Measuring Tool Embodiment in Ready-to-Hand and Unready-to-Hand Situations Using Virtual and Physical Tools

by

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

This dissertation contained contents that were collaborative efforts with several others. In this dissertation, “we” will be used when referring to the work that was a joint effort with my collaborators. While it is impossible to state each collaborator’s exact contribution to this work, the following notes describe the approximate amount and type of their contribution to various parts of this dissertation.

The first study introduced in Chapter 3 was designed and developed in collaboration with several others. While I implemented the majority of the KFAE program, my supervisors, Mark Hancock and Miguel Nacenta, provided overall guidance in the design and development of the software. They also provided insights to guide the user study design and data analysis.

The second study introduced in Chapter 5 was designed and developed in collaboration with several others. While I implemented the majority of the tool embodiment game, my supervisors, Mark Hancock and Miguel Nacenta, provided overall guidance in the design and development of the software. They also provided insights to guide the user study design and data analysis.

The third study introduced in Chapter 6 was designed and developed in collaboration with several others. While I implemented the majority of the tool embodiment game in virtual reality, my supervisors, Mark Hancock and Miguel Nacenta, provided overall guidance in the design and development of the software. They also provided insights to guide the user study design and data analysis. Software developed was implemented by Licheng Zhang.

ABSTRACT

Virtual environments can provide access to a variety of information that can be designed to mimic physical attributes or afford physical-like actions. Virtual reality and other ways of interactions such as multi-touch, tangible interaction, and mid-air gestures, often promise to be more natural, where the technology becomes invisible. However, there is limited investigation on how to measure the level of invisibility when interacting with technology with a quantitative measure. For example, virtual reality provides physical-like actions that mimics every aspect of the physical world interaction, but there is no direct methodology to measure these complex interactions. As a result, designers of novel interactive technologies do not have a clear understanding of how to measure these phenomena.

The current research in human computer interaction focuses on using performance measures or self-reports questionnaires to evaluate interactive technologies. Research in psychology and philosophy, on the other hand, provides an understanding of the human condition in the physical environment. Consequently, the aim of this dissertation is to provide an effective methodology to measure the invisibility aspect of technology that applies both experimental psychology and HCI research. Study 1 presented in this dissertation used the after-effect phenomenon as a measure of object embodiment — when interacting with physical objects can affect haptic changes in perception. Study 2 investigated tool embodiment to measure the interaction with physical and virtual tools, where change in attention was used as a measure of tool embodiment. Finally, study 3 further examined tool embodiment with different tool states (broken or working tool) and different inputs alternatives.

Over the past decade, multi-touch surfaces have become commonplace, with many researchers and practitioners describing the benefits of their natural, physical-like interactions. Study 1 presents an empirical investigation of the psychophysical effects of direct interaction with both physical and virtual objects. The phenomenon of Kinesthetic Figural After Effects — a change in understanding of the physical size of an object after a period of exposure to an object of different size, was used as a measure.

While this effect is robustly reproducible when using physical artefacts, this same effect does not manifest when manipulating virtual objects on a direct, multi-touch tabletop display.

Study 2 leveraged the phenomenon of tool embodiment as measure of interaction. Tool embodiment is when a tool becomes an extension of one’s body, where attention shifts to the task at hand, rather than the tool itself. This study tested tool embodiment framework to measure the aspect of being part of a tool by incorporating philosophical and psychological concepts. This framework was applied to design and conduct study 2 that uses attention to measure readiness-to-hand with both a physical tool and a virtual tool. A novel task where participants use a tool to rotate an object, while simultaneously responding to visual stimuli both near their hand and near the task was introduced in this study. The results demonstrated that participants paid more attention to the task than to both virtual and physical tools.

Study 3 further investigated tool embodiment to measure ready-to-hand and unready-to-hand situations. Locus of attention index (LAI) was used to measure the level of tool embodiment in virtual environments. Three different input modalities were used to control the virtual tool to accomplish the task. The results of this study showed that the LAI is higher with the working tool indicating an increased level of tool embodiment, and lower with broken tool indicating a decreased level of tool embodiment.

