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Virtual Pipetting: A Comparison of Learning Transfer in VLEs Using Handheld and Hand-Worn Controllers

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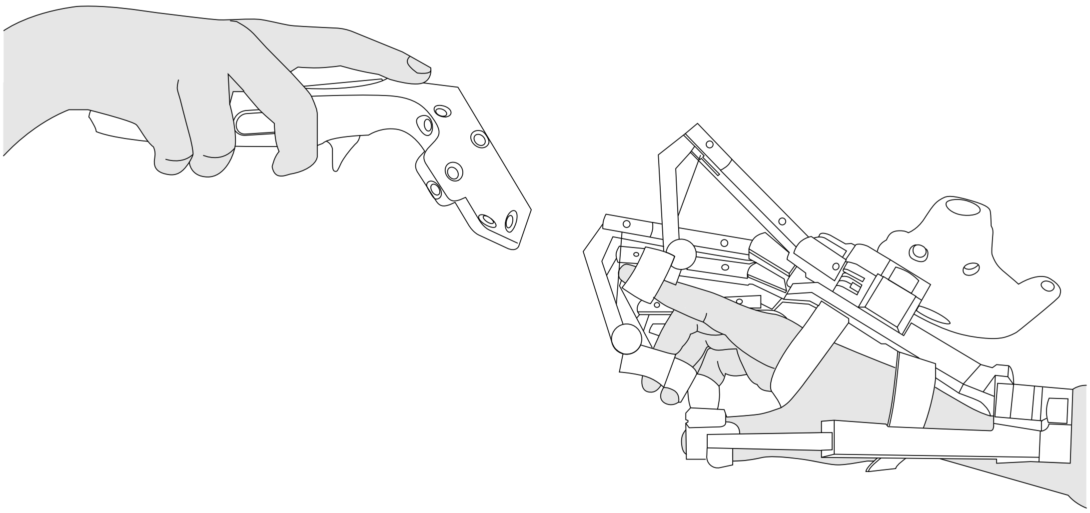
Abstract:

This paper considers the challenges and opportunities facing the teaching of procedural skills in Virtual Reality (VR). A critical evaluation was performed on a virtual learning environment (VLE) for teaching procedural skills which was stipulated by our problem statement *"Does hand-worn input controllers with a high level of execution and force feedback have an advantage over traditional handheld controllers with a lower level of execution and vibrotactile feedback for transfer of procedural skills to real life?"*. To answer the problem statement we evaluated the efficacy of learning transfer between two different treatment groups in the VLE where: (i) a Vive Controller or (ii) a SenseGlove DK1 was used. The goal was to teach forward-pipetting which is a technique that allows precise measurement of aqueous solutions such as buffers, and diluted salts. A between-subjects design was applied to prevent carryover effects from confounding the independent variable.
Participants in both groups were assessed for performance on a learning task (VP) and a transfer task (RP). In the VP participants were taught a sequence of actions in the VLE required to perform forward pipetting. In the RP, the same participants were then asked to replicate the training procedure. Performances were averaged for both tasks in each treatment group. The performances on the VP and RP were then compared amongst the two treatments. There were no significant differences of performances in the VP, however, a significant difference was found in the RP that was in favor of those who were trained with the SenseGlove DK1. The results thus indicate that hand-worn controllers with a high level of execution have an advantage over traditional handheld controllers with haptic feedback for teaching procedural skills in VR. A caveat of the present study was not all effects can be isolated and thus, it only on the compounded effect of the input system and interactions. In addition, the study used a small sample size ($N = 20$) and, therefore, it may have overpredicted performances of the SenseGlove treatment. A larger sample size should be used to get more accurate estimates.



MASTER THESIS

Virtual Pipetting: A Comparison of Learning Transfer in VLEs Using Handheld and Hand-Worn Controllers

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ABSTRACT

This paper considers the challenges and opportunities facing the teaching of procedural skills in Virtual Reality (VR). A critical evaluation was performed on a virtual learning environment (VLE) for teaching procedural skills which was stipulated by our problem statement "*Does hand-worn input controllers with a high level of execution and force feedback have an advantage over traditional handheld controllers with a lower level of execution and vibrotactile feedback for transfer of procedural skills to real life?*". To answer the problem statement we evaluated the efficacy of learning transfer between two different treatment groups in the VLE where: (i) a Vive Controller or (ii) a SenseGlove DK1 was used. The goal was to teach forward-pipetting which is a technique that allows precise measurement of aqueous solutions such as buffers, and diluted salts. A between-subjects design was applied to prevent carryover effects from confounding the independent variable.

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KEYWORDS

hand-worn controllers; haptic feedback; VR; learning transfer; virtual learning environment; education; procedural learning; force feedback; vibrotactile feedback; haptic; interaction; simulation; data glove

Contents

1. Introduction

Our ability to learn is what sets us apart from the rest of the animal kingdom. While other animals exhibit learning abilities, humans are uniquely adept. Even so, learning can still be a challenge for many of us, and it is not unusual for people to look for alternative ways to accomplish it. For example, some people claim that classical music such as Beethoven is an effective aid; others might prefer watching an online lecture. As it stands now, there is no 'silver bullet', however, in recent years we have seen the development of many new ways of learning. One of those is immersive technologies such as Virtual Reality (VR), which offer us a highly immersive alternative to traditional teaching, and is already providing a plethora of applications for learning in various fields. We are on the verge of a new paradigm for learning that will redefine the status quo of education. In this new paradigm, the classroom is no longer the 'stooges of learning'. People are free to discover and engage with real-world information in a richer, more immersive and interactive fashion with no fixed classroom location, a uniform curriculum or fixed teaching approach.

In the past few years, researchers have realized that not only is VR useful for learning and teaching in classrooms; they can be used to train workers in a number of different fields, such as communication, medical care, and even agriculture. The rise of VR education has, for that reason, become one of the buzzwords in the tech world. As with all technologies, this is only the beginning.

While the learning methods and tools available in today's classrooms can be fairly generic, it is also important to understand exactly what immersive technologies bring to the table, and if they have any benefits over traditional methods. For example, how does VR affect a student's ability to remember information and does it produce the expected learning outcome?

In the case of biochemistry, we are already starting to see proof that VR can be used to help teach students. Biochemistry is a field where the cost and safety of laboratory training are paramount. VR has the potential to be an effective tool for learning by trial and error without incurring significant financial investment in equipment. That is not to say that VR is without its risks, some people find it uncomfortable or frustrating which may hinder the learning experience. For example, one of the biggest obstacles with current VR input devices is the fact that they are usually used as a metaphor for the users hands, but oftentimes lack the fidelity to track users fingers. This can lead to sensorimotor discrepancies because the visual feedback of the user's hands conflicts with their proprioceptive feedback. To make matters worse, the absence of visual and kinesthetic sensory feedback diminishes properties and affordances that are used to convey functional value. This could severely affect learning that emphasizes the proper handling of lab equipment. Lastly, the lack of adequate feedback sometimes leads to unintentional errors, while the user interacts with virtual objects. The aforementioned issues are only exacerbated when they are all present, we should, therefore, strive for a common solution.

1.1. *Initial Problem Statement*

Based on our initial motivation for this project, we define our initial problem statement. This problem statement will serve to guide our research and identify important aspects of the design and implementation later on.

Initial problem statement:	To what extent can haptic interfaces impact the learning transfer from VR to the real environment?

2. Analysis

This chapter will serve to analyze the broader field of VR in the context of teaching procedural skills and to offer some insights into how VR can be used to improve learning and instruction. We will start with a broader look at the motor system, perception, and cognition. Once we have thoroughly established this, we shift focus to different types of skills, specifically sensorimotor skills.

The next section will examine different skills and arrive at a definition of sensorimotor competencies. After that, we cover learning theories and methodologies related to the aforementioned as well as the implications for learning transfer. The following section will give an overview of the learning affordances of 3D virtual worlds the different types of VR input devices and how they can impart signals to the sensorimotor system, that affect skills and learning as well as the performance of the VR apparatus. We will follow this up with a short literature review of haptics. Finally, we turn to input devices and how it relates to transfer with relevant examples. We finish the analysis with a reformulation of the initial problem statement and introduce our design requirements.

2.1. *Motor system*

The medium by which we feel the world around us is our body's nervous system. According to McGraw-Hill Dictionary (McGraw-Hill and Parker, 2002), the motor system is any portion of the nervous system that regulates and controls the contractile activity of muscle and the secretory activity of glands. We can divide it into various components.

Figure 1 illustrates the main components of the motor system and the neural pathways through which the motor neurons travel. Looking at the schematic we can see that muscles are the lowest level component of the motor system. It should be noted that the receptors that send impulses to the cerebral cortex can be located not only

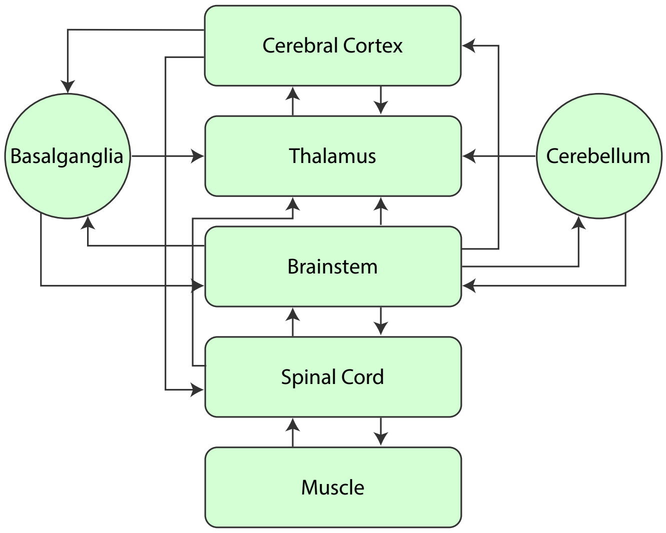


Figure 1.: Schematic diagram of the major components of the vertebrate motor systems. Adapted from (McGraw-Hill, 2004).

within the muscles themselves, but also in the joints and skin (McGraw-Hill, 2004). For example, if you touch a sharp or hot object, the reflective muscle contraction that follows right after the action is an outcome of the skin receptors sending a neural signal informing cerebral the cortex of harmful interaction with the environment (Herlihy, 2013). It only moves the part of the body that is exposed to harm, in this case, the hand or finger.

The muscle fibers that are connected to specific motoneurons create motor units which can move independently from the rest of the body (McGraw-Hill, 2004). While cardiac and smooth muscles are able to function quite independently, the skeletal muscles are entirely dependent on neural controls provided by the cerebral cortex. Since the skeletal muscle movements are carried out deliberately or voluntarily, they represent the capacity of movements and skills (William, 2010).

2.2. *Perception and Senses*

"*By means of nerves, the pathways of the senses are distributed like the roots and fibers of a tree*" (Walsh, 2017).

Our daily interaction with the surrounding world is depended on the perception of our sensory system inputs. The sensory system includes the following modalities: *audition*, *vision*, *gustation*, *olfaction*, *somatosensation*, *thermoception*, *vestibular*, *proprioception*, *nociception* and *mechanoreceptor* (Sokolowski, 2007). The perceptual system evaluates those sensory modalities allowing us to perceive the world as one unit, rather than chunks of random information (Moskowitz, 2004). Each of the sensory system modalities starts with the receptors cells that react to specific stimuli, depending on the functions of the mobility, for example, sound, light, temperature, textures of the objects, etc (Sokolowski, 2007). The sensations are then conveyed to the nerve centers spinal cord, brain, cerebellum via nerve pathways, that we have previously discussed. Here the information is analyzed and processed. Later, the nerve center sends response information to the effector organs skeletal muscles, ocular muscles, muscles of the vocal cords, etc. which as a result perform various motor actions (Fuchs, 2017). For example, when someone calls your name you turn to the direction of the sound in response. Sherrington (1911) groups the receptor into three categories:

- Exteroceptors - evaluating external stimuli from the surrounding world.
- Interoceptors - concerning the internal stimuli from within the body.
- Proprioceptors - interprets the perception of movement and position.

The dynamic between these types of receptors is also important to understand. Interestingly, sensations such as movement, can be registered not only by proprioceptors, but as also via exteroceptors (Gibson, 1983). For a long time this was not recognized due to various doctrines. For example it was believed that the individuals sense of movement, was caused by a specialized set of receptors responsible for signalling one's movements. This reflected a common connotation that had been inappropriately rationalized at the time e.g. since our eyes register light and receptors in the skin indicate touch this suggested that only special receptors were involved (Gibson, 1983). On the contrary, our eyes, ears and skin do not have specialized receptors. Rather, to resolve sensory input they often work in unison (Gibson, 1983).

2.2.1. Weber's Law

The environment that we are subjected to, as well as our bodies, are enormously complex, exposing us to an immense quantity of stimuli from the outside and from within the body. However, we react only to the stimuli which intensities are above the certain minimum level, and in some cases below certain maximum levels (Fuchs, 2017). For example, the hearing range of an average human is between 20 Hz to 20 kHz. Stimuli outside of this range will not have any effect. According to Weber's Law, the noticeable difference of stimuli is proportional to the intensity of the original stimuli (Bermejo and Hui, 2017). For example, in a quiet room you are able to hear someone whispering, while in the loud room, you might have to shout very loud in order to be heard.

Not only is the intensity of stimuli important, but the duration also plays a part. We notice only the stimuli of a particular duration. If a stimulus duration is not long enough, the stimulus will not be registered. On the other hand, if the stimulus duration exceeds a particular threshold, the sensation can weaken or completely perish (adaptation phenomenon) (Bermejo and Hui, 2017).

2.2.2. Perception

According to the Oxford Dictionaries perception is "*the ability to see, hear, or become aware of something through the senses*" (Oxford University Press). Senses without interpretation would represent a chaotic environment that would be nearly impossible to navigate. Our perception makes connections among the constant 'sensory chatter', sorting them by the source, type, direction, etc. (Macpherson, 2011). This necessarily means that we experience the same objects differently depending on context. For example, standing in front of the window we can deduct visually that the glass is transparent, and we can tell that it is solid by touch. But the pane of glass has many other properties (i.e. its temperature, whether it is wet or dry, its texture). Unless we need to pay attention to these properties in the given circumstance they are usually attenuated. We might not even pay much attention to the glass, as we are most likely interested in what is on the other side.

A glaring issue presents itself when we begin to consider what happens in our repeated encounter with a glass door. We do not simply walk into it, because we recall that it is a solid object. Although our sense and perception allow us to navigate the 'sensory chatter', it does not explain how we continue to make sense of the external world. Perceived information must be organized and stored within our memory to have any lasting impact. In the next section, we will introduce human cognition that allows us to transform incoming information into useful knowledge.

2.3. *Human Cognition*

Before we talk about learning, we need to understand cognition. Cognition is defined as the processes of acquiring and using knowledge (Jones-Smith, 2014). We often use the term knowledge interchangeably with information, but it makes sense to distinguish both in a psychological context. In layman's terms, information is facts that we can use to build knowledge. These facts are independent and therefore have no causal relationship to one another. Knowledge, on the other hand, involves the comprehension of information and arise from an internal mental organization and construction of complex mental schema (Spector, 2013). Furthermore, knowledge fuses our senses, personal experiences, emotions and/or other cognitive elements.

2.3.1. Information Processing Models

"*An information processing model is a description of the cognitive data structures a person utilizes and the sequence of cognitive operations the person executes in order to generate the cognitions and behaviors that are output from given input*" (Geen and Donnerstein, 1998)

According to the current consensus, memory can be classified following the Atkinson-

Shiffrin model which conceptualizes memory in terms of stages, types, and processes (refer to Table 1) (Atkinson and Shiffrin, 1968). The Atkinson-Shiffrin model builds on the information processing model initially suggested by Broadbent (Broadbent, 1958). It postulates that memory information passes through distinct stages before it can be stored in long-term memory. Early theories of how people process information has advocated a far simpler model where information enters the short or long-term memory directly, abandoning the notion of a serial flow of information and supplanting it with a unitary model of memory. However, it has become clear that the human mind processes information in a more complex way. Although the Atkinson-Shiffrin model remains popular, it is worth to note that there exist other alternatives such as Craik and Lockhart's (1972) Level of Processing Theory that focuses on the depth of memory processing. We will focus only on the former throughout this section.

As types	- Explicit memory - Implicit memory
As stages	- Sensory memory - Short-term memory - Long-term memory
As processes	- Encoding - Storage - Retrieval

Table 1.: Memory Conceptualized in Terms of Types, Stages, and Processes (Stangor and Walinga, 2014).

2.3.2. Memory Stages

The Atkinson-Shiffrin model (otherwise known as the modal or multi-store model) asserts that the processing or information is carried out in three stages known as short-term stimuli storage (STSS), short-term memory (STM) and long-term memory (LTM). According to the model, information starts out in sensory memory, moves to short-term memory and eventually moves to long-term memory (Stangor and Walinga, 2014) (refer to Figure 2).

Sensory Memory is considered the shortest-term stage of memory. It is affiliated with the STSS that we have previously mentioned. The STSS has a limited capacity which is constantly overwritten by new incoming stimuli. Sensory memory belongs to the category of temporary memory meaning that the information gathered is only for short periods of time (a second on average). Afterward, the information is immediately forgotten (Izawa, 1999). The main objective of STSS is to give time for the brain to find the connections between incoming stimuli. This way we can group incoming information into units rather than reacting to separate stimulus. For example, if we see a person talking we can match the sounds to the lip movements and gestures.

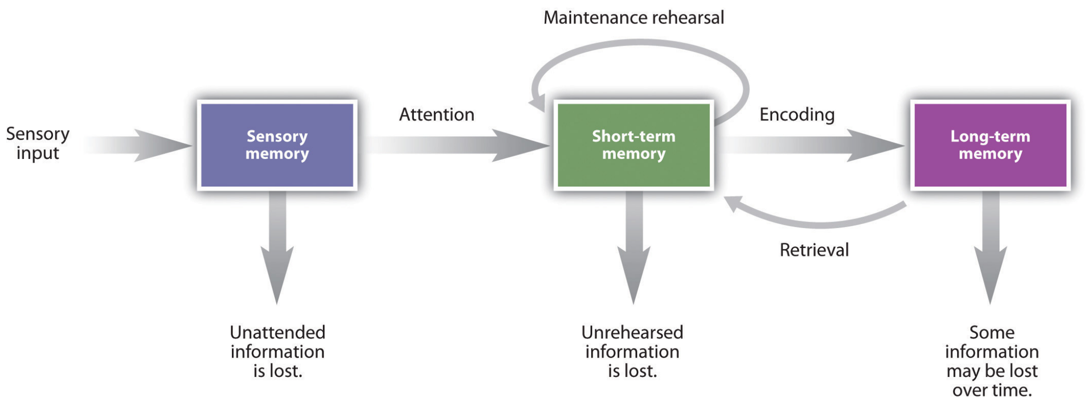


Figure 2.: The Atkinson-Shiffrin multi-store model. Retrieved from (Stangor and Walinga, 2014).

Information that we notice and attend to moves further from sensory memory to the short-term memory (Stangor and Walinga, 2014).

Short-term memory (STM) is capable of retaining information for up to 30 seconds on average. Just as sensory memory, short-term memory has a limited capacity. This means that information which is not handed off to the long-term memory can be easily forgotten.

Both short-term and sensory memory belongs to the category of temporary memory. According to Izawa (1999), a befitting metaphor is that short-term memory encodes information by neural activity in the form of electrochemical firings, referred to as an active state of memory. To better understand, we can compare the STM to a buffer, with the same characteristics as a push-down stack. In such a buffer the information is pushed down whenever it is presented with new information. Izawa (1999) states that this stack can be continuously maintained by a control process (i.e. rehearsal), while incrementally transferring information to the long-term memory. The former process also is responsible for extending the information in the STM which can be done indefinitely (Izawa, 1999). For example, one can memorize a poem by repeating it many times, thereby maintaining the information in the STM (Izawa, 1999). Due to the incremental nature of the transfer process, the rehearsal of information gives it a higher chance of transferring to the LTM. In addition, the effectiveness of this transfer may also depend on the emotional impact, associations, and achievements (Levine and Burgess, 1997).

Long-term memory is the information processing stage where information can have a seemingly timeless existence. Even in the LTM, retention of memories is not guaranteed due to decaying over time. Hermann Ebbinghaus was one of the first researchers to explore this (Stangor and Walinga, 2014).. His findings showed that information decaying is very rapid during the period of time after the information was just learned;

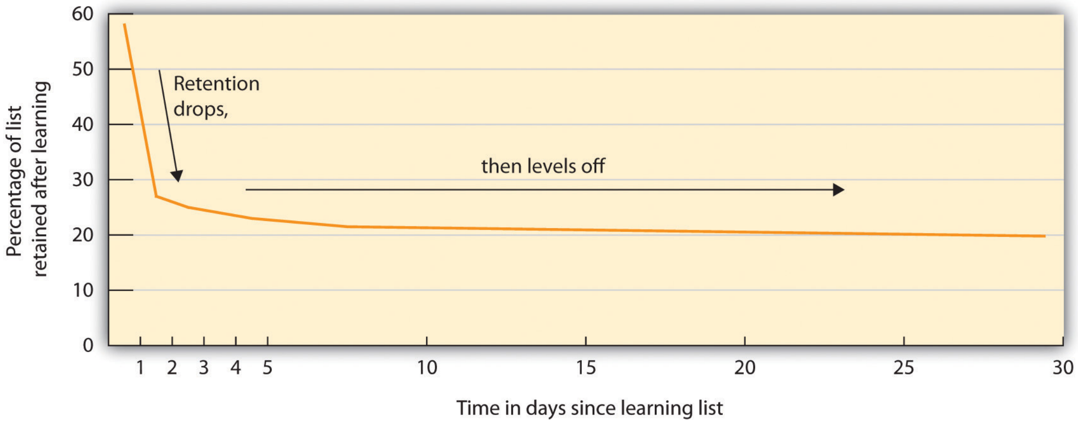


Figure 3.: Ebbinghaus Forgetting Curve. It shows that our memory of information drops off rapidly, but after some time it stabilizes. Retrieved from (Stangor and Walinga, 2014).

later, it slowly decreases until the retained information stabilizes. The possessed information remains more or less constant when the Forgetting Curve levels off (Murre and Dros, 2015) (see Figure 3).

