 08-DEC-2021

RESEARCH PARTICIPANT CONSENT FORM

Virtual Reality Augmented Hands-on Cryo-EM Training – User Study

Yingjie Victor Chen

Computer Graphics Technology

Purdue University

Key Information

Please take time to review this information carefully. This is a research study. Your participation in this study is voluntary which means that you may choose not to participate at any time without penalty or loss of benefits to which you are otherwise entitled. You may ask questions to the researchers about the study whenever you would like. If you decide to take part in the study, you will be asked to sign this form, be sure you understand what you will do and any possible risks or benefits.

This study will examine the user's interaction and performance within a virtual reality training system (cryoVR) on Cryo-EM in order to improve VR training. This study will take you less than an hour to finish. You are welcomed to take multiple sessions. This system is built on a popular commercial VR platform. The potential risk is minimum as you play with any mild consumer level VR games. Other than helping the investors to improve the VR system, this study will also help participants like you to get familiar with the cryoEM environment, equipment, and procedure, which may potentially save your time and cost on training with real cryoEM equipment

What is the purpose of this study?

As a potential cryoEM user, you are invited to participate in a user study of a Virtual Reality (VR) system (cryoVR) we have developed for helping new cryoEM users to get familiar with the equipment, environment, and operational procedures of cryoEM. This project is sponsored by National Institute of Health (NIH), aims to improve cryoEM education. You are invited because you may need to use cryoEM to conduct your research or may be interested in experiencing scientific training in VR environment. Through this user study, we want to collect data to evaluate cryoVR and further improve it to make it more realistic and useful to help researchers to master cryoEM operations as soon as possible. Through your constructive feedback, we will further explore the possibilities to improve the user experience (like operations, user interface, etc.) in the VR context. We are looking for about 100 participants to participate in this study.

What will I do if I choose to be in this study?

After reading and signing this consent form, you will start the study by 1) you will receive a short introduction about this VR training system including hardware and software; 2) you will either then put on the VR goggle to perform cryoEM operation tasks in the VR simulator, or watch a video regarding the correct operations related to cryoEM; 3) Users will also be asked to sort a list of actions in sequential order from our web page. The correctness of the sorting will also be recorded. We will also ask you some questions regarding your personal feeling of our system and your suggestions about improving cryoVR; 4) In the end, you will fill in a short form to collect your basic demographic data including your gender, research area, age group, and years of experience with cryoEM; 5) After two weeks, we will contact you to finish the task 3 again.

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Your performance with the cryoEM equipment in the VR system will be recorded. We will record your operation data such as the time taken for you to complete tasks, errors and mistakes happened, times of trials it took you to finish the task. We also video record your work with the VR system so that we can analyze how realistic the system is based on your gestures and body movements. Your video will not be published. It will only be used for data analysis.

How long will I be in the study?

This study will take you less than one hour. You are welcome to participate in multiple sessions. This study will be conducted in a closed lab space. You can stop the study at any time.

What are the possible risks or discomforts?

Since you will be put into a virtual reality environment, it is possible that you may experience slightly simulator sickness with symptoms such as discomfort, drowsiness, fatigue, and vomiting. However, since this VR application does not require extensive movement, the risk is minimum as you play with any mild consumer level VR games or watch a VR movie. If you feel uncomfortable, you can stop and quit the experiment at any time. A short rest will allow you to recover from the motion sickness.

Regarding the risk of breach of confidentiality, we have safeguards in place to reduce the risk.

Are there any potential benefits?

For all participants who complete the two tests (1. first test after the training; 2. Second test: test after two weeks) our study, we will pay you 20 dollars ($10 for test 1, $10 for test2) as a reward. This VR application may help you get familiar with the environment, equipment, and procedure of cryoEM operation, which may potentially save your time and cost on training with real cryoEM equipment.

Will information about me and my participation be kept confidential?

The project's research records may be reviewed by the Office of Human Research Protections and by departments at Purdue University responsible for regulatory and research oversight.

Your participation will be kept confidential. The data we collected will be encrypted with a password, and stored in a secured private office for three years after this project is concluded. Only the principle investigator and co-investigators will have access to the data. If you withdraw from the study at any point, all your video clips and associated data will be destroyed.

What are my rights if I take part in this study?

Your participation in this study is voluntary. You may choose not to participate or if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact

Yingjie Victor Chen (first contact) at victorchen@purdue.edu, phone: 765-494-1454, or

Wen Jiang at jiang12@purdue.edu, phone: 765-494-8436

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If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu)or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.,
West Lafayette, IN 47907-2114

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

Participant’s Signature Date

Participant’s Name

Researcher’s Signature Date