Overall, the research presented in this dissertation investigated embodied interactions with both physical and virtual environments. The contributions included the construction of an evolution measure of object interaction (using the measure of after effect with physical and virtual tools) and tool interaction (using the measure of attention and LIA with physical and virtual tools). The empirical results of study 1 revealed that the after-effect measure might not be a practical measure to evaluated embodied interactions in virtual environments. However, study 2 and 3 provided a reliable method to measures embodied interactions when using tools to interact with the virtual environments. This dissertation also provided tool embodiment framework that can be used as a guide for designers to evaluate the invisibility aspect of technology.

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I would like to take this opportunity to thank my supervisors, Mark Hancock and Miguel Nacenta for their mentorship. My journey into the wondrous world of technology started with them. They opened my eyes into limitless possibilities and continues improvement in my research career.

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I am thankful to my cherished father and my loving mother for their unconditional love and support.

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DEDICATION

To my only love, Rahaf, who stood by me in this long journey and blessed me with my children.

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Chapter 1
Introduction

An inevitable part of people's daily life is interacting with the physical world and using tools to accomplish tasks. It starts with an exploration during childhood where people observe their surroundings and learn how to interact with it effectively. People hold tools with their hands and use these tools in a variety of simple tasks. Eventually, people become proficient and use these tools to accomplish more sophisticated tasks (e.g., surgery). This level of control requires a lot of training and time; for example, opening a door might seem simple, but requires refined motor learning. This learning stage requires an understanding of how the physical environment works, such as how to use a simple physical object and the behaviour of objects in response to the environment. After this learning stage, one could even get completely immersed in a task where the tool disappears from the user's attention and he or she concentrates only on the task. This effect of being embodied with the tool has been called a state of readiness-to-hand (Heidegger, 1996). Understanding how one becomes embodied with the tool presents a challenge, primarily because it is a very difficult phenomenon to measure when actively using tools. Tool embodiment is when a tool becomes an extension of one's body, and attention shifts to the task at hand, rather than the tool itself. Technologies nowadays (e.g., virtual reality) provide a very good medium to test different measures and to investigate how interacting with virtual objects might compare to their physical counterparts. These technologies are becoming the tools that are used in daily life. As I am writing this section, I am using a combination of virtual and physical tools to accomplish my task: the keyboard, mouse and monitor. I do not think of this combination as detached, but as one coherent tool that I need to accomplish my task. All these elements affect task performance. A direct measure of how people perceive these tools while using them skillfully should be carefully considered to design embodied interactions in the virtual environments. The research presented in this dissertation investigated a measure of embodied interaction in virtual and physical environments. In particular, this work is an empirical investigation into the phenomenon of tool embodiment for goal-directed behavior using virtual tools.

This chapter is organized as follows. First, a background section will introduce the concept of embodiment within different fields of study and how past work has applied this phenomenon in virtual environments. Second, the scope of this research will be discussed. Next, I will present the research problem and goals followed by the research methods and contributions of this thesis.

1.1 Background

An integral component of cognitive development is interacting with the physical environment (Gibbs Jr, 2005). From an early age our exploration of the physical environment starts with the first few objects that are within reach. As we grasp these objects, we start to explore many more to the point where even our language would become structured to reflect properties of the physical environment. Numerous studies (Dourish, 2004; Gibbs Jr, 2005b; James J Gibson, 1962; O'regan, 2001) have explored this connection between the physical world and our perception, and have identified the essential role the physical world plays in our cognitive development. These studies have often found a link between perception and action and what we perceive through our interaction with the world. Being in the physical world requires an integration of multi-sensory experiences (Gallace & Spence, 2014). To clarify, various perceptual systems like touch and vision affect the experience people have when interacting in the physical world. These experiences help in accomplishing tasks more effectively; for example, when using a pencil to write something attention is directed to the task and not to the pencil. People's interaction nowadays however, is shifting toward the virtual world, where tools and objects are increasingly virtual instead of only physical. These virtual tools and objects help people accomplish their tasks more effectively in the virtual space; therefore, designing these virtual tools and objects should reflect people's understanding of the physical world.

Using digital artifacts, such as graphical widgets (e.g., buttons and menus) and gesture-based interaction (e.g., tapping or pinch-to-zoom on smartphones) has become increasingly part of people's life and daily activates. Therefore, interaction with technology has been based on understanding the physical world first. Indeed, many of these virtual artifacts have been designed to mimic physical attributes or afford physical-like actions (James J Gibson, 1968, 2014; James Jerome Gibson, 1966; Norman, 2013), and novel interactive technologies that support these physical-like actions are often referred to as natural and intuitive (Wigdor & Wixon, 2011). However, these nuanced phenomena are still measured with self-reported questionnaires or performance measures. These measures do not clearly distinguish the level of naturalness or intuitiveness of the technology. One way that we can evaluate these technologies is by using change in attention as a measure how people interact with virtual environments. These measures provide a better more direct evaluation of how technology effects on people's perception.