Even as we forget information, anecdotal evidence seems to suggest that forgotten or repressed memories can resurface (Izawa, 1999). There has been some discussion about whether these resurfaced memories are in fact false memories. It can even be argued that what we remember is not the original event, but the rehearsals of that event (Izawa, 1999). That being said; we sometimes fail to recall the information – not due to the information loss – but rather as a result of a search failure within the memory storage (Izawa, 1999). It is believed that the memory structure and the communication between the three memory stages is one of the main reasons why we sometimes fail to retrieve the information (Pettifor, 1997).

One last thing to note is that the LTM does not play a significant role in the recall of information. When we talk about retrieval from long-term store the important process is that which takes place in the "active" system (Izawa, 1999). In other words, the active state of memory (as represented by sensory registers and short-term stores) enables people to retrieve the information from the LTM and draw the connections between incoming stimuli and previous experiences (Izawa, 1999).

2.3.3. Types of long term memory

The Atkinson-Shiffrin multi-store information processing model groups long term memories by their type into two groups explicit and implicit (refer to Figure 4) (Atkinson and Shiffrin, 1968).

2.3.3.1. *Explicit memory.*

According to ten Berge and van Hezewijk (1999) explicit memory affords the individual capacity to store associations, be it facts or events e.g. knowing the name of your favorite restaurant. It is mainly concerned with the reminiscence, recognition, and retrieval of information related to past events and experiences (Roediger, 1990). Explicit memory requires conscious awareness of the information that we are trying to access. We may find it easy to recall and express our knowledge at times, but sometimes we struggle. Often it is due to the memory structures we talked about in the previous chapter. We can further break down explicit memory into its sub-components which have their own characteristics. They are known as episodic and semantic memory.

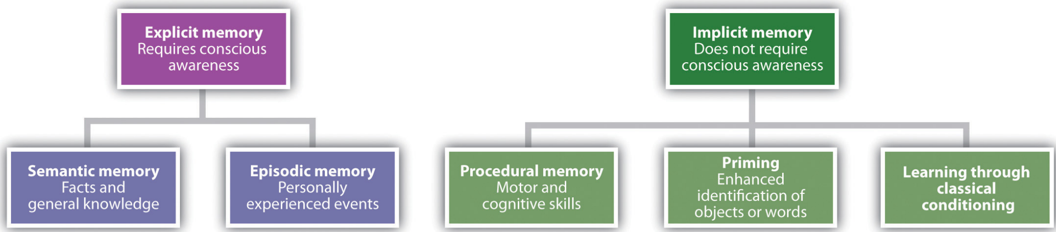


Figure 4.: Types of memory. Retrieved from (Stangor and Walinga, 2014).

Episodic memory pertains to knowledge about autobiographical or personal events with their context (e.g. time, place and associated emotions) and is linked to autonoetic awareness. Because episodic memories are tinted by ones subjective view of the world, individuals tend to also view themselves as actors in these memories (Fillit et al., 2010; Stangor and Walinga, 2014).

Semantic memory is what some refer to as generic memory because it is what generally comes to mind. Semantic memories are a more structured record of information (i.e. facts, meanings and concepts), independent from the personal experience and context from which they originated. As such, semantic memory is linked to noetic awareness characterized by personality traits and factual self-knowledge, but also includes knowledge about the external world (Stangor and Walinga, 2014).

2.3.3.2. *Implicit memory.*

Implicit memory is defined as the ability to remember things as they actually were, regardless of whether or not they relate to our current situation or our future plans. It is something that we cannot consciously control (Stangor and Walinga, 2014). The concept of implicit memory is very important because it describes information within the memory storage that you are not consciously responsible for, meaning it comes from your own experiences, rather than from anything else. There are three generic types of implicit memory: *classical conditions*, *priming*, and *procedural memory*.

Classical conditioning depicts the human capacity to associate different types of stimuli and produce a common response. For example, if we introduce a bell sound before lunchtime on a regular basis; we can be conditioned to associate the sound with food (Bitterman, 2006). This may even elicit certain bodily responses such as salivation or feeling hungry, which are conditioned responses to otherwise unconditioned stimuli (Bitterman, 2006). Conditioned responses are produced without thinking actively about them. Furthermore, we learn to associate certain actions with rewards and positive outcomes as well as others with failure and negativity. Thus classical conditioning can be actively utilized in motor activity learning by introducing various reward/penalty systems to fine tune produced actions (Bitterman, 2006).

Priming is a complex process, and only recently has it been systematically studied. It has been difficult for researchers to establish the precise mechanisms by which information is learned by the priming process (Tulving and Schacter, 1990). The priming process is unconscious and happens spontaneously in our minds (Stangor, 2012). It is often triggered by the presence of a person, a word, a situation or an environment, etc. When priming occurs we unconsciously link stimuli to information that is semantically or conceptually similar. For instance, it is common to associate an unknown person with a friend or a person we know because of their similar looks, specific behaviors, language or interests (Whittlesea and Williams, 1998). We do not learn these associations per se. Rather, the connections are made by polling existing information from our memory.

Procedural knowledge implies learned strategies, skills, or procedures that underlie the execution of various tasks and activities that we may encounter in our daily life i.e. tying your shoelaces. In other words, it is knowing "*how*" to do something emphasizing performance of motor actions and sequences (ten Berge and van Hezewijk, 1999). Procedural knowledge is typically non-conscious or tacit which makes it difficult to articulate and hence more poorly conveyed compared to declarative knowledge (Gottfredson, 2001).

2.4. *Skills*

In everyday life, procedural tasks are often just referred to as skills. A skillful person is someone that can perform and or complete a task with a high and consistent rate of success. Before diving into learning we should better understand the definition of skills and how they can be classified.

Some skills require little effort. For example, learning to prepare a simple meal can take only a few minutes. Other skills such as learning to play the guitar is a skill that requires years of training. What they have in common is that they require effort, and a willingness to take time out of the day. (William, 2010) describes three important characteristics while defining skills in his book "Motor learning and control from theory to practice".

(1) Skills involve a broad range of human behaviors.
(2) Skills are goal oriented.
(3) Skills are learned.

These characteristics apply to any type of skill. In addition, these skills can be divided into three domains: perceptual, cognitive and motor (see Figure 5). Each of the domains underlines the capabilities that are required to consistently achieve the skill (William, 2010).

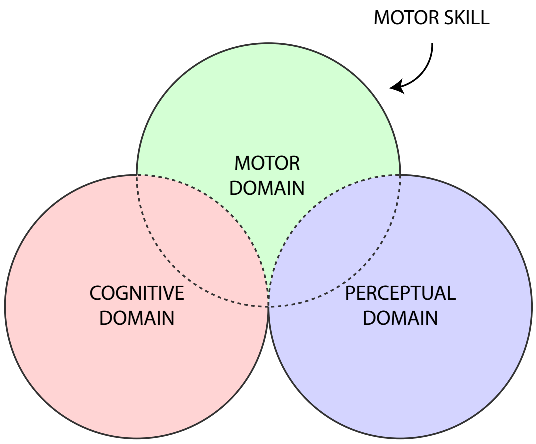


Figure 5.: Domains that encompass skills. Adapted from William (2010).

Cognitive skills define the ability to recall the theoretical knowledge of what to do and how to do it, in order to successfully perform the task. Such skills may include reading, writing, coding, poem memorization and so on (William, 2010). Cognitive skills can, in certain cases, overlap motor skills. To understand this, let us look at what it takes to write code. Programming requires logical thinking such as understanding conditional statements, syntax and mathematical expressions. However, the process of writing code also requires proper coordination of fingers and spatial understanding of the keyboard layout.

Perceptual skills mainly focus on tasks that require discrimination of sensory stimuli or rather it is the ability to detect important things in the environment (William, 2010). Such skills may include determining whether it is safe to cross the road, sorting objects by size or recognizing good strawberries in the store, etc. (William, 2010). One thing to note is that perceptual skills often accompany motor skills. Awareness of sensory stimuli and knowing when and how to act is in many cases followed by the corresponding movement. For that reason, the term perceptual-motor skill is typically used.

Motor skills are concerned with tasks for which success is reliant on the quality of movements. In other words, motor skills are concerned with doing the task and doing it correctly. Examples of different motor skills include most of the professional sports activities such as kicking a football, performing a high jump, skiing, running, and so forth. We should also mention that many of our daily routines involve motor skills, for instance, opening doors, washing dishes or flipping a switch (William, 2010). It is also important to note that motor skills are not performed in isolation from our perceptual and cognitive processes (William, 2010). We will expand further on the definition of motor skills in the following section, as it will be relevant to our understanding of sensorimotor skills and acquisition.

2.5. *Motor Skills*

To further evaluate the motor skills we can identify the three major features that defines them. William (2010) in his book describes these features as follows:

(1) Motor skills cover a wide range of behaviors, mainly by the coordination of the limbs and segments of the body through musculature.
(2) The motor skills are aimed at achieving certain environmental objectives and the achievement of these objectives depends principally on movement.
(3) Motor skills are learned

As we can see, motor skills stress the importance of the quality of movement through the body's musculature as the deciding factor in successfully accomplishing the skill. The third feature is immensely important since skills should not rely on randomly and/or accidentally performed actions, but rather focus on consistent performance of tasks or movements.

Motor skills can be categorized as either discrete motor skills or procedural motor skills. The latter describes the majority of the motor skills that we encounter throughout our life; for instance tool handling, repairs, making a call on your phone. Procedural skills involve not only the motor system but also other sensory systems responsible for sight, hearing, touch, sense of motion, etc. (William, 2010).

2.6. *Sensorimotor Skills*

We have discussed the important role of sensory information in sensory perception and different thresholds relating to intensity and duration of stimuli. Earlier we also looked at the motor system, and it should be clear now that it is intertwined with the receptors through the vertebrate motor systems. In other words, sensing and motor skills are distinct, but they are not completely separated and are involved in many different activities. We will now turn our attention to sensorimotor skills which exist at the intersection between the two. According to Curzon and Tummons (2013), sensorimotor skills can be defined as "*motor (physical) activity initiated and controlled by sensory input (sight, sound, touch)*".

These skills are highly depended on the quality of movements and actions, but would not be possible to accomplish without addition to sensorimotor inputs (Mishra, 2008). For instance writing down a dictated text (hearing, and speech processing), performing a surgery (vision, memory, touch), riding a bike (vestibular and proprioceptive system), using your phone (vision, pattern recognition), and so on. All of these tasks use the sensory information and selective attention to evaluate the progress of actions and to re-adjust the muscular performance in order to successfully reach the goal (Marteniuk, 1976). As any other skill sensorimotor skills are learned. However, due to its complex nature, the learning of advanced procedural sensorimotor skills requires special attention. In order to find the most convenient and efficient ways of learning or teaching such skills, it is necessary to understand and examine empirical studies on learning.

2.7. *Learning*

Learning concatenates various cognitive processes that take place after the inception of new information. It can be defined as the relatively permanent change in knowledge or behavior that is the result of experience (Hilgard and Marquis, 1961). Our memory provides our brain with the ability to store and retrieve our acquired knowledge. The holy grail of teaching is to optimize this process of learning, i.e. ensuring that the encoding of new information occurs with minimal distortion while also facilitating the subsequent transfer of what was learned to a new or different context. However, this is easier said than done. For example, comprehension of any subject presupposes that our prior knowledge is accurate, well-organized, and is somewhat aligned with our internal representation of the world. This chapter will explore learning in detail, specifically, the components of motor learning and the transfer of skills and how the process can be optimized by utilizing different learning strategies.

2.7.1. Motor Learning

Over the course of many years, researchers have sought to determine how we learn to perform various tasks. Specifically, they have looked for processes that drive the acquisition and application of knowledge that underlies our ability to use tools to accomplish particular tasks. This has been an important topic since it is one of the ways we differentiate ourselves from other animals. Previously, we have seen how our motor system is responsible for movements and coordination of limbs (refer to chapter 2.1 "Motor system"). Furthermore, we have argued that the motor system, cannot act in isolation from our sensory system (hence the term sensorimotor) (refer to chapter 2.6 "Sensorimotor Skills"). A crucial part that we have not yet addressed is how motor skills are acquired.

Behavioral psychologists Skinner (1968) and Guthrie (1930) in their work accentuate the importance of practice, rehearsal and skill refreshment. They both argue that maintenance and enhancement of the performance of sensorimotor skills demand a continuous and sustained cycle of periodic practice. Training and repetition prevent "retention drop" mentioned in an earlier section (refer to section 2.3.2 "Memory Stages"). In addition to that, we should mention that the distribution of training and practice time is not crucial to procedural learning. It is argued that while learning procedural skills, training and repetition can be both continuous or spaced producing the same learning outcomes (Haberman and Olivero, 1968; Guthrie, 1930).

In addition to Marteniuk's (1976) emphasize the role of feedback in procedural motor skills based on the information processing theory. According to the theory, the feedback is important to guide the attention and to correct the motor behavior. We should mention that both the quality and the quantity of feedback is important. Two principles to promote procedural learning were also proposed by (Marteniuk, 1976). He states that learning can be enhanced by (1) reducing the rate of incoming information and (2) by limiting the magnitude of information that should be processed at the time.

The final set of guidelines is introduced by (Singer, 1975). The author accentuates learning with guidance and learning through experience. His study shows that complex skills require guidance to effectively facilitate learning. On the other hand, trial and error can be more beneficial while applying already learned strategies to new scenarios (Singer, 1975). Although there is no specific way to learn that suits everyone, considering the above strategies and methods, could improve the process and outcomes of procedural learning considerably.

2.7.2. Learning Transfer

The term transfer is used to describe a process where the learning is carried from one context to a new context. This is not to say that a learning process that has been successful in one context will be successful elsewhere. Oftentimes, the term positive and negative transfer is used; one enhances performance and the other undermines a related performance in another context (Perkins and Salomon, 1999). Positive transfer is the primary goal of learning as stated by Subedi (2004): "*Transfer is a key concept in adult learning theories because most education and training aspires to transfer. The end goals of training and education are not achieved unless transfer occurs*". There is also evidence to support the occurrence of transfer in procedural learning from virtual to real environments (Rose et al., 2000; Wilson et al., 1996; Cromby et al., 1996), which makes it especially relevant to our further discussion.

In addition to positive and negative transfer, many ways are described in the literature for the classification of transfer. Researchers and authors have classified transfer as either near transfer or far transfer. Near transfer, is the transfer between very similar but not identical contexts (Perkins and Salomon, 1999). According to Misko (1995), near transfer of training often involves tasks that are procedural in nature where a sequence of operations is repeated every time the task is performed. The transfer rate of learning is typically high, but as a consequence, the learner often has a hard time adapting such skills or knowledge when confronted with a new environment (Subedi, 2004). Far transfer, on the other hand, describes transfer between contexts that involve new tasks or stimulus properties (Reschly and Robinson-Zañartu, 2000). In other words, the distance between prior knowledge or learning and application is much greater (Simons, 1999). This does not imply a dichotomy according to Simons (1999), but rather a dimension of distance. Furthermore, Bassok and Holyoak (1989) states that this distance can sometimes be measured or manipulated. As stated by (Subedi, 2004), the far transfer goes beyond the repetitive application of learned behavior as it involves cognition and analogy by which learners adapt knowledge and skills to a new context.

Some authors refer to 'vertical transfer' and 'horizontal transfer'. The latter is a bit more complex; horizontal transfer can require either near or far, and that transfer should be general or specific (Bossard et al., 2008). Vertical transfer refers to the process in which the learner uses his or her prior knowledge in building new knowledge (Bossard et al., 2008). This presupposes that the context in which transfer occurs is similar to the original context. In other words, the process occurs when older concepts are used to understand or learn new, more complex concepts. Due to their similarities vertical and near transfer can be equated as they are not conceptually different (Bossard et al., 2008). In a case of horizontal (or lateral) transfer, prior knowledge is not essential to solve a new problem or to perform a new task even when it is of high complexity (Bossard et al., 2008). Instead, knowledge must be abstracted or connected to the new context.

Lastly, we will take a look at the terms general transfer and specific transfer. When the learning task can be extended to many fields of knowledge, that is what is referred to as general transfer. Conversely, we say the transfer is 'specific' when learning and transfer tasks are close or in the related field (Bossard et al., 2008). There are many more types of transfer described in the literature that goes much further than this exposition. Our aim was to set a precedent for the following section, in which various examples of transfer in VR will be examined. In the next section, we will see that it is not enough to simply state what type of transfer we are dealing with. We have to describe how the process of learning is achieved, especially so when transfer of knowledge is our explicit goal.

2.7.2.1. Consideration for transfer.

According to Cormier and Hagman (1987), some research aims to determine where spontaneous transfer takes place. Some authors, however, dismiss it in its entirety. For example, (Detterman and Sternberg, 1993) states that 'The lesson learned from studies of transfer is that, if you want people to learn something, teach it to them. Dont teach them something else and expect them to figure out what you really want them to do. This seems a bit misconstrued as it has been shown that uninformed transfer does, in fact, take place (although much less frequent than informed transfer) (Gick and Holyoak, 1987). It most likely stems from early research that has found that subjects often have failed to apply adequate knowledge in the absence of a guided training (Gick and Holyoak, 1987),

The lesson here is perhaps that we should not rely too much on spontaneous transfer. According to Simons (1999), training and explicitly stated goals should be considered in combination with a learning task. This is consonant to (Smith and Ragan, 2004), in that near transfer requires the learner to recognize key features of the task that are similar to the new situation. In order to recognize the key features, one strategy is to explicitly inform or encourage the learner to express the characteristics of a learning task.

The takeaway is that it is probably a good idea to give the learner a hint before they attempt to conduct a task. But the possibility of uninformed transfer should be kept open. For example, it seems to be the case that the similarity between two contexts, in terms of goals and processing, call upon transfer even when a hint was not provided (Smith and Ragan, 2004). Conversely, when we talk about informed transfer, we should be aware that it is not the be-all-end-all. In certain instances, giving the learner a clue can be ineffective "[...] *the benefit of a hint may be reduced if the problem solver first attempts the transfer task in the absence of a hint and does not spontaneously apply the knowledge acquired during training*" (Smith and Ragan, 2004). If the learner attempts a learning task, the hint should preferably be given beforehand.

2.7.3. Learning Affordances and Transfer in 3D VLEs

"[...] *technologies themselves do not directly cause learning to occur but can afford certain learning tasks that themselves may result in learning or give rise to certain learning benefits.*" (Dalgarno and Lee, 2009).

The notion of affordances, according to Benyon (2018), refers to the "[...] *properties that things have (or are perceived to have) and how these relate to how the things could be used*". Dalgarno and Lee (2009) state, that technology alone is not in itself beneficial to learning; instead, it has the potential to assist and facilitate learning by virtue of its affordances. Dalgarno and Lee (2009) in their article "What are the learning affordances of 3D virtual environments?"outlines five learning affordances of

3D virtual learning environments (3D VLEs) (see Table 2) that are relevant to our problem formulation. In the sections that follow, we analyze each one of five affordances from Dalgarno and Lee's (2009) article. We will also bring in perspectives relating to transfer, that we introduced in the previous chapter.

Affordance 1	3-D VLEs can be used to facilitate learning tasks that lead to the development of enhanced spatial knowledge representation of the explored domain
Affordance 2	3-D VLEs can be used to facilitate experiential learning tasks that would be impractical or impossible to undertake in the real world.
Affordance 3	3-D VLEs can be used to facilitate learning tasks that lead to increased intrinsic motivation and engagement
Affordance 4	3-D VLEs can be used to facilitate learning tasks that lead to improved transfer of knowledge and skills to real situations through contextualisation of learning
Affordance 5	3-D VLEs can be used to facilitate tasks that lead to richer and/or more effective collaborative learning than is possible with 2-D alternatives.

Table 2.: Five learning affordances of 3D virtual environments.

2.7.3.1. Affordance 1: Spatial Knowledge Representation.

Active exploration and interaction with virtual objects in VEs are recognized as some of the major benefits of 3D VLEs. Already in the early stages of VR research, it has been reported that learners were able to understand complex and dynamic object behaviors while interacting with them in VR (Jonassen, 1999). To put it into context, Dalgarno and Lee (2009) give an example of a simulation that could be applied to physics classes. In such a simulation, students could be taught how different physical forces interact with objects. VR is a good candidate for these types of learning scenarios i.e. it allows for full physical behavior of objects to be modeled as in real life. Consequently, students are allowed passage to observe dynamic behaviors helping them construct a personal knowledge representation. This knowledge construction can be aided by various means i.e. enabling students to measure and manipulate objects in ways that are not possible in real life. One can argue this raises the likelihood of transfer. VLEs power lie in its ability to elucidate and make relations between concepts more explicit, by enabling learning to take place in a natural context, and thereby strengthening connectedness of the learners' internal memory representation (Simons, 1999).

2.7.3.2. Affordance 2: Experiential Learning.

In real life, it is often impractical or outright impossible to facilitate experiential learning due to limitations imposed by the laws of nature, limited budgets or safety concerns. VEs provides the affordance of experiential learning in these types of scenarios. The term "Microworld" refers to VLEs which aid the learners conceptual formation by depicting abstract concepts (Rieber, 1992). To comprehend this, imagine an "old-growth forest" where trees can easily be more than 1,000 years of age. Trees are living organisms that go through phases of decay and growth, but understanding such a life-cycle can be difficult. The timescale of growth of a tree is an order of magnitude greater than our perception of change in the world. In a microworld, we can accelerate time and observe how the tree grows over centuries, and how they contribute to the forest ecosystem. Winn W. (1999) give an example of a VLE that could enable students to control greenhouse emission and observe the impact on the climate, or civilization. Another interesting way to use microworlds is to portray how our world would look with more than three spatial dimensions. The 4D Toybox is a great example of this, offering a vast collection of four-dimensional objects, such as 4D hypercubes, that can be interacted with using a regular computer, VR or a touchscreen interface (see Figure 6). Users can poke, throw and roll objects, and observe them as they disappear into other dimensions.

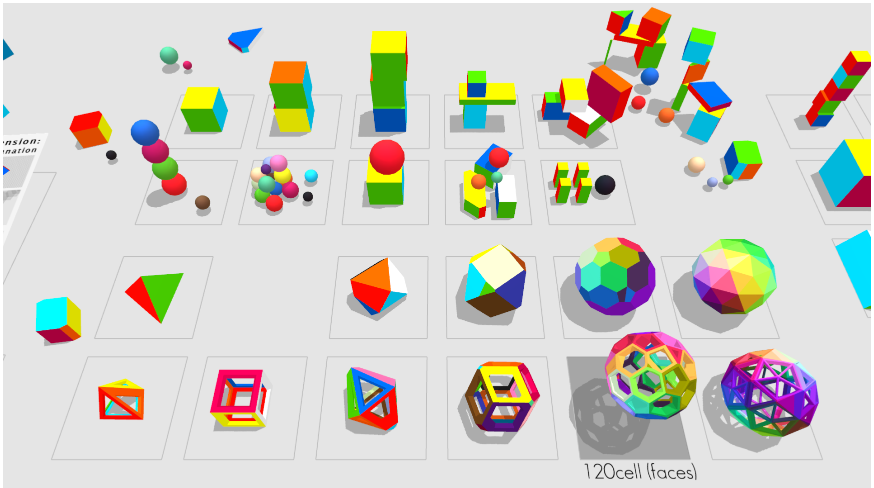


Figure 6.: The 4D Toybox enables users to interact with 4-dimensional objects in a physically based simulation. Retrieved from (ten Bosch, 2017).

In summary, microworlds have the ability to capitalize on the intrinsic ability of VR to facilitate an assortment of experiences. Furthermore, these microworlds can easily be modified and customized to the learners' needs (Dalgarno and Lee, 2009; Rieber, 1992). This flexibility allows students to approach the environment individually, such as enabling students to construct their own 3D environments to articulate their spatial model or 'externalize' their understanding of certain abstract concepts (Dalgarno and Lee, 2009; Winn, 2002). This supports what we know about transfer, since allowing students to experiment can help them generalize knowledge. In a study by Simons (1999), students were encouraged to experiment and to try out new things, when learning how to work with Wordperfect 5.1 (WP). Compared to a control group that was taught in ordinary lessons, the experimental condition had people taught participants how to learn the rest of WP on their own accord. Not only did users in the experimental condition learn more than those in the control condition, they learned new parts of WP by themselves much faster and far more effectively.

2.7.3.3. *Affordance 3: Engagement and Motivation.*

Motivation refers to the drive that encourages action. It is a complex notion, given that every individual has different preferences and therefore there is no universal answer to what motivates a person. However, generally speaking, we respond more or less the same when the learning experience engages our senses. Research has shown that active and immersive learning in 3D VLEs, that include feedback and reflection on the performance, motivates a wide range of students to learn and engage with presented tasks (Dede, 2009). Moreover, Dede (2009) examined the difference between an experimental group exposed to a 3D VE and a control group that carried out paper-based exercises. The results indicated that students, as well as educators, were more engaged when the immersive virtual environment was introduced into the study curriculum. In addition, the authors noted a significant improvement in attendance rate and drop in disruptive behavior during class. After the learning sessions, the participants in the experimental group improved performances as much as 32-35%. In comparison, the control group improved by only 17% (Dede, 2009). This goes to show that motivation has great implications for learning. Subedi (2004) also suggests that transfer and motivation are linked: "*Transfer of training (or lack of it) is a complex process and depends upon the intent or motivation of the learner*".

2.7.3.4. *Affordance 4: Contextual Learning.*

"*According to contextual learning theory, learning occurs only when students process new information or knowledge in such a way that it makes sense to them in their own frames of reference (their own inner worlds of memory, experience, and response)*" (The Center for Occupational Research and Development, nd).

The situated nature of VR makes it ideal for many learning scenarios. That does not mean that we should use VR haphazardly and expect it to always benefit learning. As we have already talked about, transfer of knowledge is a matter of generalizing knowledge from one context and applying it in another context. VLEs have the potential to ease transfer since the virtual environment can be modeled in the real life context. This is further supported by the fact that visual or sensory realism and interactivity has reached a point where it is consistent with the real world. In the research paper "*Virtual Reality Based Space Operations – A Study of ESAs Potential for VR Based Training and Simulation*" Olbrich et al. (2018) describe a space station environments shown below (see Figure 7), which was used to train astronauts to deal with possible emergency situations. The virtual environment was equipped with stationary and portable equipment normally found on a space station (control panel with intractable buttons and switches, fire extinguishers, torches, oxygen masks, etc.) (Olbrich et al.,

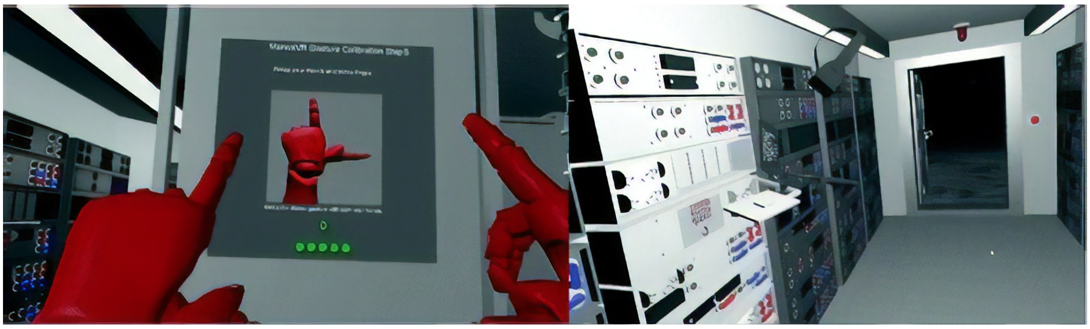


Figure 7.: Trainee perspective. Left: Calibration and interaction tutorial. Right: Sharing the space with a second trainee, who is represented by his HMD and controllers. Retrieved from (Olbrich et al., 2018).

2018). This is a form of contextualization which is effective for near transfer; to be effective training should be contained in a small range of situations (Perkins and Salomon, 1999). Contrariwise, if far transfer is the goal, decontextualization is necessary (training in a wider range of situations) (Perkins and Salomon, 1999).

To summarize, that recent advancements of the fidelity of the 3D VEs provide the learning applications a potential to be useful and effective because the "*learning environment can be modeled on the context in which the knowledge is expected to be applied*" (Dalgarno and Lee, 2009).

2.7.3.5. Affordance 5: Collaborative Learning.

We are often presented with tasks which require a certain degree of collaboration. Various desktop applications offer collaborative functionalities, however, they are often low fidelity or mainly geared towards communication purposes (i.e. collaborative annotations, telecommunication and so forth). 3D VLEs can be used to design immersive multi-user experiences that not only allow users to communicate but also introduce physical activities that can be accomplished together, leading to more effective collaborative learning (Dalgarno and Lee, 2009). Jarmon et al. (2008) gives an example of students from graduate interdisciplinary communication course using an online virtual world called Second Life to collaborate with architecture students and design sustainable urban housing meant to be built in a low-income neighborhood. In this case, the collaborative virtual environment empowered students to use and share their academic skills, learn from volunteer builders, seek out guidance from their teachers and create models in VE to achieve common goals. In another example, medical doctors were trained for a knee arthroplasty operation using the ovidVR system (see Figure 8) (Papagiannakis et al., 2018). The system was used to perform the worlds first shared collaborative orthopedic surgery in VR linking together the Stanford Medical School, the USC Keck School of Medicine, the NYU Langone Medical School and the Aristotle

Figure 8.: The ovidVR psychomotor VR simulation system. Retrieved from (Papagiannakis et al., 2018).

University Medical School (Coffaro, 2018).

Since collaborative VLEs are a fairly new learning medium, little is known about how it can be used effectively (Jarmon et al., 2008). Nielsen (2009) stresses the importance of looking at the collaborative aspects of learners in order to ensure transfer. In a study enlisting 243 apprentices from Danish vocational educations, questionnaire and interviews were used to understand how they learned from collaborative learning processes. Roughly 90 percent said the traineeship at a workplace was the most important place for learning when they studied their trades. To put this into perspective, just 10 percent of apprentices considered the vocational university central. When asked to justify this, many apprentices emphasized as important for learning in the workspace, the personal relationship with the master, journeyman or other apprentices. Fuller and Unwin (2004) argues that learners function as teachers for each other when learning the workplace. Furthermore, joint learning activities seem to give an incentive to "[...] *active interpreting, modifying, and reconstructing the skills and knowledge to be transferred from a college context into a workplace practice*" (Nielsen, 2009). This is an important proponent of transfer (in a participatory context) because generalization "[...] *is not associated with abstract representations, but notions of generalization lie in the power to renegotiate the meaning of past and future events in relation to the meaning of present circumstances*" (Nielsen, 2009). In other words, the act of renegotiating existing knowledge – as can be accomplished by various collaborative arrangements – is essential for transfer to occur.

2.7.4. Considerations for 3D input devices in VEs

One of the benefits of virtual reality is the ability to deliver highly immersive experiences compared to monitor based (non-immersive) video displays. One explanation could be that the standpoint of the viewer relative to the world is egocentric or subject-centred (Milgram and Kishino, 1994). Moreover, high-end VR is now capable of providing high reproduction fidelity with respect to displays with sufficiently rapid update rates, high resolution and realistically looking virtual environment. Arguably, the observer's visual sensations of the VE can get very close to unmediated reality. But is this alone sufficient to immerse users? Although visuals are what comes to mind given the visually invasive nature of VR, immersion is as much about accommodating our other senses. To understand this better we can look at some of the factors which could break the immersive experience.

2.7.4.1. Sensory Motor Discrepancies.

Users face a large number of sensorimotor discrepancies which can be established on the basis of three Virtual Behavioural Primitives (VBPs) which includes elementary tasks that can be performed by a person in VR (Fuchs, 2017):

- Observing the virtual world
- Moving in the virtual world
- Acting on the virtual world

Observation VBPs concerns what we discussed previously; it refers to what is sensed with our eyes. There are several discrepancies such as low frame-rate, the lag between the head motion of the observer and the correct display of the VR headset viewpoint and many more. Some of these issues can be dealt with using different techniques i.e. Reprojection, Asynchronous Timewarp (ATW) and Asynchronous Spacewarp (ASW) (Antonov, 2015; Technologies, nd). Others have to be addressed through hardware iterations. Spatial visual-motor discrepancies are probably more relevant, as they are typically invoked by the designer. According to Fuchs (2017), it may be caused by amplifying the virtual rotation translation of the observer or by forcing a different perspective. Passive visual-motor discrepancies can also occur if we were to rotate the VE without the user.

Navigational VBPs are related to our physical (and virtual) movement from point A to B. In many high-end headsets, the user's body is translationally and rotationally tracked. However, as the tracked area is physically restricted, it may not be possible to walk to a point in the virtual space. Workarounds exist but may cause their own discrepancies, which can lead to motion sickness. For example, amplifying the users motion in VR might lead to a conflict between the visual and vestibular senses. Walk-in-place techniques may cause temporal visual-vestibular discrepancy due to starting and stopping latency (Bruno et al., 2013).

Manipulation VBPs is about how we interact, typically with our hands, with virtual objects. For this, the user usually has a motion controller, that is superimposed into the virtual space acting as the users own hands. Fuchs (2017) mentions the visual discrepancy that occurs when the users real hands are positioned incorrectly as compared with the hands he sees in the VR headset.

2.7.4.2. Types of input devices.

This chapter provides a brief overview of the current state of the VR input devices. The sensory-motor discrepancies in the previous sections will be drawn into a discussion on the differences between the different controllers and what they mean for user experience.

An input device is any peripheral hardware that allows us to interact with the computer by providing inputs. VR controllers are just one of many peripheral technologies that allow users to interact with the virtual environment. Each has its own unique characteristics, such as sensors (either internal or external), its shape, encumbrance, and affordances (Jerald, 2015). Less obvious features may relate how the device is mapped i.e. direct vs. indirect manipulation, relative vs. absolute input, rate control. positional control or isometric/isotonic (Jerald, 2015). There are exists a plethora of VR devices which can roughly be divided into tracked controllers and locomotion interfaces (Jerald, 2015). To fit our area of inquiry, we are mainly interested in controllers that allow hand-related tasks i.e. virtual grasping and object manipulation. In Jerald's (2015) work, we find a classification of different hand input devices. There are classified as world-grounded input devices, non-tracked hand-held controllers, tracked hand-held controllers, hand-worn devices, and bare-hand controllers (Refer to Figure 9).

	Proprioception	Consistent	Usable in Lap or the Side	Haptics Capable	Unencumbered	Physical Buttons	Hands Free to Interact with Real World	General Purpose
Hand Input Device Class								
World-Grounded Devices	✓	✓		✓	✓	✓	✓	
Non-Tracked Hand-Held Controllers		✓	✓	✓		✓		
Bare Hands	✓				✓		✓	✓
Tracked Hand-Held Controllers	✓	✓	✓	✓		✓		✓
Hand Worn	✓	✓	✓	✓		✓	✓	✓
Non-Hand Input Device Class								
Head Tracking	✓	✓					✓	✓
Eye Tracking							✓	
Microphone			✓		✓		✓	✓
Full-Body Tracking	✓	✓	✓	✓			✓	✓
Treadmills	✓	✓			✓		✓	

Figure 9.: Comparison of hand and non-hand input device classes. Adapted from (Jerald, 2015).

World-grounded devices are, as the name suggests, fixed in the real world. Keyboard and mice are the most well-known example, however, they are more suitable for 2D desktop applications. Steering wheels and brake pedals are world-grounded devices that can be used to simulate a driving experience in VR and may work extremely well. Other devices for simulating vehicles and aircrafts typically appear in this category.(Jerald, 2015)

Non-tracked handheld devices are those we often associate with traditional video game input devices. A trademark of these controllers the analog sticks, buttons, and triggers. They are offering precise control, but lack tracking which is why they are not widely used for VR applications. They are better for VR applications that are seated, where the user does not interact with his own hands i.e. controlling a character in third person such as in the games Super Luckys Tale, Moss or the strategy game Landfall.(Jerald, 2015)

Tracked handheld controllers are the most typical implementation of VR controllers. In many cases, external tracking devices are used to provide positional and rotational tracking. An external tracking device is one that is mounted in the surrounding area and is positioned so that the controllers are visible. This allows the system to track controllers which are often equipped with photodiodes that indicate when a laser emitted by the tracker hit them. The time difference when lasers hit the photodiodes allows the position and orientation to be recovered. This comes at a cost. Usually, high-end VR systems are expensive, requiring investment in a powerful computer. Low-cost tracking devices can be found in a range of products that come in the form of standalone devices or mobile VR such as Google Daydream. Typically, the position of the controller is inferred by the controllers accelerometer which can lead to imprecision. Inside-out tracking solutions seek to mitigate this problem in a cost-effective way, but with caveats such as blind spots since the controllers are tracked by sensors on the headset. (Jerald, 2015)

Tracked handheld controllers have several advantages, e.g. the controllers can also be visually co-located, providing proprioceptive cues. They can also be felt due to their physical manifestation, providing the user with passive haptics or touch cues. This is especially beneficial when the user is performing a confirmation action or when triggering (Argelaguet and Andujar, 2013).

Hand-Worn Devices are a class of input devices that can be mounted or worn on the users hands (as the name suggests), allowing the system to track different hand poses. Hand-Worn devices as opposed to devices that provide discrete input (e.g. button press) which is typical of handheld devices, often rely on gesture recognition. This might have repercussions for certain types of interaction. One issue is that tracking algorithms are unreliable. In Kessler et al.'s 1995a own words: "*If the sensors of the* *device report that the hand is in a particular posture, how certain can the application be that the hand is actually in that posture?*"

If we rely on gestures that are inaccurate we risk making our system feel unresponsive. This is a common problem with gesture-based tracking systems, since they, unlike handheld controllers usually lack passive feedback. Sensorimotor discrepancies can arise from this "impoverished physicality" leading to various detrimental effects (Wigdor, 2014). According to Kessler et al. (1995b), a central factor in the sense of agency is the congruency between an action and its feedback, that is, the anticipated outcome compared to the actual outcome. For example, in a study by Sato and Yasuda (2005), it was shown that the participants feeling of agency diminished, when the presentation of the tone was unpredictable in terms of timing and frequency, even though it was self-produced. Similarly, the user may be performing what he believes is the correct gesture (i.e. picking up an object); if the system is uncertain as to the users hand posture it could trigger an event earlier or postpone it.

Bare-hand input devices differ from the hand-worn devices in that they are not physically felt, which some would argue is a relief, as hand-worn devices can be uncomfortable and limit finger dexterity. Some systems are already available to consumers, most notable Leap Motion, which can be mounted on a VR headset and then be used to predict the users hand posture. Bare-hand input often suffers from similar issues as hand-worn devices, with the difference being that localized feedback is more difficult to implement. Some research has looked into stimulating the users skin with compressed air pressure fields (Sodhi et al., 2013), or by using ultrasound-generated pressure waves (Iwamoto et al., 2008). However, such systems often have to be mounted in a fixed location.

2.8. *Haptic Feedback*

"*Haptic feedback is a design element for human-computer interfaces*" (MacLean, 2000). The term *haptic* refers to touch and muscular proprioception. This can be simulated via so-called haptic interfaces (Fuchs, 2017). In this chapter, we will examine different types of haptics that can help to prevent sensorimotor discrepancies. In VR, haptic interfaces are used to simulate physical control while interacting with purely digital environments (Fuchs, 2017). The motor actions provided by a user are evaluated in the virtual context and transformed into haptic feedback (Fuchs, 2017). Haptic feedback can be classified into two main categories: *active haptics* and *passive haptics*.

Passive haptic feedback comes from the user's own body as influenced by the device's physical properties, i.e. the sensation when a button is depressed or when an object is held in a hand (Wigdor, 2014). It is believed that passive haptic feedback plays a significant role in the spatial knowledge training tasks and improves the sense of presence (Insko et al., 2001). It is a challenging task to introduce passive haptics in virtual worlds due to the lack of physical interaction (Insko et al., 2001). For example, the ability to walk through virtual objects can reduce the sense of presence and intercept spatial perception of the space (Insko et al., 2001). Usually, the passive haptics that we experience in VR are related to the interaction with a controller, e.g pressing buttons, triggers, squeezing the controller, etc. Those motor actions are mapped to specific interactions in VR, such as picking up an object, replicating a physical sensation we get of the action in a real environment.

Active haptic feedback is generated by the input device based on actuators and software. According to Rovers and Essen (2006) "*active haptics can be applied as the only means of feedback in an interface, it can replace other forms of feedback, and it can be applied as augmented feedback*". The term augmented feedback describes the use of haptics to enhance another source of feedback such as visuals or sound. Active haptic feedback is widely used to accommodate the sense of touch in VEs since the physical interaction with the objects is absent.

The most common goals of using active haptics for digital application are *functional feedback* and *feedback on the interaction itself* (Rovers and Essen, 2006). Functional feedback defines the internal state and conditions of the system (Rovers and Essen, 2006). For instance, it could indicate that the door in the scene is locked or interaction with an object is inactive. On the other hand, feedback on the interaction itself often illustrates the accuracy of the interaction (Rovers and Essen, 2006). This is essential for virtual worlds where the absence of physical contact often causes difficulties while picking up or manipulating objects. Active haptic feedback could signal a successful contact with the object, indicating that further actions are now active, such as object pick up or scaling, etc. In addition to what was said, according to (Bermejo and Hui, 2017) haptics can also be grouped by sensations into *cutaneous/tactile* and *kinesthetics*.

Kinesthetics provides force or motion feedback to the user (Bermejo and Hui, 2017). Most of the kinesthetics devices are grounded (with 3-6 degrees of freedom), however more and more wearable technology reaches the market, especially in the field of AR and VR. Force-feedback gloves are one of such solutions. It provides users an ability to feel the dimensions and solidity of the virtual objects they interact with (Bermejo and Hui, 2017). However, users receive force feedback only while grasping, pinching or holding virtual objects, since constraints endowed by the gloves are applied to fingers alone (Zhou and Ben-Tzvi, 2015). Ideally, force feedback gloves should restrict movements only during the interactions, otherwise allowing for free movement (Zhou and Ben-Tzvi, 2015).