Since 1968, there has been an enormous increase in novel interactive technologies. Virtual reality (Sutherland, 1968) for example, has been developed to integrate the physical environment and the virtual in an immersive user experience and completely enter the user in a virtual space. Moreover, Tangible computing provides a bridge between physical attributes of objects and virtual information presented on a digital media (Ullmer & Ishii, 2000). These and other interactive technologies present the user with a set of possibilities for more natural interaction. However, evaluating or measuring these interactions has only been conducted using indirect measures like performance measures (Hespanhol, Tomitsch, Grace, Collins, & Kay, 2012), or self-reports (Grandhi, Joue, & Mittelberg, 2011). Although these measures might contribute to the naturalness and intuitiveness of interactive technology, it is still not clear how these technologies directly affect our actual perception. Consequently, there is a gap in our understanding of how to measure these complex, nuanced phenomena.

The research presented, will investigate a measure of embodied interactions in both physical and virtual environments by applying experimental psychology phenomena. These phenomena are commonly applied to physical interactions; this research will attempt to test these phenomena in the virtual environments with virtual interactions. For example, in study 1 (Chapter 3), a Kinesthetic Figural After Effects phenomenon was applied as a direct measure of embodied interactions that affects people's haptic memory. Similarly, in Study 2 and 3 (Chapters 5 and 7) attention was used as a measure of embodied interactions with tools when actively using it to accomplish a specific task. This research will investigate a measure of embodied interactions with the physical and virtual artifacts.

1.2 Scope

This thesis contributes to the domain of human-computer interaction by leveraging research from cognitive psychology as shown in the below Figure 1. The field of human-computer interaction is concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them (Hewett et al., 1992). Within human-computer interaction, my research will focus on measurements used to evaluate various interactive technologies (e.g. natural user interface, and virtual reality). In the field of psychology, my research will centre on Gestalt psychology which includes different Gestalt theories, sensory perception, and human performance. Finally, my research will combine diverse modalities of interaction within the field of HCI (e.g. direct touch, and VR) and different modalities of perception within the field of Gestalt psychology (e.g. visual and motor perception) that will result in an interdisciplinary work presented in this thesis.

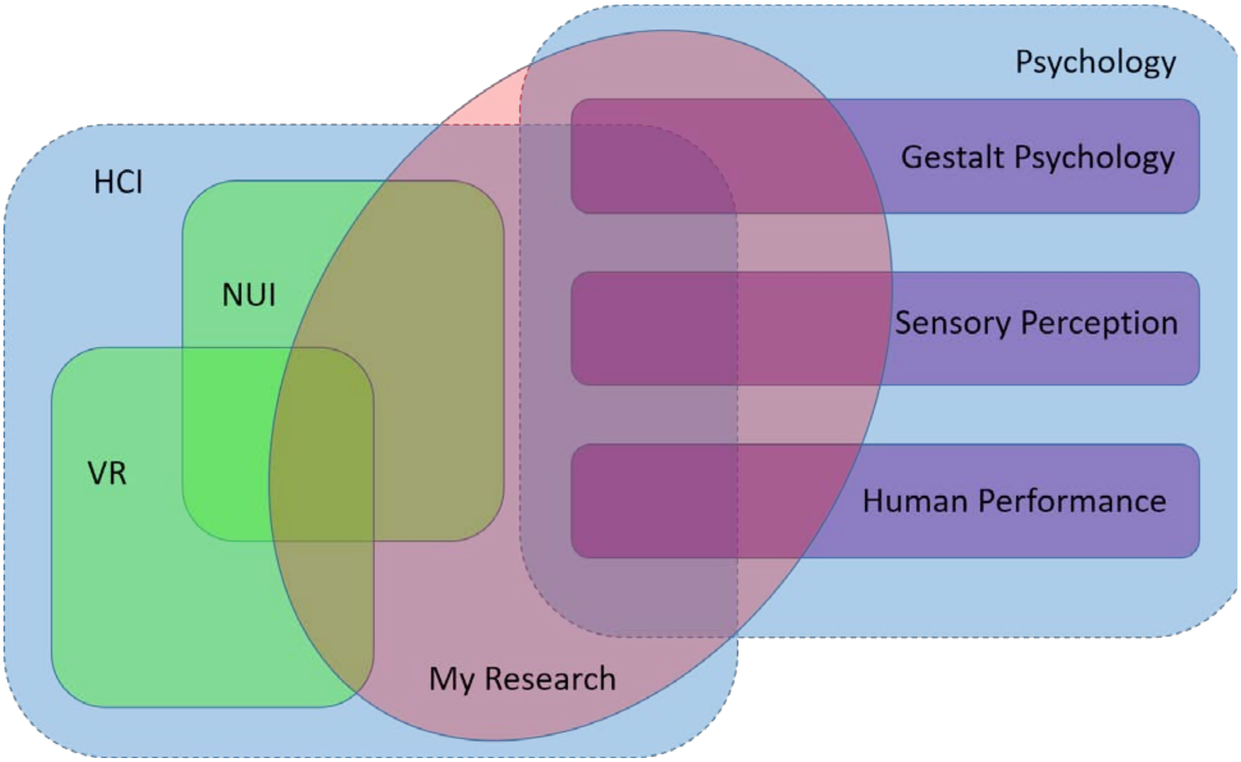


Figure 1: The scope of this dissertation. This dissertation contributes mainly to two fields Psychology and HCI. This research made several connections to understand tool embodiment. This research was situated in three main areas of psychology: Gestalt, Sensory perception, and Human Performance. This research also intersects with two areas in HCI: Natural User Interface (NUI) and virtual reality (VR).

1.3 Definitions

This section will present some definitions used throughout out this dissertation.

The original definition of body schema was introduced by the neurologist Sir Henry Head as a posture model of the body that actively organizes and modifies "the impressions produced by incoming sensory impulses in such a way that the final sensation of [body] position, or of locality, rises into consciousness charged with a relation to something that has happened before" (Head et al., 1920).

For simplicity this dissertation defines Body schema as how people use their sensory perception to organize and modify their body boundaries. Body schema in this work will be used to show how external objects or tools get integrated into the body schema.

Embodiment can be defined as the innate ability to perceive the localization of one's body within one's body outlines (Arzy, Thut, Mohr, Michel, & Blanke, 2006).

Object embodiment occurs when an object's properties are processed in the same way as one's body (De Vignemont, 2011). This property is often extended beyond the body and includes other physical objects in contact with our body, such as clothes, tools, or prosthetic limbs. In other words, when an object becomes part of our body schema (Ullmer & Ishii, 2000).

Tool embodiment in the above definition could be part of object embodiment definition as well. Where tool's properties are processed in the same way as one's body when using the tool. This dissertation has also introduced another more specific definition of tool embodiment presented below.

Tool embodiment. tool embodiment is a characteristic of skilled action in which the attention shifts from the manipulation of the tool to the goal action itself.

Embodied interactions. Embodied interaction is a concepted introduced in the field of HCI by Dourish (2001) as "the creation manipulation and sharing of meaning through engaged interaction with artifacts."

These definitions helped in identifying possible ways to investigate embodiment and embodied interactions. This dissertation used different approaches to understand embodiment and finding a measure of a specific type of embodiment type (e.g. object, tool). The three studies presented in this work have been inspired by these definitions to discover different ways to measure embodiment with objects and tools.

1.4 Research Problems and Goals

Overall, this research was concerned with finding a measure of embodied interaction that can be applied to both physical and virtual environments. This measure later can be used to evaluate the level of embodiment of different objects and tools (e.g. physical or virtual). This section describes the research problems and goals.

1.4.1 Problem 1: No Measurement of Embodied Interactions Exists in the Physical and Virtual Environment.

There is a growing interest in the understanding of the effects of the physical environment on people's cognitive development. An extensive discussion of the embodied cognition literature shows different aspects of these cognitive developments and how they affect people's daily activity (Douglas, 1970: 93). Embodied interactions research has taken a considerable amount of investigation in forming different theories and their effects on behavior. Embodiment, however, as a specific phenomenon was not presented in the literature clearly. Some recent examples such as rubber hand illusion (Kammers, de Vignemont, Verhagen, & Dijkerman, 2009; Yuan & Steed, 2010) or cutaneous rabbit illusion (Blankenburg, Ruff, Deichmann, Rees, & Driver, 2006) present a glimpse or an indication of the embodiment phenomenon, but no direct measure is created beyond the use of questionnaires. Consequently, there is a gap in the literature on how to apply these theories to test interactive technologies.