Cutaneous/tactile feedback is the most popular haptic feedback approach (Bermejo and Hui, 2017). Cutaneous feedback is commonly used in a variety of devices such as smartphones, game consoles controllers, joysticks, most of the VR controllers, etc. All of these devices generate vibrotactile stimuli directly on to a users skin (Bermejo and Hui, 2017). Cutaneous devices are very useful since vibration motors are low-cost and easy to implement. However, problems may occur in differentiating feedback i.e. if feedback is applied to high-threshold cutaneous mechanoreceptors. Usually this is not a problem because since our palms and fingertips are very sensitive. (Bermejo and Hui, 2017; Oey and Mellert).

2.8.1. *Tactons*

Brewster and Brown (2004) introduces the concept of tactile icons, called Tactons. "*Tactons are structured, abstract messages that can be used to communicate complex concepts to users non-visually*" (Brewster and Brown, 2004), i.e. it could communicate the progress inside an application. Tactons can be designed by combining and manipulating various feedback parameters, such as frequency, amplitude, duration, delays, etc, (Brewster and Brown, 2004). One of the examples of a vibrotactile tacton can be seen in Figure 10.

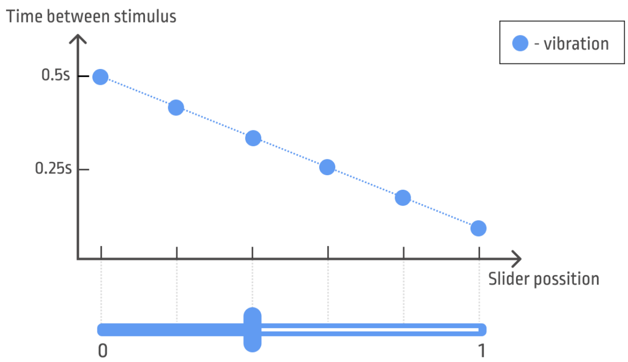


Figure 10.: Visual example of tacton feedback for a sliding bar.

In this case, a vibrotactile icon is used to express the logic of the slider. The decrease of the time between vibrations indicates the user that he or she is approaching the top value and vice versa. However, Azadi and Jones (2013) emphasize the need for understanding of sensory perception for tacton pattern design. The perceptual limitation might obscure the readings if the feedback is not within the limits of our sensory perception system. Tactons just like an icon has no language dependency, meaning that it could be universally used (Brewster and Brown, 2004).

2.9. *Input devices and transfer*

The exact role of input devices in facilitating the transfer of learning is not well understood. For many years, research has been centered primarily around the acquisition of technical skills at the sensorimotor level in a virtual environment for training (VET) (Ganier et al., 2014). For example, a simulation was developed at the SMS-Lab at ETH Zurich, with the purpose of teaching rowing to athletes (Rauter et al., 2013). Similarly, another study demonstrated transfer of training from virtual to real baseball batting (Gray, 2017). A number of studies are also focused on rehabilitation or helping people with disabilities (Rose et al., 2000; Wilson et al., 1996; Cromby et al., 1996). Consequently, less emphasis has been placed on the learning of procedures at higher levels of abstraction such as procedural tasks (Ganier et al., 2014) which is pivotal in our discussion of how different input devices can be used for learning purposes. While several studies have developed VEs for the purpose teaching procedural tasks (Draper et al., 1998; Ragan, 2010; Tichon, 2007; Verna and Grumbach, 1998), these are mainly concerned with the technical accomplishments, i.e. interface design to improve the sense of presence or immersion while using VR equipment (Ragan, 2010; Draper et al., 1998).

Recent interest has shed some light on the effectiveness of transferring procedural skills. In one study by Ganier et al. (2014), procedural skills were successfully taught in a generic virtual training (GVT®) environment to maintenance workers who were assigned with tank maintenance operations (Ganier et al., 2014). The workers were later asked to apply the knowledge in the same simulation a few days later. This shows that teaching procedural knowledge is feasible, however, it did not prove that transfer occurs. Evidence of transfer was later reported in a different study by Ganier et al. (2014) in a similar setup. In the study forty-two adults were divided into GVT®, conventional training (using a real tank suspension and preparation station) and control (no training) (Ganier et al., 2014). After training participants were asked to perform the learned procedures in real life. Results of the study showed that both training types (conventional and virtual) produced similar levels of performance. Neither of these studies was actually conducted in VR; nonetheless, they show that VEs can be effective tools to teach procedural information. The authors argue that: "[...] *carrying out actions in the virtual environment can act as a cognitive learning tool by allowing the learner to memorise and recall the different procedural steps more efficiently*" (Ganier et al., 2014). By extension of this, the author claims that: "[...] *a VET that allows a high level of execution of actions from the trainee (i.e. analog action via motion capture or haptic gloves) should induce better performance recall compared with a virtual environment that allows only a low level of action execution (i.e. symbolic action via the keyboard and mouse)*" (Ganier et al., 2014). To examine the statements, let us look at some examples.

A paper by Carlson et al. (2015) provides an excellent example. In their paper, they used a simple virtual reality training scenario to investigate the efficacy of training to improve assembly tasks for factory workers. In the study, participants were asked to wear a 5DT glove (in their non-dominant hand), and Phantom Omni R was used in the

Figure 11.: 5DT Glove (left hand) and Phantom OmniR® (right hand) in virtual training. Retrieved from (Carlson et al., 2015).

dominant hand (refer to Figure 11). The 5DT offered a wide range of movement and positioning, and the Phantom Omni R with haptics was better for fine motive control. To test whether the training helped with learning the assembly process, participants were given a burr puzzle to assemble as many times as possible within a twenty minute time period. They were then retested two weeks later. The experiment was conducted on two groups: an experimental group that performed in a VLE and a control. In the experimental condition, a visual presentation based on a bimanual input was presented to the participants, who were then able to manipulate the puzzle pieces with the bimanual input. These participants were compared to a group which was offered traditional physical training. The results showed that virtual training improved recall of the assembly process, but not to the same extent as conventional physical training. The caveat of the virtual training the time it took to reach the same level of proficiency as those who trained in real life, but this is not necessarily a problem. Although the performance of virtual training was not as effective to that of traditional physical training, the VLE could be leveraged for the benefit of factory workers because interruptions in production or time lapses between training and on-the-job performance, especially for procedural training tasks, can be avoided with virtual training (Carlson et al., 2015).

Another study examined the effects of force feedback on the performance of three groups of subjects in the construction of a LEGO biplane model (Adams et al., 2001). A computerized simulation of the construction of the biplane model was used to simulate real-world construction. The first group was trained on a Virtual Building Block (VBB) simulator using a 3-DOF Excalibur interface which simulated force feedback. In contrast, the second group trained on the VBB system, which did not simulate force feedback. The last group received no virtual reality training. The experiment showed that force feedback applied to the training of the LEGO biplane model is much better at facilitating transfer to a manual task in the real world, than when no force was felt by participants.

These examples show that procedural learning transfer from the virtual to the real world is plausible. However, an important thing to keep in mind is that transfer can be both positive and negative. The concept of transfer, therefore, needs to be applied carefully to ensure that it does not undermine the learning process. For example, a study on VR simulators evaluating the haptic-enabled LapSim® VR simulator for surgical training found that the effects of simulation on participants yielded negative learning effects (Våpenstad et al., 2017). The study developed a criterion-based training program on a VR simulator with Xitact® IHP handles with haptic feedback applied to basic tasks: coordination, clip applying, lifting and grasping, a fine dissection and pattern cutting. It was then tested by comparing the performances of a simulator group against a control group (Våpenstad et al., 2017). The study concluded that poor mechanical performance of the simulated haptic feedback caused the negative training effect. In spite of the conclusion, the study had several oversights as admitted by the authors i.e. participants in the study were medical students who may differ in technical abilities from actual surgeons. Despite this, the training program failed to include procedural training which is crucial to developing surgical competences (Våpenstad et al., 2017).

This chapter summarized some of the available research on VR training as applied to manual factory assembly, surgical training and maintenance work. Most of this research up to this point has focused on teaching sensorimotor skills. Recent studies, however, show promise in terms of using virtual reality to develop training sessions that teach procedural skills. That being said, our understanding of transfer on this topic is still scarce and mandates further research. For example, what are the ideal conditions (physical, functional, perceptual or psychological) that allow for transfer to take place?

3. Final Problem Statement

Our analysis has thus far focused on clarifying the extensive information concerning our initial problem statement: "*To what extent can haptic interfaces impact the learning transfer from VR to the real environment?*". We have identified some examples where the training of procedural skills can be achieved in VR using different input devices. However, it remains to be seen whether such examples are universal and if they have broad applicability for VR learning. Withal, the discourse on whether VR might be able to deliver procedural training is controversial. For one thing, it is difficult to define what conditions are necessary to facilitate transfer in VR. This could explain why some studies encounter negative learning effects. Secondly, it is unclear what dimension of fidelity that is required for achieving the desired level of training transfer. According to Ragan (2010), a key factor in fostering learning in VR is arguably the immersive aspect, this includes the induced physicality made possible by different input devices. In line with this idea, Ganier et al. (2014) proposes that we focus on the level of execution of actions, in training procedural tasks since: "[...] *a VET that allows a high level of execution of actions from the trainee (i.e. analog action via motion capture or haptic gloves) should induce better performance recall compared with a virtual environment that allows only a low level of action execution (i.e. symbolic action via the keyboard and mouse)*". Taking this as inspiration we can formulate a more concrete problem statement:

Final problem statement: Do hand-worn input controllers with a high level of execution and force feedback have an advantage over traditional handheld controllers with a lower level of execution and vibrotactile feedback for transfer of procedural skills to real life?

4. Requirements

To design an effective procedural learning application in VR, we must evaluate the findings from the analysis chapter. This chapter will list a set of requirements, based on the literature review, which will guide us throughout the development process.

Learning

R1 Use rehearsal and repetition to sustain information retention.
R2 Use guided training to accommodate learning while teaching unknown skills.
R3 Avoid high information load at the time while teaching new skills, as it can be detrimental to learning.
R4 Reduce information rate while teaching new skills, as it can be detrimental to learning.
R5 Allow trial and error when teaching known skills.
R6 Use feedback to help fine tune motor actions.

Learning Transfer

R7 Avoid using low fidelity equipment, as it can lead to the negative training effect.
R8 To accommodate near transfer make the learning environment and the learning procedure similar to the original task in real life.
R9 State the explicit goals of a task to the learner, prior to him/her attempting the transfer task.

R10 Refrain from providing hints after the learner has attempted a transfer task. This may lessen the benefits the hint making the informed transfer less likely.

Learning affordances and transfer in 3D VLEs

R11 Consider modeling of physical forces and or behavior of dynamic objects to strengthen connectedness of the learners' internal memory representation.

R12 Construct a microworld to help generalize abstract knowledge.

R13 Consider tailoring the experience to the individual learner or letting him/her customize the learning experience. This is can be a way for the learner to externalize abstract knowledge.

R14 Encourage exploration of the VLE, as it is known to improve the transfer of skills to other areas.

R15 Utilize immersion in the VLE to motivate learner as it may benefit transfer.

R16 For procedural skills (near transfer) consider contextualizing by limiting the range of situations where a particular skill is taught.

R17 For learning with the goal of adapting to dissimilar contexts (far transfer) expand the range of situations where a particular skill is taught (decontextualization).

R18 Consider joint training to help renegotiate existing knowledge, thereby aiding generalization or transfer into a new context.

Considerations for 3D input devices

R19 Avoid gesture-based input devices as they are prone to inaccuracies.

R20 Ensure congruency between anticipated and actual outcome to create a sense of agency.

R21 Avoid using low fidelity equipment, as it can lead to the negative training effect.

R22 Include procedural training if it is crucial to accomplishing the transfer task.

Haptics

R23 Use passive haptics to replicate physical sensations on interactions with digital objects.

R24 Use active haptics to express functional feedback.

R25 Use active haptics on the interaction itself to communicate the accuracy of the performance.

R26 Use tactons to communicate complex instructions non-visually.

R27 Use force feedback to represent the dimensions and solidity of the virtual objects (if possible).

The virtual learning application should be developed following the aforementioned requirements. We must note that due to the application specifications, hardware choice and or target group related factors, some of the requirements may not be applicable.

5. Methods

In this chapter, we will present our research methodology to explore the impact of glove-based input device on procedural learning as compared to a traditional input device.

Our focus on force feedback was predicated upon a number of important observations. Firstly, our exposition of the role of different input devices in the transfer of skills showed promising and clear evidence of how different types of input devices can lead to different learning trajectories (i.e. sensorimotor learning, but most importantly procedural learning). However, it was evident that not all these types of input devices were equally important and impactful. Secondly, a key factor in fostering learning in VR is arguably the immersive aspect. For these and other reasons, we focus on different types of input devices. Finally, we were particularly interested in the effect that haptics in VR can have on procedural learning.

We begin with a general overview of the procedural task that was chosen for this study. As a case in point, we decided to design our application around pipetting which is commonly used by biologists to measure extremely small volumes. This is a task that might be difficult to perform well without force feedback. Furthermore, there are many physical aspects such as holding the pipette, pressing buttons and turning dials that may need to be mastered before we can achieve transfer from virtual to a real environment. For simplicity, we assume that this individual has no prior experience with pipetting. Thus, our focus should be to introduce pipetting from the ground up both practical and theoretical aspects of it.

5.1. *Pipetting*

Pipetting is a complex task which requires tool handling knowledge, precision and consistency. Micropipettes were invented in 1970 and are widely used in different industries, such as food, pharmaceutical, chemistry, biology, forensic chemistry, and medical research, etc. There are several ways pipetting can be performed (forwards, reverse, holding angle variations). The procedure depends on the liquid types and required volumes. The most commonly used pipetting technique is forward pipetting, which is performed while holding pipette at an 90° angle. Forward pipetting can be performed while working with buffers, diluted acids, and other aqueous solutions. Learning the forward pipetting technique should be the main objective in our application.

5.1.1. Forward Pipetting

Forward pipetting is qualified as "*normal*" and most commonly used pipetting technique (Coward and Wells, 2013). The visual representation of the forward pipetting can be seen in Figure 12. In the book "*Textbook of Clinical Embryology*" Coward and Wells (2013) forward pipetting is divided into 6 steps (refer to letters in Figure 12):

(1) "*Press down* (plunger button) *to 1st stop* (**A**)."
(2) "*Immers tip a few millimeters into a liquid*"
(3) "*Release* (plunger) *slowly. A tip will fill up* (**B**)"
(4) "*Dispense liquid by pressing down (plunger button) to the first stop* (**C**)"
(5) "*Then blow out remaining liquid by pressing down* (plunger) *to the second stop* (**D**)"
(6) When finished, release the plunger button (**E**).

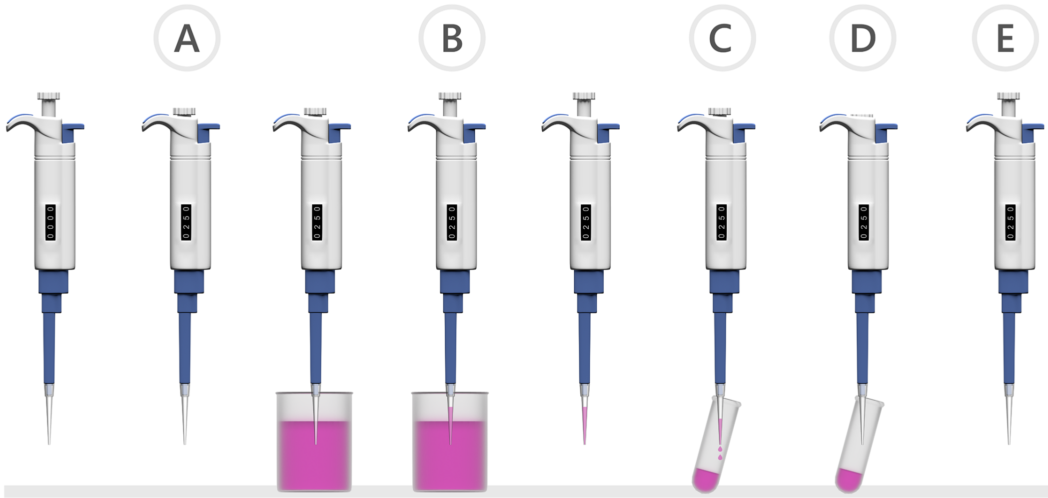


Figure 12.: Forward pipetting procedure.

Knowing the steps of forward pipetting and performing them in the right order does not imply that pipetting will be performed accurately. Inaccurate pipette handling can produce errors up to 5% per action. In the next section, we will introduce some of the most common handling errors.

5.1.2. Pipette handling

Pipettes are designed to accurately measure and transfer a small amount of liquid. The smallest handheld pipette measures to 0.1µL. The liquid transfer accuracy is largely depended on the pipette handling. Learning how to handle a pipette is a crucial task and often involves hours of practice. Most common pipetting errors are produced when (Coward and Wells, 2013):

- Setting dials incorrectly resulting in a wrong measurement.
- The plunger is pressed to the second stop during liquid intake resulting in too much liquid in the tip.
- Aspiration rate is too high leading to inaccuracies.
- The plunger not pressed all the way when dispensing liquid, leaving some liquid in the tip.

All this knowledge have to be learned in order to successfully perform a pipetting procedure.

5.2. *Target Group*

Our target group should consist of students who are not familiar with pipetting, and have no prior experience in pipetting themselves. This should serve as a fair comparison by ensuring that the students start at the same level. The age of our target group should be in the range of 18-35 years old, including undergraduates and postgraduates. Because the application is experienced in VR, we have chosen to restrict the participants to people with no visual impairments; unless this can be corrected for i.e. with prescriptions. Due to technical convenience users should be right-handed.

5.3. *Application Design*

As we learned in the previous chapter (see chapter 5.1), pipetting is a complex procedure consisting of multiple steps and various additional knowledge that is necessary to ensure the success of the performance. Taking into account the novice users and learning requirements [**R3**] and [**R4**] (chapter 4) we limited the procedure including only the fundamental steps of forward pipetting. To be more specific, we measured the accuracy of the liquid measures, time spent making a recipe and completion of the task. Such a compromise was made to ensure the validity of the test result by reducing the number of dependent variables within the procedure. To answer our final problem statement we designed two virtual reality application following the same interaction and learning principles based on the requirements. The only independent variable between the application was the input device. The control condition relied on the default *HTC Vive Pro VR controller*, while the experimental condition had implemented force feedback hand-worn controller, from *SenseGlove* (SG). Later we will discuss in depth the specifications of each of the devices.

5.4. *Development*

The application was prepared based on both an analysis of the design of the system (the most fundamental requirement), and an assessment of learning procedural skills. The development process of the applications adopted iterative and incremental (progressive) methods (C. and V.R., 2003). There were four stages for each iteration: *planning*, *development*, *evaluation*, and *improvements*. This allowed us to identify and eliminate mistakes and impressions early in the process. Each successful iteration was further incremented with additional features. Furthermore, each iteration had a sprint cycle, which helped to quickly progress with the development process. To keep an overview of the development process and to divide the workload we used Gantt diagram from the Agganty web app (refer to Figure 13).

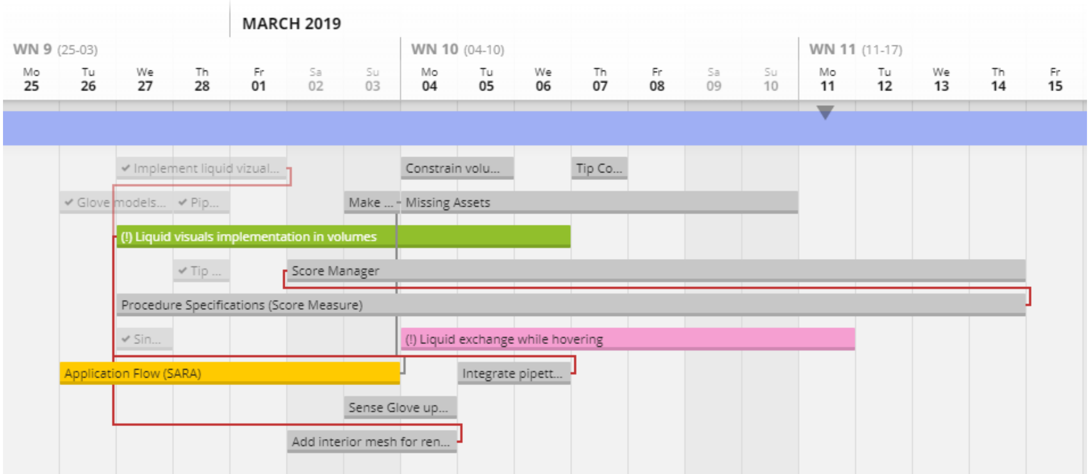


Figure 13.: Screenshot from Gantt diagram in Agganty.

Both applications were developed and iterated in parallel. They both share the majority of the scripts, with the exception for those specific to the input device. This ensured the unified general experience of the application (i.e. liquid simulation, lab environment, flow of the application).

The last iteration of the development process was to design and develop the interactive tutorial. The main objectives of this tutorial were to familiarize users with the controls of the input devices and to introduce the theoretical knowledge of the pipetting techniques. Automated tutorial allowed us to avoid the interruption between theoretical instructions and practical test procedure.

5.5. *Evaluation*

In order to answer our final problem statement, we have to consider what measurements are needed and how transfer can be quantified. For that, we figured it would be best to design an experiment with the necessary components to teach forward-pipetting in VR and in real life. The VR simulation should compare at minimum two different controllers. A traditional controller with low-level execution of action and hand-worn controller with high-level execution of action. We decided to use HTC Vive

Controller and a hand-worn controller called SenseGlove DK1 (refer to Figure 14). The SenseGlove has a comparatively higher level of execution than the Vive Controller allowing for 24 DoF tracking of individual fingers, force feedback, and tactile feedback. It is also capable of positional and rotational tracking in space using the Vive Tracker peripheral. The Vive Controller on the other hands allows only for positional and rotational tracking with tactile feedback.

Figure 14.: Vive Controller (left) and SenseGlove (right) with a Vive Tracker.

Furthermore, the design requirements should be used to guide the design of the simulation to make transfer more likely. For this, we believe the plunger interaction associated with aspirating and dispensing liquids should be in focus. The pipetting task, as we have discussed earlier, involves pressing the plunger on the pipette the right way. The transfer of this task requires the learner to associate the feedback from the controller with the physical force exerted in real life by the plunger when it is pressed. Measuring different qualities of the interaction with the plunger in VR can easily be done, but while we can measure these qualities, we need to make sure they are associated with transfer. For this it is necessary that we can make the same measurements in real life, to have something to compare against.

Our solution is to measure the accuracy of the pipetting task that the learner is conducting. During the experiment, the learner will be asked to perform numerous transfers of liquid with specific volume requirements. To test whether or not they have learned forward pipetting, we can simply check the resultant volume after a transfer of liquid has taken place. We also define a measurement error that is twice the volume indicated on the pipette dial. For example, if the learner is asked to measure 20µL, but push the plunger all the way before taking liquid into the pipette tip, the resultant intake would be 40µL. This way we are able to easily discern when the learner failed to apply the correct technique.

Finally, we equate the results of pipetting with the transfer of procedural skills by comparing the simulation with its real-life counterpart. In order to make the same measurement in real life, the learner will have to transfer liquid to individual containers instead of mixing them. Each container can then be weighted with a precise scale. The containers are weighted beforehand to subtract their individual weights from the corresponding measurement.

5.6. *Hypothesis*

Final problem statement:	Do hand-worn input controllers with a high level of execution and force feedback have an advantage over traditional handheld controllers with a lower level of execution and vibrotactile feedback for transfer of procedural skills to real life?

Based on the methodology explained in this chapter we define the following hypotheses:

H0: *Training in VR with the SenseGlove controller yields no difference in the precision of volume measurements for real-life pipetting as compared to those who trained with a Vive Pro controller.*

H1: *Training in VR with the SenseGlove controller yields higher precision of volume measurements for real-life pipetting as compared to those who trained with a Vive Pro controller.*

H2: *Training in VR with the Vive Pro controller yields higher precision of volume measurements for real-life pipetting as compared to those who trained with a SenseGlove controller.*

6. Design

In this chapter, we will walk through the design of a pipetting simulation for the teaching of procedural skills in VR in conjunction with a handheld controller (Vive Pro Controller) and a hand-worn controller (SenseGlove). The simulation sits the user in a virtual lab, where they can perform pipetting. The goal is to teach the forward pipetting technique used to mix different liquids.

6.1. *Pipette*

Pipetting in VR requires a micropipette that emulates the real one, to the extent that transfer can take place [R8]. We, therefore, decided to make it as realistic as possible. To comply with [R11], the pipette model is a 1:1 replication of a real pipette, with different moving parts (refer to Figure 15). The moving parts of the pipette are essential to provide feedback on the users actions [R23, R25]. For example, the user can turn the plunger on top of the pipette (A) and see the dials turn on the display

(B). Pressing the ejector (C) moves the lower body of the pipette (D), and pushes off the attached tip at the end (E).

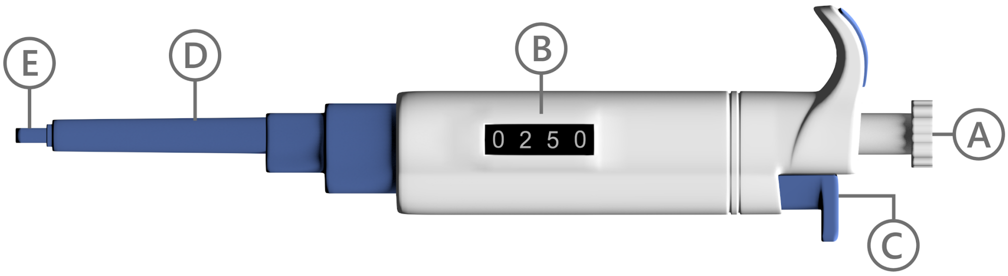


Figure 15.: Micropipette that was developed for the simulation. (A) Plunger (B) Dials (C) Ejector button (D) Piston (E) Sealing end.

When it comes to pipetting, this is a more complex ordeal. The pipetting of liquids can be broken into different stages depending on the direction of liquid exchange and whether the tip is above or below the surface of a liquid. We define three stages: (1) exchange to liquid above the surface (2) exchange to liquid below the surface (3) exchange to tip below the surface.

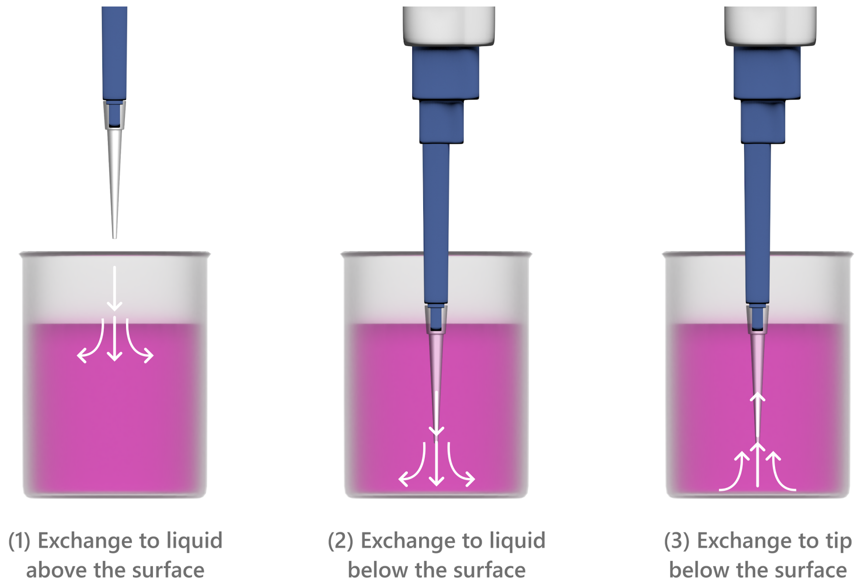


Figure 16.: Different stages of pipetting.

6.2. *Liquids*

The liquid mixing should at a minimum allow for an exchange of volumes (between containers) while also maintaining the total volume of the system during an exchange

[R11]. Additionally, the liquid containers should correctly display the volume at all times, providing accurate visual feedback to the user [R6]. This means that the system which handles liquids should be performant, however, given the complex nature of chemicals, this will not be easy in the simulated environment.

We found the best solution was also the simplest. Since the application revolves around learning the specific interactions associated with aspirating and dispensing liquids and not other lab routines or theory our representation of liquids can be greatly simplified [R16]. In our simulation, the representation of a chemical compound is denoted by a name (i.e. "salicylic acid") but does not refer to individual constituents ("salicylic acid" is compounded of carbon, hydrogen, and oxygen). This saves us the trouble of modeling all the characteristics of the chemical compound. We can also ignore physical and chemical properties as they are not needed to learn the pipetting task (pressing or depressing the pipette). The only property we are interested in is the volume of the liquids and that this information is not made inexplicable after mixing. For example, if we add liquid A to liquid B we obtain a mixture of the two. The total volume of this resultant mixture can be calculated by tracing back the volume of liquid A and B respectively. This leads us to our next point which is the distinction between chemical elements and liquids in our system. Chemical elements are what we have discussed above; they are our simplified description of a chemical compound. A liquid, on the other hand, is comprised of one or more elements and has a total volume made up by the individual contribution of its elements

6.3. *Types of Liquids and Containers*

For the simulation, we decided to create five fictive elements (refer to Figure 17). Each of these makes up a liquid in the simulation, and are placed into five different beakers (refer to Figure 18).

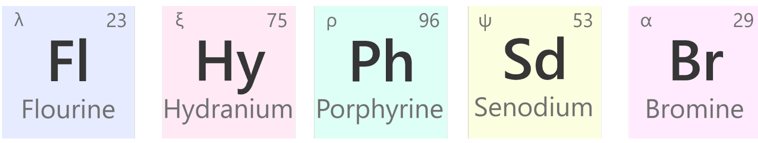


Figure 17.: Fictive liquids made for the simulation.

The main purpose of having beakers is to make the experience more immersive since beakers are usually present in a lab setting [R15]. All the liquids had the same color since we do not have to account for different colors mixing. To increase readability in VR, we added big letters for all the elements. The labels were also given different colors to more easily distinguish them.

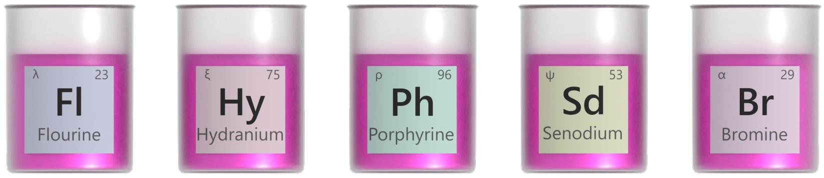


Figure 18.: Beakers with liquids.

Tubes were also created with different labels spanning from A to F in the alphabet (refer to Figure 19). The purpose of these tubes is to hold the different elements that make up a recipe. The letter denotes which recipe should be mixed in the tube.

Figure 19.: Tubes with labels A to F.

6.4. *Miscellaneous Objects*

In the simulation, the user can interact with different types of objects (refer to Figure 20) typically found at the biochemistry lab [R8], with an exception to the button . For both the Vive Pro controller and the SenseGlove the interaction is the same with these objects. One is the tip holder (A), which contains the tips (B) that attach to the micropipette. Tips are attached when there is a collision between the end of the pipette with the tip holder. Furthermore, a timer is started when a tip is attached to the pipette. A waste bin (C) is used to dispose of used tips. Buttons (D) are another type of object; a single button is included in the simulation and the user simply presses on it to interact. The button is mainly used to ask the user to confirm the activity before proceeding. After the timer starts, the timer stops by pressing the button.

6.5. *Walkthrough of the Simulation*

The VLE that was developed for the pipetting simulation is setup inside the pipetting simulation a lab environment that contains all the lab equipment necessary to perform

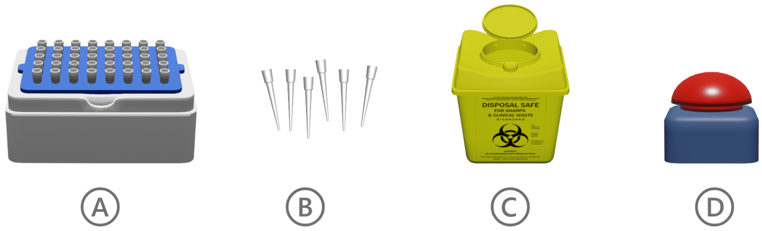


Figure 20.: Different game objects that the user can interact with.

pipetting . On the table different beakers and tubes are visible (refer to Figure 21) On the left side, a pipette is hanging on a rag with a tip holder next to it. A waste bin is visible on the right of the tubes and a button is next to it. A whiteboard is shown behind the beakers, and it is used to display the written instructions to the user.

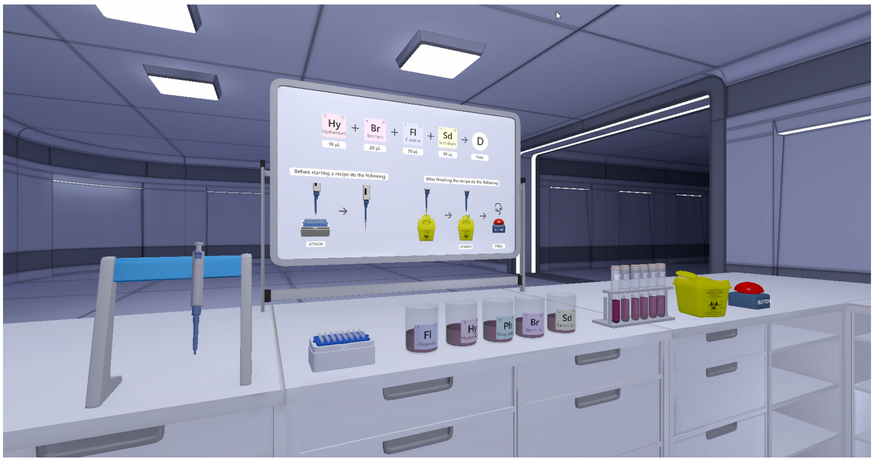


Figure 21.: Lab setup inside the pipetting simulation.

When the simulation starts the user is greeted by the voice of a virtual lab assistant that guides them through the learning simulation [R2]. In addition to guidance the assistant voice introduce explicit goals throughout the application to accomodate the learning transfer requirement [R9].

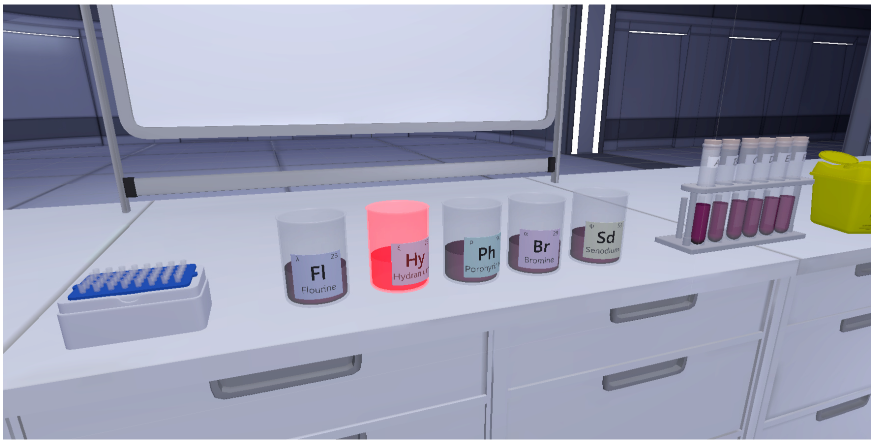


Figure 22.: Example of highlights used in the simulation.

To begin the application user is instructed to first press the red button on the table in front of them. After pressing the button the beakers and tubes are highlighted and presented in order from left to right (see Figure 22). Following this is an introduction to the learning objective and an introduction to the pipette. Considering [R3] and [R4] the knowledge is presented by identifying one element at the time with 1-2 seconds break between each statements. Furthermore, taking into account [R2], highlights are used to guide users actions In the following excerpts of these instructions, words encased in "⟨ ⟩" indicate highlights, while square brackets "[ ]" indicates the users actions. The first instruction on how to operate the dial is given immediately following the learning goal:

Excerpt #1

Virtual assistant: "Today you will have to use a pipette to mix the liquid from beakers into the empty tubes. You will receive different recipes. Make sure to follow them precisely. To continue, try to pick up the micropipette from the pipette holder." [The user picks up the pipette (refer to Table 4) "This is a micropipette. I will show you how to use it, so pay attention. First, we need to set the volume measure that we will be using. Look at the dials, they should be highlighted now. ⟨Dial is highlighted⟩ "Try to set the dial position to 30 microliters".

Two options depending on the controller (refer to Table 5):

- Vive Pro controller: "Use the touchpad button on the controller. Press and drag to adjust the number on the dial." [User adjusts the dial].
- Sense glove: "Grab the plunger button on the top of the pipette and twist it to adjust the number on the dial." [User adjusts the dial].

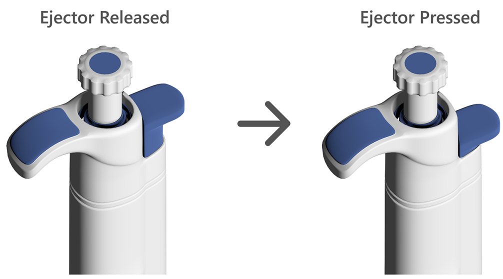
After learning how to set the dial, the user has to learn how to put on a tip and how to dispose of it. This is shown in the next excerpt:

Excerpt #2

Virtual assistant: "Now you have to put on the tip. There is a box of tips next to the pipettes holder" ⟨Tip box is highlighted⟩ "Touch any of the tips with the bottom of your micropipette to attach it." [User attaches tip] "Well done. Remember, you have to use a new tip every time you need to mix a new recipe. Now lets try to remove the tip. Always discard tips into the yellow waste bin" ⟨Waste bin is highlighted⟩ "To remove the tip you have to press the ejectpr button on the micropipette".

Two options depending on the controller (refer to Table 3):

- Vive Pro controller: "It is controlled by a small button above the touchpad on the controller. Press it now" [User ejects tip].
- Sense glove: "Reach out with your thumb and try to press it now" [User ejects tip].



Pressing the ejector	
Controller	Description
Vive	The user presses on the menu button on the Vive Controller (the button marked "1" in Appendix B "Vive Button Layout").
SenseGlove	Similar to real life, the user moves the thumb to the button location and presses it. Force feedback is felt when the button is pressed.

Table 3.: Table showing the how to press the ejector depending on the controller.

Picking up the pipette	
Controller	Description
Vive	(1) Hover your virtual hand over the pipette (2) Press the trigger button on the back of the controller.
SenseGlove	Move your virtual hand to the pipette pickup zone.

Table 4.: Table showing the different interactions for picking up the pipette.

Adjusting the dial	
Controller	Description
Vive	(1) Press down and hold your thumb on the trackpad [marked ”2” in Appendix B ”Vive Button Layout”] (2) Slide to left or right to adjust the dial (3) Release when the dial shows the correct number or repeat to make further adjustments.
SenseGlove	(1) Move your virtual hand in the proximity of the plunger (2) Make a pinch gesture until a slight force is felt (3) Twist your hand either left or right; the dial should spin at a constant rate (4) Move your hand away from the dial when the dial shows the correct number.

Table 5.: This table shows how the dial can be adjusted depending on the controller.

In order to successfully execute a pipetting procedure, a sequence of actions needs to be performed. It is necessary to implement the same action sequence in the VLE to teach procedural skills. Furthermore, to get the correct measurements, the appropriate sequence of actions must be performed. As stated earlier, the correct way to do forward-pipetting is to press the plunger to the first stop before submerging the tip into the liquid. In the simulation pressing to the second stop (before submerging) yields twice the volume as the one indicated on the dials. This allows us to discern whether or not the user pressed to the first or second stop when we look at the results. The following is an excerpt of the pipetting instructions:

Excerpt #3:

Virtual Assistant: ”The plunger button is located on the top of the pipette” ⟨Plunger is highlighted⟩ ”Use the plunger to control the intake and release of the liquid in and from the pipette tip”

Two options depending on the controller.

- Vive Pro Controller: ”You can press and release the plunger button using the trigger button on the Vive controller. Press it now” [User presses the plunger].
- SenseGlove: ”Press it now” [User presses the plunger].

  Virtual Assistant: ”Great! Before you take in liquid, it is important that the plunger is pressed to the first stop. Make sure you have attached an unused tip to your pipette. The plunger button must be pressed and released in slow motion. If you press or release the button too fast, the results will be inaccurate. It is very important that you press and hold the plunger button down before the pipette tip is submerged into a liquid.”

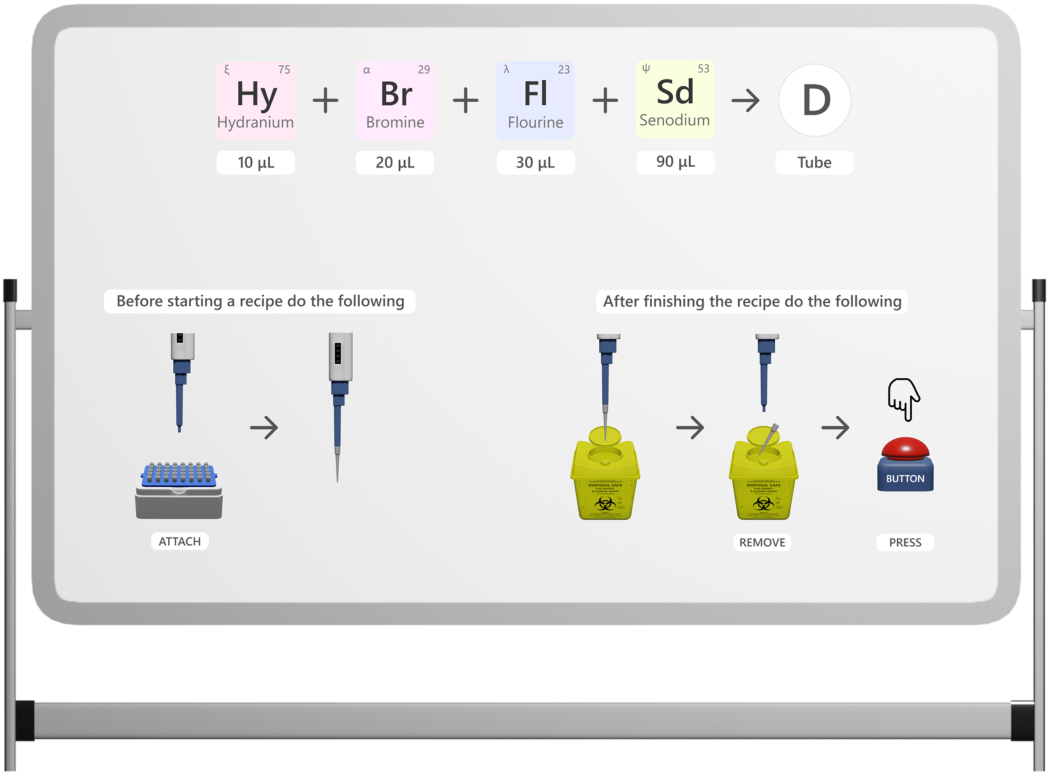


Figure 23.: Whiteboard with instructions. The recipe is shown on top. Below instruction are provided for starting a recipe (left) and what to do when the recipe is finished (right).