Both experimental psychology and human computer interaction research have explored embodied interactions. On one hand, experimental psychology research focuses on exploring the internal mechanism of embodied that happens in the brain which makes it difficult to apply these techniques to measure technology. On the other hand, human computer interaction research uses performance measures or self-repeated questionnaire to measure technologies, which does not provide a measure of when technology disappears. Therefore, problem 1 can be divided into problem 1a and problem 1b as presented below.

1.4.1.1 Problem 1a: Current Measures of Object Embodiment do not Explore the Phenomenon of ‘Disappearing’ when an Object Becomes Embodied

Existing literature on object embodiment in the field of experimental psychology is difficult to adapt to measure technologies. The work that exists focuses on how object interaction affects perception (e.g. visual or haptic) but lacks the methodology to apply this work with virtual interactions. The experimental psychology research also does not explore the aspect of technology disappearing. For example, how interacting with a virtual cube effects haptic perception.

This part of the thesis aims to design and evaluate virtual object interaction using a Kinesthetic Figural After Effect as a measure. This research will also explore various design alternatives to understand the effectiveness of KFAE measure in improving virtual object interaction on touch screens.

1.4.1.2 Problem 1b: Current Measures of Tool Embodiment do not Explore the Phenomenon of ‘Disappearing’ when a Tool Becomes Embodied

While an understanding of how physical and virtual objects affect human perception and sense of body can help in the design of virtual artifacts in the environment, the ability to use these artifacts as *tools* and have them “disappear” or become a part of one’s own body when leveraging them to interact in the virtual space still warrants further exploration. How can the designer identify that a tool has become embodied or know whether one design leads to a tool “disappearing” whereas other leads to focusing on how the tool works? Building on that, a different approach was taken that concentrates on understanding the moment the tool is actively being used. Heidegger (1996) proposed that actively using a tool would put the user in the state of readiness-to-hand. This concept was also explored in the field of HCI with Dourish (2001) and Winograd (1985) where it was related to how people behave with technologies. However, these connections were general in nature and did not precisely link to how a tool, physical or virtual, can be embodied or not when using an interactive technology.

This part of thesis will focus on constructing a tool embodiment framework, design and test the framework. This framework will incorporate Dourish's and Winograd's interpretation on how Heidegger's philosophical phenomenon can be applied to different technologies. The proposed study will also incorporate different experimental psychology concepts to construct a measure using attention. Concepts such as sensory-motor contingency theory (O'Regan, 2001), change blindness (Suma et al., 2011), and inattentional blindness (Jensen, Yao, Street, Simons, 2011) will be used to construct a measure of tool embodiment. Study 2 will be implemented using both physical and virtual tools.

1.4.2 Problem 2: Tool Embodiment has not Been Tested with Different Interactive Technologies

Study 2 revealed a general change in attention using a tool in both physical and virtual environments. Designer of interactive technologies, however, are still not able to practically apply tool embodiment framework to evaluate different inputs. How can a measure of tool embodiment test diverse physical tools when interacting in the virtual world? Study 3 will focus on practically testing tool embodiment framework in a virtual reality (VR) environment with three types of interactions (hands only, a physical prop, and a VR controller) in both ready-to-hand (working) and unready-to-hand (broken) states. This study will demonstrate how can the tool embodiment framework be applied and used by designers to improves embodied interactions.

1.5 Method

This research started with systematically identifying relevant psychological phenomena to test embodied interactions. Then an iterative design cycle of design-implement-evaluate was used to compare the phenomena in both physical and virtual environments. For each study, a specific phenomenon with an applicable measure for both physical and virtual interactions was identified. Then, several low fidelity prototypes were developed and tested by conducting pilot tests. Finally, for the evaluation, a mixed-methods approach (Creswell & Clark, 2017) was used to interpret both quantitative and qualitative data that was collected. The focus of this research was to identify and use quantitative measures to evaluate both physical and virtual interactions. Quantitative data collection was vital to evaluate and compare the introduced measure of the interactive technology in both physical and virtual environments.