After performing these steps the user is instructed how to mix liquids. On the whiteboard, instructions appear (refer to Figure 23) together with a trial recipe (on top) the user has to mix. The following is an excerpt of the liquid mixing instructions users:

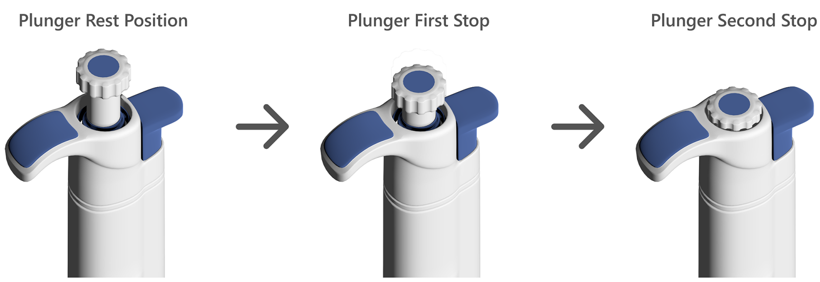
Excerpt #4:

Virtual assistant: "Before you take in liquid, it is important that the plunger is pressed to the first stop".

Two options depending on the controller.

- Vive Pro Controller: "Press and hold the plunger button now until you feel a vibration " [User presses the plunger] "Great, when you feel the controller is vibrating, the plunger is at the first stop. Now release it"
- SenseGlove: "Press and hold the plunger button now until you feel a vibration and a force acting on your finger" [User presses the plunger]. "Great, when you feel the force and vibration, the plunger is at the first stop. Now release it"

Virtual Assistant: "This is very important. The plunger has to be in the first stop before the tip is submerged into a liquid. If not done correctly, the measurement will be imprecise."



Pressing/depressing the plunger	
Controller	Description
Vive	The user presses/releases the trigger button (the button marked "7" in Appendix B "Vive Button Layout"). To reach the first stop, the button should be pressed halfway at which point a vibration is felt. The vibration is followed by a continuous pulse. The pulse is felt until the user moves out of the first stop which is given some spacing around the triggers middle point. To go to the second stop, the user simply presses the trigger all the way down.
SenseGlove	A user presses/releases the button with the virtual hand. When vibration is felt, the plunger is in the first stop. Continuous force feedback is used to indicate that the user is still in the first stop. To move to the second stop the user has to press against the force acting on the finger until the plunger reaches all the way.

Table 6.: Table showing the how to press the ejector depending on the controller.

As seen in Table 6, when interacting with plunger button the user is provided with haptic feedback, which indicates the validity of the action (vibrates when pressed to the 1st stop) [R25], and it could help users to fine tune the motor action (since user should learn how to adjust the pressure to feel the vibration) [R6].

Following the explanation of how the plunger works, the user is asked to try transferring liquid from a beaker to a tube. A trial recipe is provided which is not counted as part of the final results. Once this trial is completed, the user has to mix six different recipes (refer to Appendix A "Recipes").

The top of the whiteboard shows the current recipe the user has to mix. Below that are the instructions to start a recipe and what to do after finishing it. A timer starts counting once the user puts on a tip, and stops when the button is pressed. The user is not aware of the timer at any point during the mixing. After six rounds the exercise is completed and measurements can be obtained regarding liquids and their volumes inside each tube.

In the final procedure we support [R1] and [R5] requirements by introducing repetition of the task and removing the guidance.

7. Implementation

This chapter looks at the software tools used in the development process and discusses the system implementation with an emphasis on the application's interaction aspects.

7.1. *Software*

The simulation is composed of a VE that takes advantage of the Unity game engine to leverage real-time graphics rendering and scripted behavior in the C# programming language through the Mono runtime (Technologies, 2019). Unity complements VR development by offering third-party support for many types of VR hardware. In this project, we used SteamVR 2.0 together with the HTC Vive Pro. SteamVR provides many pre-made game objects and tools to kickstart development i.e. the skeleton poser and the input system. That being said, we had to develop many game objects and behaviors from scratch. Most of the 3D models, for example, were modeled or modified in the Blender, which is a free and open-source 3D computer graphics software toolset.

7.2. *Optimization*

We had to consider our performance targets. Our target frame rate was 90 fps as this is the refresh-rate of modern HMDs. Going below this can cause unwanted effects such as dizziness or visual artifacts caused by frame by frame interpolation (Vlachos, 2018). As for the number of draw calls we specified 500-1000 draw calls per frame. Draw calls happen when Unity draws an object on the screen. It then has to issue a draw call to the graphics API. To lower draw calls, we can limit the number of lights in the scene that cast real-time shadows, combine objects or use fewer materials. Another way we can increase performance is to limit the number of triangles in our scene, we specified our triangle budget to a maximum of 1 million triangles per frame.

7.3. *Web Services*

We used Google TTS high-fidelity speech synthesis to generate the voice of the virtual assistant in real-time. We wrote a custom implementation that sends a POST request to Googles servers and retrieves the audio data bytes encoded in LINEAR16. LINEAR16 is a 16-bit linear pulse code modulation (PCM). It is an uncompressed, signed data type with little-endian byte order (Groovenauts, nd). In order to use it, we have to convert the bytes into something Unity recognizes (refer to the source code

"GoogleTextToSpeech.cs"). In addition to this, we constructed a queue that takes snippets of strings that will be converted to speech in the order they were queued. Action delegates were used to trigger events when each voice snippet is played and when it ends. This made it possible to easily implement the pipetting introduction by linking different highlights to parts of the assistants manuscript.

7.4. *3D Modeling Workflows*

Depending on the model, different workflows were used. In general, a subdivision surface modeling workflow was adopted for 3D models using the Catmull-Clark algorithm to smooth surfaces. This method allowed us to easily control the level of details (LOD) as it retains lower subdivision levels. For each model, we had to consider the number of details depending on how close they are viewed in VR.

The pipette was the most intricate of the objects that were developed. It has several moving parts (refer to Figure 24), and objects hierarchies (refer to Figure 25) necessary to animate it. The plunger, eject button and dials were procedurally animated inside Unity to make sure they act the same as in real life.

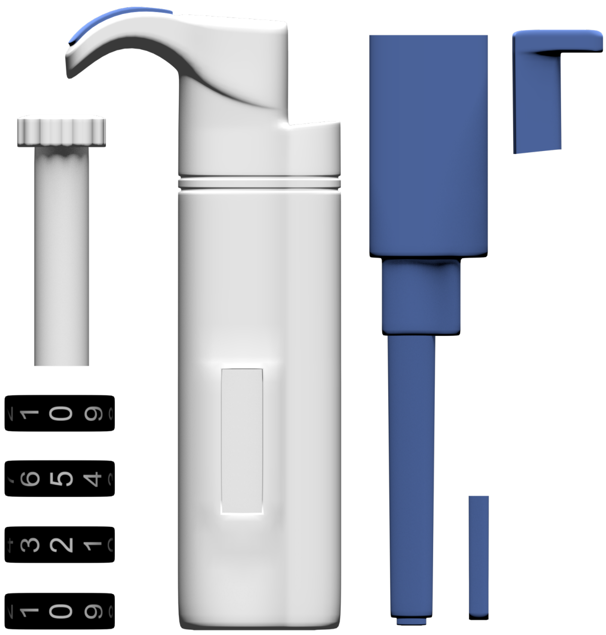


Figure 24.: Different parts that make up the virtual pipette.

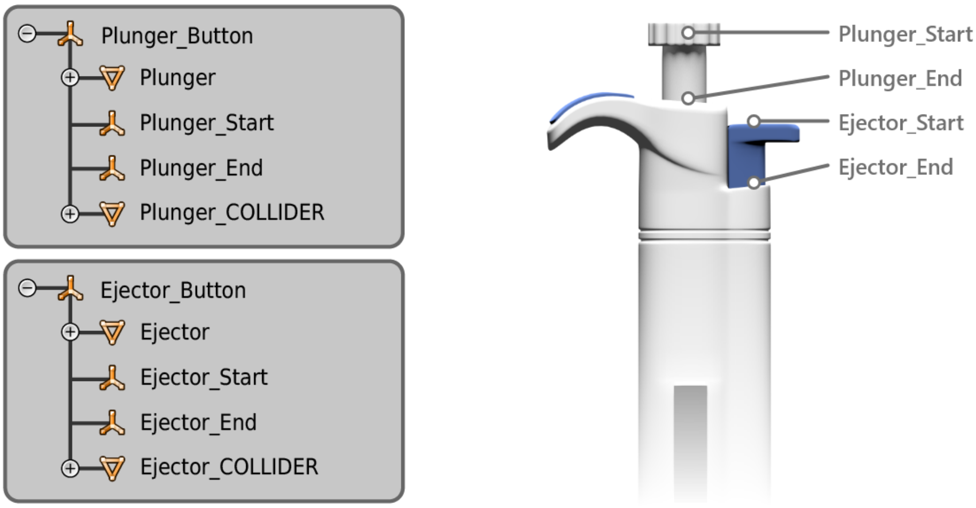


Figure 25.: Example of objects hierarchies in Blender. These hierarchies are used in Unity to enable procedural animation between a start transform and an end transform.

7.5. *Turning dials*

Turning the dials on the virtual pipette was necessary to implement. We chose to implement one shared system that sets the dials on the pipette; this system is controlled by two separate input systems. One thing they have in common is that they both are linked to the plunger (when the plunger rotates, the dial follows suit) (refer to Figure 26).

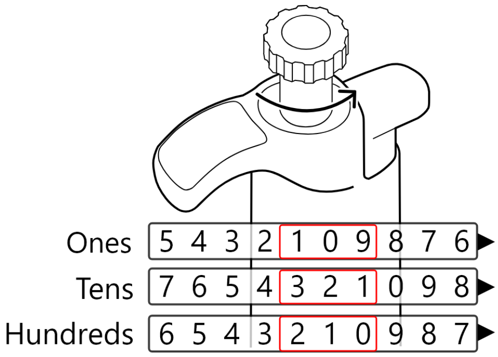


Figure 26.: The numbers on the dials move in the positive direction when the plunger is rotating anticlockwise. The rotation of the 10s and 100s are delayed as they only have to change when the dial above them moves from 9 to 0.

7.6. *Vive Controller*

Turning the dial on the Vive controller requires the user to perform a trigger action followed by a swipe action on the trackpad. The trigger action is linked to a boolean that tells the dial it can rotate. Triggering requires the user to press and hold the trackpad button. While holding it and swiping, the initial position (when the trackpad was pressed) and the current one (after swiping) will be used to determine the dial position.

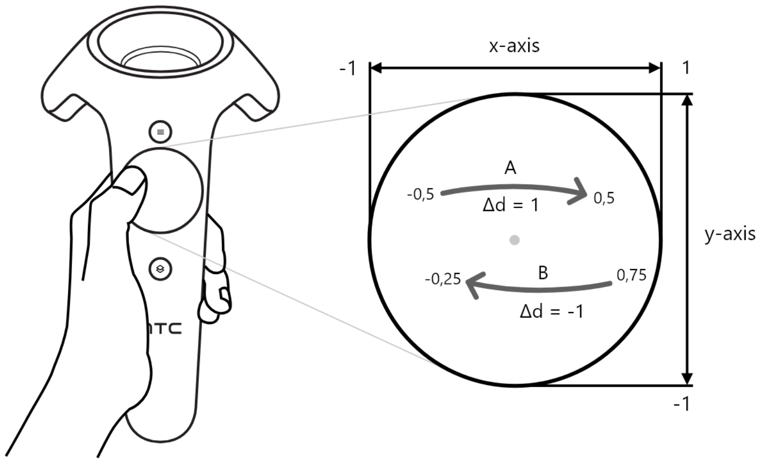


Figure 27.: Example of the swiping action on the trackpad. (A) shows an arrow with a length of 0.5-(-0.5) = 1, while (B) has a length of 0.75-(-0.25)=1.

Expressed mathematically, the dials angle is determined by the distance traveled (Δd) horizontally on the trackpad (refer to Figure Fig. 28) added to the initial dial angle θ_0 which is constant in the duration of the action. The max speed of the action $|\frac{d_\theta}{dt}| = |v_\theta|$ plus one (to avoid multiplying by zero) is used to determine how far the dial turns. An additional factor is also added to control the sensitivity of the rotation s. The angle of the dial calculated in one frame θ is given by:

$$\theta = \theta_0 + \Delta d \cdot (1 + |v_\theta|) \cdot s \tag{1}$$

The implementation of this formula (refer to Algorithm 1) was done in a ViveKnobControl-class, which is a generalization of the plunger button (a type of knob). On line **3**, we calculate the speed and acquire the maximum speed when the user is sliding on the trackpad. Furthermore, the speed is arbitrarily mapped to an interval [1;3]. This achieves the same result as adding 1 to the speed, while also setting the upper speed limit.

```
1  Function TurnKnob(Hand hand):
2      [...]
3      speed = Mathf.Max(speed, Map(Mathf.Abs((distance - pDistance) /
        Time.deltaTime), 0, 40, 1, 3));
4      if reached lower dial limit then
5          return;
6      end
7      if reached upper dial limit then
8          return;
9      end
10     _knobPosition = Mathf.Lerp(_knobPosition, _initialKnobPosition +
        positionDifference * speed * _turnSensitivity , Time.deltaTime * 5);
11     [...]
```

Algorithm 1: Setting the dial using the Vive controller

The formula is implemented on line **10**, with a lerp function to interpolate the rotation of the plunger. This provides are smoother motion when turning the dial. We multiplied the deltaTime which 5 to achieve a faster interpolation, but this could be any number.

7.7. *SenseGlove*

To adjust the dials with the plunger using SenseGlove it is also necessary to perform a trigger action. This involves performing a pinch gesture on an invisible collider that is placed above the plunger. Once the collider detects at least two fingers touching it it will allow the dial to rotate. To control the rotation, the users hand has to tilt either clockwise or anticlockwise while remaining inside the collision area.

The plunger and dial should start rotating at a constant rate based on the tilt direction. Expressed mathematically the final angle θ is determined by the turn rate calculated as the angle between the initial touch position φ_0 (when the action was initiated) θ_0 and the current touch position φ in relation to the plunger:

$$\theta = \theta_0 + \varphi_0 - \varphi \tag{2}$$

The code used to calculate this looks a bit different (refer to Algorithm 2) as we have to account for 3-dimensions and coordinate space.

To get the angle we define two different vectors, P and Pn . The first one is defined in line **2**, and takes the local touch position which is the position of the fingers (relative to the plunger). In line **7**, we set the second vector to the transform of the plunger and transform it to the same coordinate space as vector P. We then project both vector positions onto the movement axis (lines **8-9**). This allows us to calculate the a signed angle (line **10**) which is then used to calculate the angular difference (line **11**) and

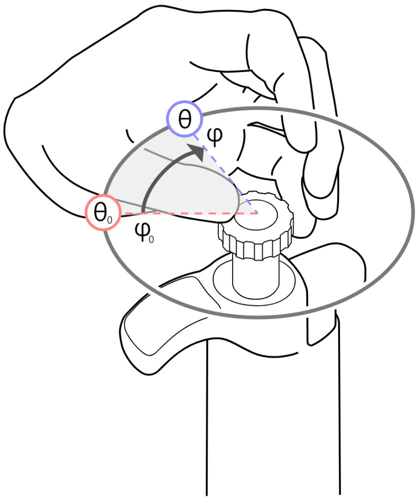


Figure 28.: The rotation of the dial is determined by the plunger's rotation. The initial plunger angle is denoted θ_0 and the current one is denoted theta. The tilt angle is determined by the user's hand and is calculated as the difference between the initial touch position φ_0 and the current position φ in relation to the plunger.

replaces the current angle (line **12**). Finally the plungers angle is calculated as the prior angle plus the angular difference (line **13**).

7.8. *Pressing plunger*

One of the important aspects of the interaction is the feedback felt when pressing the plunger. There were two different implementations of the feedback; one was based on the Vive Controller and SteamVR libraries while the other one was based on the SenseGlove and its SDK. The parts of the SenseGlove SDK used in this project was developed in collaboration with the company.

The pipetting was implemented using Unitys Animation Curves which is part of the engines core modules. These animation curves are usually not used for this purpose, but we found that it had the functionality we needed. The curve maps the input of the position of the plunger to a volume multiplier used to calculate the displaced volume (refer to Figure 29). The X-axis represents the input from the plunger position and is normalized (between 0 and 1), while the Y-axis corresponds to the volume multiplier. Displaced volume can be expressed as the difference between the Y-components of two points on the curve times the volume indicated on the pipette dials. For example, if the user sets the dials to 50µL, and the difference of the Y-components equals 0.5, only 25µL is displaced. Conversely, if the difference is 1.5, the user will displace 50% more volume than indicated. To get the right amount, the difference of the Y-components should always equal 1. This is made possible by forward-pipetting e.g. suppose Y_0 is the

```
Function UpdateAngularDifference(MovementAxis axis):
    Vector3 P = LocalTouchPos;
    Vector3 Pn;
    if plungerTransfrom == null then
        throw new Exception("Something went wrong! Did you forget to set the
          plungerTransform?");
    end
    Pn = PlungerTrans-
      form.InverseTransformPoint(FeedbackScript.transform.position);

    P[(int)axis] = 0;
    Pn[(int)axis] = 0;
    float newAngle = Vector3.SignedAngle(P, Pn,
      SenseGlove_Util.GetAxis(axis));
    dAngle = newAngle - CurrentAngle;
    CurrentAngle = newAngle;
    TotalAngle = TotalAngle + dAngle;
```

Algorithm 2: Calculates the angular difference between the initial angle of the touch and the current angle.

value when the tip is submerged into the liquid, and Y_1 is the current Y value (based on the input) after moving the plunger an arbitrary distance. We start by pressing the plunger to the first stop which gives us $Y_0 = 1$ as indicated in Figure 29. Releasing the plunger to the neutral position $(0, 0)$ then yields a volume multiplier equal to 1 after subtracting Y_1 from Y_0.

As we mentioned earlier (refer to section 5.5), we allow users to make a measurement error that we define as twice the volume indicated on the dial. We derived a factor α based on this which takes the percent error $\%Error$ and scales our curve on the Y-axis.

$$\alpha = (\%Error + 100)/100 \tag{3}$$

Put simply the $\%Error$ indicates how many percent extra volume the tip can take (relative to the dials indicated volume); in our case α=2 corresponding to hundred percent more volume $\%Error = 100$ in the worst case scenario (when the plunger is pressed all the way before taking in liquid).

7.9. *Controller Feedback*

Depending on the controller the user will experience different feedback. When pressing to the first stop both controllers triggered has vibrotactile feedback that is triggered

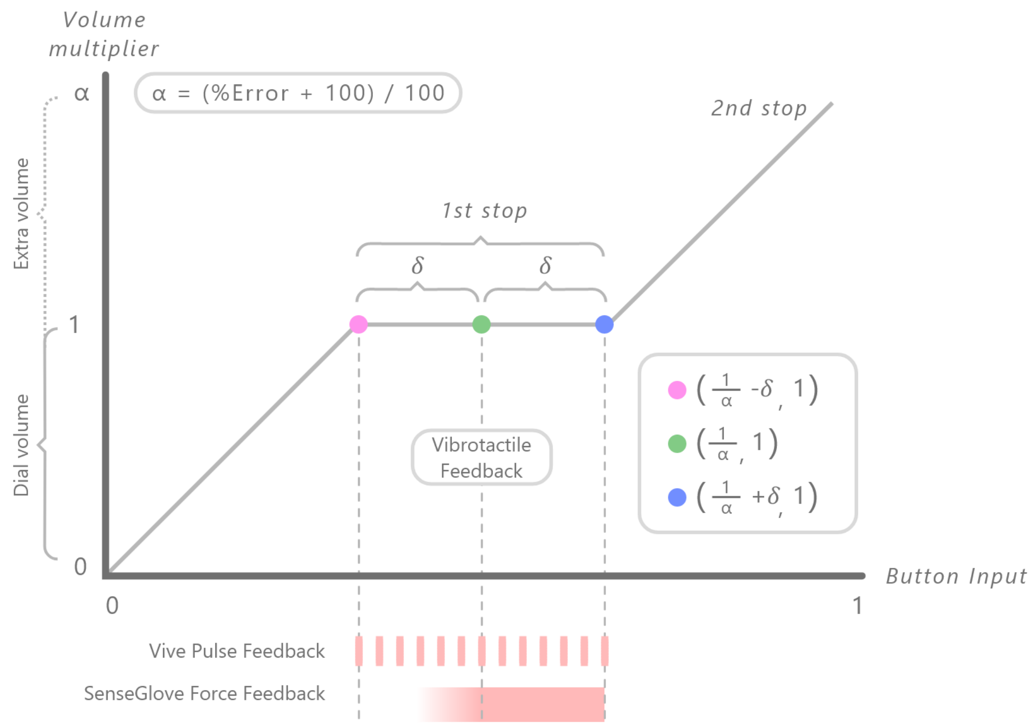


Figure 29.: Graph showing how the plunger feedback is implemented.

around midway into the first stop $X = \frac{1}{a}$ (refer to Figure 29). This provides some spacing δ away from the edges which stabilize the volume measurement. After the vibrotactile feedback is triggered the feedback depends on the controller.

7.9.1. Vive Controller

On the Vive Controller, the plunger is controlled by the trigger (marked "7" in Appendix B "Vive Button Layout"). After reaching the trigger, continuous pulse feedback is present in the interval $\frac{1}{a} - \delta > x > \frac{1}{a} + \delta$. This indicates to the user that the plunger is still in the first stop. To move to the second stop, the user must press the trigger all the way down.

7.9.2. SenseGlove

The SenseGlove controller works a little bit differently. Instead of a pulse, the user feels continuous force feedback pushing on the thumb (refer to Figure 29). When the user's thumb feels enough resistance, this indicates that the first stop is reached. This is implemented by placing an invisible object on top of the plunger, that only reacts to the users finger. The object has physical properties determined by the SenseGlove_Material-class that contains material properties for virtual objects. These can be customized, hard-coded or loaded during runtime. To move to the second stop, the user has to apply enough force to push against the force exerted by the invisible object; if sufficient force is applied the users finger should clip through the object; at this point, no force is felt and the plunger will be at the second stop.

8. Evaluation

In this chapter, we will evaluate our application design in regards to the final problem statements to see if hand-worn input controllers with a high level of execution and force feedback have an advantage over traditional handheld controllers with a lower level of execution and vibrotactile feedback for transfer of procedural skills to real life.

8.1. *Method*

To test our problem statement we developed two different training applications to teach pipetting. One using a Vive Controller and the other using a SenseGlove controller. To exclude any learning effects a between-group design was chosen. We evaluate the learning transfer from virtual simulation training by replicating the applications procedure in real life.

8.1.1. Equipment

In the control condition, the default controllers that come together with the HTC Vive Pro are used to train participants in the simulation, see Figure 30. The experimental condition uses the same HTC Vive Pro head-mounted display together with force feedback capable hand-worn controller from SenseGlove. HTC Vive trackers are used together with hand-worn controllers to track the position and orientation.

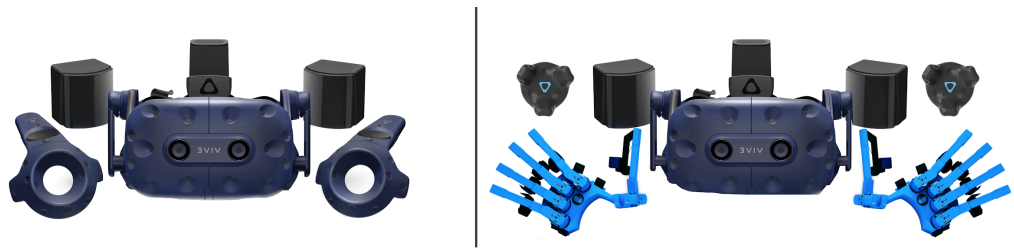


Figure 30.: VR equipment for the control (left) and experimental (right) condition applications.

8.1.2. Applications

The pipetting application consists of two parts for both treatment groups: Vive (control condition) and SenseGlove (experimental condition). First part is an interactive tutorial phase. During the tutorial, the participants have a chance to familiarize themselves with the VR equipment, the virtual environment, and interactions with virtual objects in the scene. A theoretical introduction to pipetting techniques is also presented in this phase. In addition to this, the participants have to perform a step-by-step walk-through of how to transfer liquids with the pipette. This is a necessary step to teach them the controls. To minimize the learning effects, participants are only told the bare minimum information related to pipetting.

The second part of the application is pipetting exercise. In this part, participants receive six different recipes they will have to mix. The recipes are made up of two to five liquids inside different beakers, that has to be transferred to six test tubes (one per recipe) (see Appendix A). The recipes are presented on a virtual whiteboard one at the time. During the exercise, no assistance is provided except for a few instructions displayed on the virtual whiteboard (refer to Figure 31).

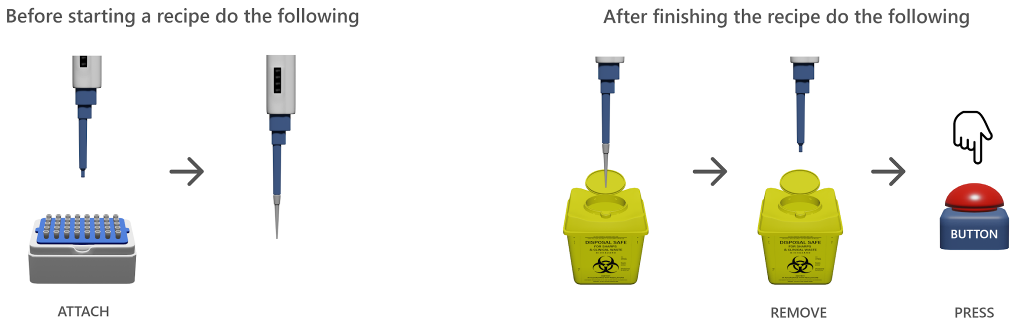


Figure 31.: Instructions displayed on the whiteboard. On the left instructions are given on how to begin a recipe. The user has to put on a tip (one tip is used per recipe). Upon finishing the recipe the user must discard the tip and press the red button to continue.

To begin a recipe the participant has to first put on a tip. One tip is used per recipe and is discarded upon completing a recipe. To complete a round the participant has to press a red button after which a new recipe is shown. The application is complete when participants complete all six recipes and press the red button one last time.

8.1.2.1. Measurements.

The application measures the exact volume transferred into the six test tubes (corresponding to the six different recipes). The total amount of measurements is 21 per person. We also measure the time it takes to complete each recipe. A timer starts counting once a tip has been attached to the pipette. After mixing the participant presses the red button, ending the timer.

8.1.3. Real-life Pipetting Exercise

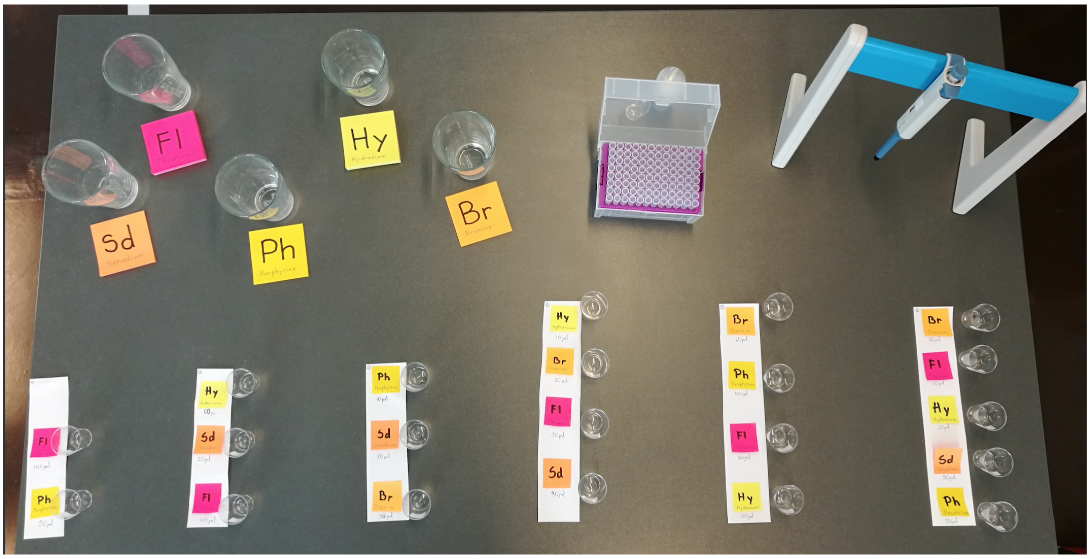


Figure 32.: Setup for the real-life pipetting exercise.

To measure learning transfer, we asked testers to perform an identical task (with some exceptions) in real life, to the one they did in the virtual world. The real-life pipetting exercise setup can be seen in Figure 32. To measure the accuracy of the performance we asked participants to transfer each element from the recipe into a different container. Furthermore, instead of pressing the button, testers had to verbally confirm when the task was finished.

8.1.3.1. Measurements.

In the real-life pipetting task, water was transferred to individual containers. We measured the volumes of each container using a digital weight with a precision of 0.01g. The recipe volumes were bigger by a factor of 10 compared to the recipes in the application (i.e. 1000µL instead of 100µL). This allowed the weight to measure three significant digits for each volume. We know this because of the density of water (1 kilogram per liter (kg/L) at 39°C or 9.982310^{-4} grams per microliter at room temperature). The largest measurement of 1000µL amounted to 0.99823g $\approx$ 1g and the smallest of 100µL weighs approximately 0.1g. Thus, we can say beyond a reasonable doubt that our 0.01g weight is more than capable of measuring the small volumes.

8.1.4. Questionnaires

In addition to the application, users had to fill out 3 questionnaires: *pretest*, *posttest* and *final questionnaire*.

8.1.4.1. Pretest.

The pretest consisted of 12 questions examining participants personal qualities (age, gender, background, vision, etc.) and their experience with virtual reality if any. The VR related questions were important in this stage. Testers who were familiar with equipment might outperform those who had no prior knowledge. This can happen due to the distractions related to the new, inexperienced environment itself (Wrzesien and Raya, 2010) as well as due to controls of novice input device.

8.1.4.2. Posttest.

The posttest questionnaire had three parts: learning, application, and interface. Learning part examined the theoretical knowledge of the pipetting procedure. The application section of the questionnaire was developed using the System Usability Scale (Lewis and Sauro, 2009). This part of the questionnaire contained 10 items with a 7-point Likert scale. These items evaluated the usability and acceptance of the application. The last part of the posttest was evaluating questions related to the interface. The interface section had 17 items with a 7-point Likert scale analyzing interaction, the flow of the application, instruction design and overall experience, etc.

8.1.4.3. Final questionnaire.

The final questionnaire section had 6 items with a 7-point Likert scale. These items examined testers learning experience and information transfer to the real life setting.

8.1.5. Procedure

Our test procedure had 3 major elements, (see fFigure 33): virtual learning application (red), real-life pipetting (green) and questionnaires (blue). The questionnaires were divided into 3 sessions. Test participants were randomly assigned to the specific test conditions using a pseudo-random number generator (0 - control, 1 - experimental).

Test procedure stated with the pretest questionnaire. During this stage, we collected dated about our testers and learned more about their VR experience if any. After the pretest was completed, participants were introduced to the VR setup depending on the condition (see Figure 30). For the experimental condition, we had to help test participants to put on the SenseGlove equipment and make sure that hands are calibrated correctly. Once the hardware was ready testers started the VR application. Both VR tutorial and VR pipetting exercise were performed without interruption (refer to Figure 33). When the application was finished test participants proceeded to answer the posted questionnaire. In this stage, we asked questions related to learning of the pipetting procedure as well as usability and interaction specific questions. The posttest questionnaire was followed by the real-life pipetting exercise (32). Testers were asked to perform an identical procedure as they did in VR. The final stage of the testing was a summary questionnaire. Testers had to evaluate their learned knowledge and experience.

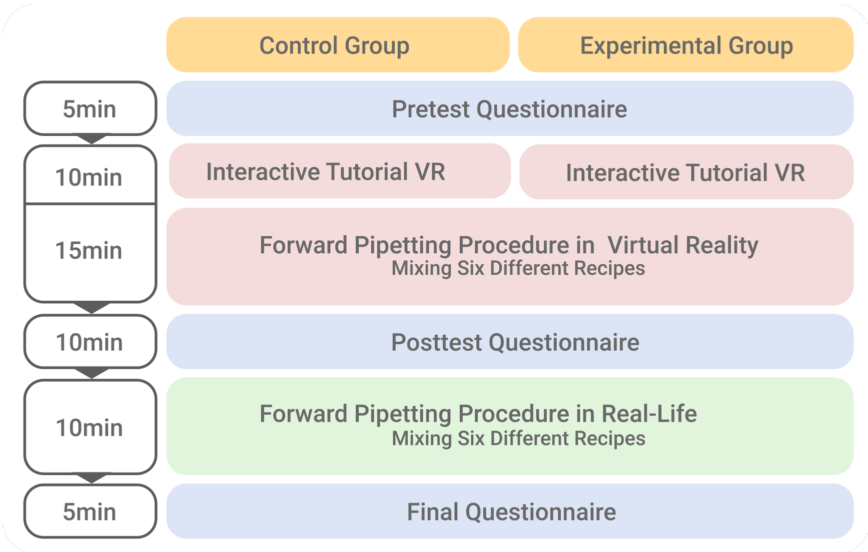


Figure 33.: Flow diagram of the test procedure.

8.1.6. Testing

Testing was conducted on a total of 23 undergraduates and graduate students at the faculty of psychology at Copenhagen University. Participants median age was 26 with the youngest being 22 and the oldest 32. 80% of participants were males and 20% were females. All participants described themselves as right-handed with no color vision deficiency. Furthermore, people with prescriptions were allowed to wear glasses or contacts in VR. 18 out of 20 participants had some experience with VR. 11.1% only tried it once or twice, 61.1% reporting that they have used VR more than a few times and 27.8% describing themselves as very frequent users. For 88.9% of the participants who used VR, the experience involved a handheld controller. The vast majority of testers used Vive or equivalent VR devices in the past.

Location: Virtual Learning Lab KU, ster Farimagsgade 2A, 1353 Kbenhavn K, Denmark
Dates: 26th of April to 4th of May, 2019
Time: Between 10 am and 5 pm
Test subjects:

- Novice pipette users without any prior knowledge.
- Right Handed (due to application constraints)
- Not colorblind (due to color-coded visuals) age 26, minimum age 22, maximum age 32
- Undergraduate and graduate students

Duration: 1 hour
Sample size: 23 (11 control condition, 12 experimental)
Outliers: During the testing procedures we registered 3 outliers (2 in the experimental group, 1 in the control). Data corresponding to outliers was removed from the results.

8.2. *Results*

In this chapter, we present the results that we gathered during our experiment. 23 test participants completed the test (11 control condition, 12 experimental). Three participants were marked as outliers and later excluded from the evaluation. The data of the remaining 20 participants (10 control condition, 10 experimental) is presented below.

The experiment was divided up into two tasks. The *Virtual Pipetting (**VP**)* and the *Real-life Pipetting (**RP**)*. We first compared the performances of the Vive (control) and SenseGlove (experimental) controllers for the VP task.

8.2.1. *Virtual Pipetting (VP)*

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Group	Statistic	df	Sig.	Statistic	df	Sig.
Volume Error Means (VP)	Vive	,196	10	,200*	,946	10	,620
	SenseGlove	,190	10	,200*	,903	10	,234

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

A one-sample Kolmogorov-Smirnov criterion and Shapiro-Wilk test were used to test for the normality with regard to the data. The Kolmogorov-Smirnov test indicates that the control condition, $D(10) = .196$, $p = .200$ and the experimental condition,

$D(10) = .190$, $p = .200$ both follow a normal distribution. Likewise, the Shapiro-Wilk test reported that the control condition, $D(10) = 0.946$, $p = 0.620$ and experimental condition, $D(10) = 0.903$, $p = 0.234$, are both normally distributed.

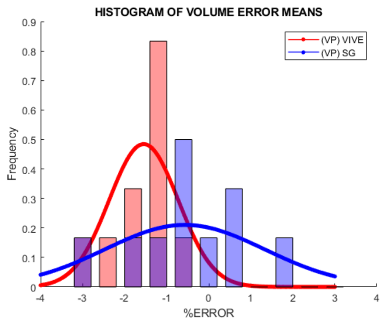
Group Statistics

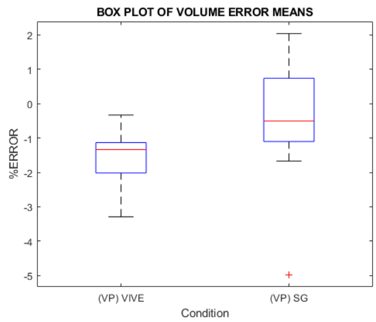
	Group	N	Mean	Std. Deviation	Std. Error Mean
Volume Error Means (VP)	Vive	10	-1.5471	.82382	.26052
	SenseGlove	10	-.5703	1.89776	.60012

To test for homogeneity of variance we used Levene's test. The results indicated equal variances for both conditions when the VP task was performed, $F(1, 18) = 2.070$, $p = .167$. An independent-samples t-test (2-tailed) was conducted to compare pipetting performances in Vive and SenseGlove conditions. There was no significant difference ($p > .05$) in the scores for Vive ($M = -1.547, SD = .824$) and SenseGlove ($M = -.570, SD = 1.898$) conditions; $t(18) = -1.493, p = .153, d = 0.667713$.

Independent Samples Test

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Volume Error Means (VP)	Equal variances assumed	-1.493	18	,153	-.977	.654	-2.351	.398
	Equal variances not assumed	-1.493	12.276	,161	-.977	.654	-2.399	.445





8.2.2. Real Pipetting (RP)

Tests of Normality

	Group	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Volume Error Means (RP)	Vive	,149	10	,200*	,950	10	,667
	SenseGlove	,166	10	,200*	,956	10	,739

A one-sample Kolmogorov-Smirnov criterion and Shapiro-Wilk test were used to test for the normality with regard to the data. The Kolmogorov-Smirnov test indicates that the control condition, $D(10) = .149$, $p = .200$ and the experimental condition, $D(10) = .166$, $p = .200$ both follow a normal distribution. Likewise, the Shapiro-Wilk test reported that the control condition, $D(10) = .950$, $p = 0.667$ and experimental condition, $D(10) = 0.956$, $p = 0.739$, are both normally distributed.

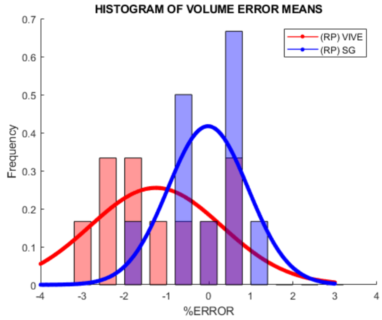
Group Statistics

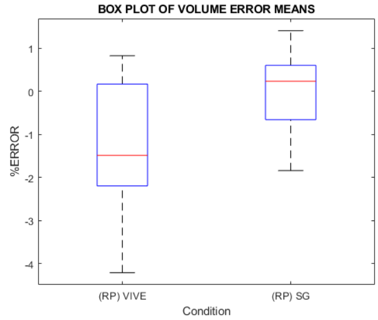
	Group	N	Mean	Std. Deviation	Std. Error Mean
Volume Error Means (RP)	Vive	10	-1.2586	1.56584	.49516
	SenseGlove	10	-.0172	.95674	.30255

To test for homogeneity of variance we used Levene's test. The results indicated equal variances for both conditions when the VP task was performed, $F(1, 18) = 2.616$, $p = 0.123$. An independent-samples t-test (2-tailed) was conducted to compare pipetting performances in Vive and SenseGlove conditions. There was a significant difference (p¡.05) in the scores for Vive $(M = -1.259, SD = 1.566)$ and SenseGlove $(M = -.017, SD = .957)$ conditions; $t(18) = -2.139, p = .046, d = 0.956735$.

Independent Samples Test

		t-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Volume Error Means (RP)	Equal variances assumed	-2,139	18	,046	-1.24142	.58028	-2.46054	-.02230
	Equal variances not assumed	-2,139	14,898	,049	-1.24142	.58028	-2.47899	-.00385





8.2.3. System Usability Scale

Vive Scores	SenseGlove Scores
81.7	71.7
91.7	78.3
81.7	51.7
85.0	70.0
90.0	66.7
81.7	38.3
83.3	63.3
83.3	68.3
91.7	68.3
85.0	78.3
85.5	65.5
Treshold	**0-64** Not Acceptable
	65-84 Acceptable
	85-100 Excellent

System Usability Scale			
Statistic	**Overall**	**Vive**	**SenseGlove**
N	20	10	10
Minimum	38.333	81.667	38.333
Meximum	91.667	91.667	78.333
Mean	**75.5**	**85.5**	**65.5**
Variance	193.389	16.698	148.796
Standard Deviation	13.906	4.086	12.198
Standad Error	3.030	1.292	3.857
Median	80.000	84.167	68.333

From the System Usability Scale results, we can see that for the Vive condition 5 testers scored the application within the range of acceptable threshold $(65 - 84)$, and 5 testers scored the application within the range of excellent threshold $(85 - 100)$. For the SenseGlove condition, 3 participants scored the application within the range of not acceptable threshold $(0 - 64)$, and 7 participants scored the application within the range of acceptable threshold $(65 - 84)$. On average Vive (control) condition scored 85.5, which is in the range of the excellent threshold, while SensGlove (experimental) condition scored 65.5, which is in the range of acceptable threshold.

8.2.4. Application related questions

This section will report the posttest questionnaire results of the application related questions ($Q9$ to $Q25$). The usability questionnaire statistics of all items in the Vive condition were $M = 6.24$, $Mdn = 7$, $Mo = 7$, $\sum = 1060$. The usability questionnaire statistics of all items in the SenseGlove condition were $M = 4.68$, $Mdn = 5$, $Mo = 6$, $\sum = 795$. The usability questionnaire statistics of means in the Vive condition were $M = 6.25$, $Mdn = 6.5$, $Mo = 6.7$, $\sum = 106.2$. The usability questionnaire statistics of means in the Sense condition were $M = 4.68$, $Mdn = 4.8$, $Mo = 4.3$, $\sum = 79.5$.

Vive Usability	of Means	Total
Mean	6.25	6.24
Median	6.5	7
Mode	6.7	7
Sum	106.2	1060

SenseGlove Usability	of Means	Total
Mean	4.68	4.68
Median	4.8	5
Mode	4.3	6
Sum	79.5	795

8.2.5. Interaction

In this section, we will report questionnaire data from the question related to interaction with pipette dials (*Q15 and reverse-coded Q16*), plunger (*Q11 and reverse-coded Q17*), and ejector (*Q12 and reverse-coded Q18*). For the dial interaction question Q15 ("*I understood how to turn the dials*") the results in the Vive condition were $M = 7$, $Mdn = 7$, $Mo = 7$, $\sum = 70$, and the results in the SenseGlove condition were $M = 5$, $Mdn = 5.5$, $Mo = 7$, $\sum = 50$. For the reverse-coded dial interaction question $Q16$ ("*I found it difficult to accurately turn the dials*") the results in the Vive condition were $M = 6.8$, $Mdn = 7$, $Mo = 6$, $\sum = 68$ (values inverted), and the results in the SenseGlove condition were $M = 1.7$, $Mdn = 1.5$, $Mo = 1$, $\sum = 17$ (values inverted).

Question		Q15		Q16 *	
		I understood how to turn the dials		[.]difficult to accurately turn the dials	
		VIVE	SENSE	VIVE	SENSE
N	Valid	10	10	10	10
	Missing	0	0	0	0
Mean		**7**	**5**	**6.8**	**1.7**
Std. Error of Mean		0	0.44721	0.13333	0.26034
Median		**7**	**5.5**	**7**	**1.5**
Mode		**7**	**7**	**6**	**1**
Std. Deviation		0	1.41421	0.42164	0.82327
Variance		0	2	0.178	0.678
Sum		**70**	**50**	**68**	**17**
Minimum		**7**	**3**	**6**	**1**
Maximum		**7**	**7**	**7**	**3**
Percentiles	25	7	3.75	6.75	1
	50	7	5.5	7	1.5
	75	7	6	7	2.25
*** - reverse-coded question**					

For the plunger interaction question $Q11$ ("*I found that pressing the plunger was easy*") the results in the Vive condition were $M = 6.7$, $Mdn = 7$, $Mo = 7$, $\sum = 67$, and the results in the SenseGlove condition were $M = 5.5$, $Mdn = 5.5$, $Mo = 5$, $\sum = 55$. For the reverse-coded dial interaction question $Q17$("*I found that pressing the plunger was frustrating*") the results in the Vive condition were $M = 6.6$, $Mdn = 7$, $Mo = 7$, $\sum = 66$ (values inverted), and the results in the SenseGlove condition were $M = 5.3$, $Mdn = 5$, $Mo = 4$, $\sum = 53$ (values inverted).

Question		Q11		Q17*	
		[.] pressing the plunger was easy		[.] pressing the plunger was frustrating	
		VIVE	SENSE	VIVE	SENSE
N	Valid	10	10	10	10
	Missing	0	0	0	0
Mean		**6.7**	**5.5**	**6.6**	**5.3**
Std. Error of Mean		0.15275	0.42817	0.26667	0.42295
Median		**7**	**5.5**	**7**	**5**
Mode		**7**	**5**	**7**	**4**
Std. Deviation		0.48305	1.35401	0.84327	1.33749
Variance		0.233	1.833	0.711	1.789
Sum		**67**	**55**	**66**	**53**
Minimum		**6**	**3**	**5**	**4**
Maximum		**7**	**7**	**7**	**7**
Percentiles	25	6	4.75	6.5	4
	50	7	5.5	7	5
	75	7	7	7	7
*** - reverse-coded question**					

For the ejector interaction question $Q12$ ("*I found that pressing the ejector was easy*") the results in the Vive condition were $M = 2.7$, $Mdn = 5.5$, $Mo = 2$, $\sum = 47$, and the results in the SenseGlove condition were $M = 2.9$, $Mdn = 3$, $Mo = 3$, $\sum = 29$. For the reverse-coded dial interaction question $Q18$("*I found that pressing the ejector was frustrating*") the results in the Vive condition were $M = 5.5$, $Mdn = 5.5$, $Mo = 4$, $\sum = 55$ (values inverted), and the results in the SenseGlove condition were $M = 3.4$, $Mdn = 3$, $Mo = 3$, $\sum = 34$ (values inverted).

Question		Q12		Q18*	
		[.] pressing the ejector was easy		[.] pressing the ejector was frustrating	
		VIVE	SENSE	VIVE	SENSE
N	Valid	10	10	10	10
	Missing	0	0	0	0
Mean		**4.7**	**2.9**	**5.5**	**3.4**
Std. Error of Mean		0.7	0.17951	0.5	0.4
Median		**5.5**	**3**	**5.5**	**3**
Mode		**2**	**3**	**4**	**3**
Std. Deviation		2.21359	0.56765	1.58114	1.26491
Variance		4.9	0.322	2.5	1.6
Sum		**47**	**29**	**55**	**34**
Minimum		**2**	**2**	**4**	**2**
Maximum		**7**	**4**	**7**	**6**
Percentiles	25	2	2.75	4	2.75
	50	5.5	3	5.5	3
	75	7	3	7	4.25
*** - reverse-coded question**					

8.2.6. Final Questionnaire

For the final questionnaire, the statistics in VIve condition were $M = 4.53$, $Mdn = 5.5$, $Mo = 5.5$, $\sum = 40.8$, and in SenseGlove condition the statistics were $M = 4.56$, $Mdn = 5.5$, $Mo = 5.5$, $\sum = 41.1$.

Condition	N	No. of questions	Mean	Median	Mode	Sum
Vive	10	6	4.533333333	5.5	5.5	40.8
Sense	10	6	4.566666667	5.5	5.5	41.1

9. Discussion

This chapter discusses and interprets the results obtained from our experiment of using a Vive controller or a SenseGlove controller to teach pipetting. To begin the discussion we should recall our problem statement and hypotheses:

Final problem statement: Do hand-worn input controllers with a high level of execution and force feedback have an advantage over traditional handheld controllers with a lower level of execution and vibrotactile feedback for transfer of procedural skills to real life?

H0: *raining in VR with the SenseGlove controller yields no difference in the precision of volume measurements for real-life pipetting as compared to those who trained with a Vive Pro controller.*

H1: *Training in VR with the SenseGlove controller yields higher precision of volume measurements for real-life pipetting as compared to those who trained with a Vive Pro controller.*

H2: *Training in VR with the Vive Pro controller yields higher precision of volume measurements for real-life pipetting as compared to those who trained with a SenseGlove controller.*

9.1. *Quantitative data*

Since our problem statement emphasizes transfer, but we cannot necessarily measure it directly, we opted to measure the performances of participants in the virtual (VP) pipetting task and the real (RP). Performances in the RP are thought to be dependent on the VP we, therefore, compared how participants performed in the treatment groups. The results of the VP showed no significant difference in performance, thus indicating that participants in both groups were able to perform the pipetting task regardless of which controller was used. Both groups performed well with the Vive averaging, $M = -1.55\%$ measurement errors while those who used SenseGlove averaged, $M = -0.57\%$. The small deviation could be caused by the way we implemented plunger controls to take up liquids since both controllers use their own systems. In contrast, the results of the RP showed a significant difference in the pipetting performance between control and experimental conditions in favor of the **H1** ("*Training in VR with the SenseGlove controller yields higher precision of volume measurements for real-life* *pipetting (RP) as compared to those who trained with a Vive Pro controller.*"). Corroborating this we can not say that the performances in the VP caused the observed differences for RP performances, since in the VP both groups performed equally. This suggests that the application was not the catalyst of transfer, but rather the characteristics of the input device. One such characteristic could be the high level of execution i.e. fingers are tracked allowing users to interact naturally with the pipette. This could lead to a higher likelihood of near transfer. But it does not exclude the possibility that other factors had an impact.

9.1.1. Limitations

Due to the limited sample size ($N = 20$), we should be cautious about the results, since participants might not represent the population. Sufficiently large sample size should be used to ensure convergence according to the central limit theorem. We should also mention that participants who used SenseGlove in the VP spend significantly more time in the simulation (17 min.) than those who used the Vive Controller (7.5 min.). The difference was due to the difficulty of using the SenseGlove-controller (we will discuss this in the next section). It must also be mentioned that the SenseGlove controller is still in a prototype stage, meaning that it is not yet ready for consumers. Lastly, it is difficult to say what impact the haptics had on the results, as we cannot isolate the effects. This would be interesting to address in a future study.

9.2. *Qualitative data*

From the system usability scale (SUS) we can see that training with the Vive Controller was generally more accepted by the participants, scoring 85.5. The SenseGlove, on the other hand, scored much less, 65.5 meaning that it was barely acceptable. This indicates that the SenseGlove could be improved since there were many problems. For example, the exoskeleton in the current iteration restricts the hand and is clunky and heavy. This leads to fatigue with extended use and difficulty interacting with the virtual pipette. In particular, turning the dials was rated negatively (refer to the results $Q16$). In contrast, the same question was rated very positive for the Vive Controller. Additionally, the interaction with ejector was not very positive for the SenseGlove compared to the Vive controller (refer to the results $Q18$). If improvements were made to the hardware this could better the experience.

An important observation is that the negative perception of the SenseGlove did not impact the overall performance in the VP and the subsequent transfer to the RP.

9.3. *Outliers*

Three outliers were encountered during the experiment (two in the SenseGlove condition and one in the Vive condition). Two of the three participants failed to perform the forward pipetting in the VP task, while the last forgot to mix the recipes.

10. Conclusion

The results indicated that hand-worn input controllers with a high level of execution and force feedback had a significant improvement in transfer of procedural skills to real life. Further research is required to determine whether hand-worn input controllers offers other advantages in the teaching of procedural skills. The limitation of this research is that not all effects can be isolated and thus, we report only on the compounded effect of the input system and interactions.

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λ 23 Fl Flourine 100 μL + ρ 96 Ph Porphyrine 50 μL → A Tube

ξ 75 Hy Hydranium 60 μL + ψ 53 Sd Senodium 20 μL + λ Fl Flourine 40 μL → B Tube

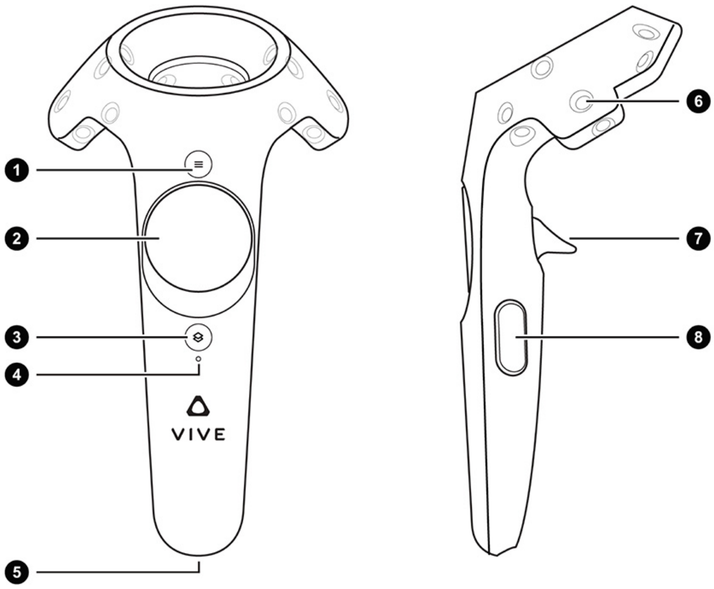
ρ 96 Ph Porphyrine 10 μL + ψ 53 Sd Senodium 80 μL + α 29 Br Bromine 30 μL → C Tube

ξ 75 Hy Hydranium 10 μL + α 29 Br Bromine 20 μL + λ 23 Fl Flourine 30 μL + ψ 53 Sd Senodium 90 μL → D Tube

α 29 Br Bromine 60 μL + λ 23 Fl Flourine 20 μL + ρ 96 Ph Porphyrine 40 μL + ξ 75 Hy Hydranium 30 μL → E Tube

α 29 Br Bromine 20 μL + ψ 53 Sd Senodium 90 μL + λ 23 Fl Flourine 10 μL + ρ 96 Ph Porphyrine 50 μL + ξ 75 Hy Hydranium 30 μL → F Tube

Appendix B. Vive Button Layout



Appendix C. Questionnaire Analysis

C.1. *VIVE*

Vive

		Q9	Q10	Q11	Q12	Q13	Q14
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		6.4000	6.7000	6.7000	4.7000	6.8000	5.0000
Std. Error of Mean		.16330	.15275	.15275	.70000	.13333	.33333
Median		6.0000	7.0000	7.0000	5.5000	7.0000	5.0000
Std. Deviation		.51640	.48305	.48305	2.21359	.42164	1.05409
Variance		.267	.233	.233	4.900	.178	1.111
Minimum		6.00	6.00	6.00	2.00	6.00	4.00
Maximum		7.00	7.00	7.00	7.00	7.00	6.00
Percentiles	25	6.0000	6.0000	6.0000	2.0000	6.7500	4.0000
	50	6.0000	7.0000	7.0000	5.5000	7.0000	5.0000
	75	7.0000	7.0000	7.0000	7.0000	7.0000	6.0000

Vive

		Q15	Q16*	Q17*	Q18*	Q19*	Q20*
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		7.0000	6.8000	6.6000	5.5000	6.3000	6.4000
Std. Error of Mean		.00000	.13333	.26667	.50000	.15275	.40000
Median		7.0000	7.0000	7.0000	5.5000	6.0000	7.0000
Std. Deviation		.00000	.42164	.84327	1.58114	.48305	1.26491
Variance		.000	.178	.711	2.500	.233	1.600
Minimum		7.00	6.00	5.00	4.00	6.00	4.00
Maximum		7.00	7.00	7.00	7.00	7.00	7.00
Percentiles	25	7.0000	6.7500	6.5000	4.0000	6.0000	6.2500
	50	7.0000	7.0000	7.0000	5.5000	6.0000	7.0000
	75	7.0000	7.0000	7.0000	7.0000	7.0000	7.0000

Vive

		Q21	Q22*	Q23	Q24	Q25
N	Valid	10	10	10	10	10
	Missing	0	0	0	0	0
Mean		6.0000	6.5000	6.7000	6.8000	5.3000
Std. Error of Mean		.00000	.16667	.15275	.13333	.15275
Median		6.0000	6.5000	7.0000	7.0000	5.0000
Std. Deviation		.00000	.52705	.48305	.42164	.48305
Variance		.000	.278	.233	.178	.233
Minimum		6.00	6.00	6.00	6.00	5.00
Maximum		6.00	7.00	7.00	7.00	6.00
Percentiles	25	6.0000	6.0000	6.0000	6.7500	5.0000
	50	6.0000	6.5000	7.0000	7.0000	5.0000
	75	6.0000	7.0000	7.0000	7.0000	6.0000

Page 1

C.2. *SenseGlove*

SG

		Q9	Q10	Q11	Q12	Q13	Q14
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		4.1000	6.5000	5.5000	2.9000	5.2000	4.3000
Std. Error of Mean		.40689	.22361	.42817	.17951	.53333	.59722
Median		4.5000	7.0000	5.5000	3.0000	5.0000	5.0000
Std. Deviation		1.28668	.70711	1.35401	.56765	1.68655	1.88856
Variance		1.656	.500	1.833	.322	2.844	3.567
Minimum		2.00	5.00	3.00	2.00	1.00	1.00
Maximum		6.00	7.00	7.00	4.00	7.00	6.00
Percentiles	25	3.0000	6.0000	4.7500	2.7500	5.0000	2.7500
	50	4.5000	7.0000	5.5000	3.0000	5.0000	5.0000
	75	5.0000	7.0000	7.0000	3.0000	6.2500	6.0000

SG

		Q15	Q16*	Q17*	Q18*	Q19*	Q20*
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		5.0000	1.7000	5.3000	3.4000	4.6000	4.3000
Std. Error of Mean		.44721	.26034	.42295	.40000	.73333	.57831
Median		5.5000	1.5000	5.0000	3.0000	5.0000	4.5000
Std. Deviation		1.41421	.82327	1.33749	1.26491	2.31900	1.82878
Variance		2.000	.678	1.789	1.600	5.378	3.344
Minimum		3.00	1.00	4.00	2.00	1.00	1.00
Maximum		7.00	3.00	7.00	6.00	7.00	6.00
Percentiles	25	3.7500	1.0000	4.0000	2.7500	2.0000	2.7500
	50	5.5000	1.5000	5.0000	3.0000	5.0000	4.5000
	75	6.0000	2.2500	7.0000	4.2500	7.0000	6.0000

SG

		Q21	Q22*	Q23	Q24	Q25
N	Valid	10	10	10	10	10
	Missing	0	0	0	0	0
Mean		5.8000	3.9000	5.9000	4.8000	6.3000
Std. Error of Mean		.24944	.65744	.37859	.44222	.30000
Median		6.0000	4.0000	6.0000	5.0000	6.5000
Std. Deviation		.78881	2.07900	1.19722	1.39841	.94868
Variance		.622	4.322	1.433	1.956	.900
Minimum		4.00	1.00	3.00	3.00	4.00
Maximum		7.00	7.00	7.00	7.00	7.00
Percentiles	25	5.7500	2.0000	5.7500	3.7500	6.0000
	50	6.0000	4.0000	6.0000	5.0000	6.5000
	75	6.0000	6.0000	7.0000	5.5000	7.0000

Page 1

Appendix D. Final Questionnaire

D.1. *VIVE*

Vive Statistics Final Questionnaire

		V Q 26	V Q 27	V Q 28	V Q 29	V Q 30	V Q 31
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		5.5000	5.8000	6.5000	7.0000	6.8000	5.5000
Std. Error of Mean		.16667	.29059	.16667	.00000	.13333	.16667
Median		5.5000	5.5000	6.5000	7.0000	7.0000	5.5000
Mode		5.00[a]	5.00	6.00[a]	7.00	7.00	5.00[a]
Std. Deviation		.52705	.91894	.52705	.00000	.42164	.52705
Variance		.278	.844	.278	.000	.178	.278
Minimum		5.00	5.00	6.00	7.00	6.00	5.00
Maximum		6.00	7.00	7.00	7.00	7.00	6.00
Sum		55.00	58.00	65.00	70.00	68.00	55.00
Percentiles	25	5.0000	5.0000	6.0000	7.0000	6.7500	5.0000
	50	5.5000	5.5000	6.5000	7.0000	7.0000	5.5000
	75	6.0000	7.0000	7.0000	7.0000	7.0000	6.0000

a. Multiple modes exist. The smallest value is shown

D.2. *SenseGlove*

SenseGlove Statistics Final Questionnaire

		SG Q26	SG Q27	SG Q28	SG Q29	SG Q30	SG Q31
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		5.9000	5.7000	5.5000	6.4000	5.5000	5.5000
Std. Error of Mean		.43333	.44845	.50000	.22111	.50000	.37268
Median		6.5000	6.0000	6.0000	6.5000	6.0000	6.0000
Mode		7.00	7.00	7.00	7.00	7.00	6.00
Std. Deviation		1.37032	1.41814	1.58114	.69921	1.58114	1.17851
Variance		1.878	2.011	2.500	.489	2.500	1.389
Minimum		4.00	4.00	3.00	5.00	3.00	4.00
Maximum		7.00	7.00	7.00	7.00	7.00	7.00
Sum		59.00	57.00	55.00	64.00	55.00	55.00
Percentiles	25	4.0000	4.0000	4.0000	6.0000	4.0000	4.0000
	50	6.5000	6.0000	6.0000	6.5000	6.0000	6.0000
	75	7.0000	7.0000	7.0000	7.0000	7.0000	6.2500

D.3. *Q26, Q27 and Q31*

Question		Q26 I felt comfortable with the task		Q27 I felt familiar with the equipment		Q31 I feel that I learned how to use a pipette.	
		VIVE	SENSE	VIVE	SENSE	VIVE	SENSE
N	Valid	10	10	10	10	10	10
	Missing	0	0	0	0	0	0
Mean		**5.5**	**5.9**	**5.8**	**5.7**	**5.5**	**5.5**
Std. Error of Mean		0.16667	0.43333	0.29059	0.44845	0.16667	0.37268
Median		**5.5**	**6.5**	**5.5**	**6**	**5.5**	**6**
Mode		**5.00a**	**7**	**5**	**7**	**5.00a**	**6**
Std. Deviation		0.52705	1.37032	0.91894	1.41814	0.52705	1.17851
Variance		0.278	1.878	0.844	2.011	0.278	1.389
Sum		**5**	**4**	**5**	**4**	**5**	**4**
Minimum		**6**	**7**	**7**	**7**	**6**	**7**
Maximum		**55**	**59**	**58**	**57**	**55**	**55**
ercentile	25	5	4	5	4	5	4
	50	5.5	6.5	5.5	6	5.5	6
	75	6	7	7	7	6	6.25

Appendix E. Testing Images

E.1. *VIVE*

E.2. *SenseGlove*

E.3. *Real Pipetting*