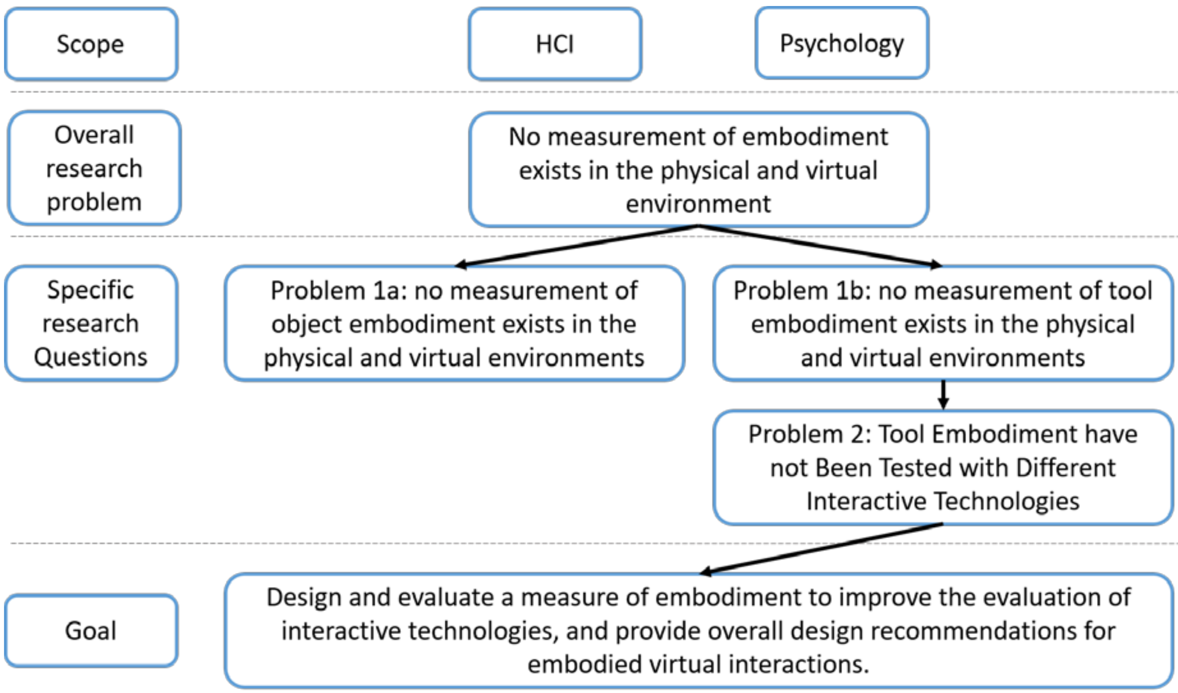


Figure 2: An overview of the research problems and goals. The overall research concerned with finding a measure of embodiment that can be used in virtual environments. The research question was broken down into two problem: finding a measure of embodiment with objects and finding a measure of embodiment with tools. Problem 2 was further investigated with different tools in virtual environments. This research sought to design and evaluate a measure of embodied interaction in virtual environments.

1.6 Contributions

This dissertation contributes to the field of human computer interaction by leveraging experimental psychology research to investigate embodied interactions using objects and tools in virtual environments. More specifically, this work provides the following contributions:

1. A study comparing the effects of holding both physical and virtual objects on haptic memory, which revealed that this haptic memory is robust to interference from haptic stimuli but was not measurable when "holding" virtual objects (chapter 3).

2. The design of a framework for measuring tool embodiment in physical and digital media and the creation of the Locus of Attention Index (LAI) which can be used to measure the level of tool embodiment by comparing attention to the task to attention to the tool (chapter 4).
3. A study that applies this measurement framework to compare a tangible user interface to a touch interface for a “wrench” tool in a ready-to-hand state (working), which revealed that both tools reliably led to a change in attention (chapter 5).
4. A study that applies this measurement framework to compare three interactions techniques in a virtual reality (VR) environments (hands only, a physical prop, and a VR controller) in both ready-to-hand (working) and unready-to-hand (broken) states, which revealed that attention was focused more on the task when the tool was working, but more on the tool when it broke (chapter 6). This contribution also helps to confirm the theoretical basis of the framework.

Overall, this research sought to empirically investigate embodied interactions in virtual environments. More specifically, virtual tool embodiment will be examined with different interactive technologies. Most of the objects and tools that people use nowadays are virtual in nature and tasks are accomplished using these virtual tools. This work will provide design recommendations for embodied interactions with virtual tools. By introducing a tool embodiment framework, a designer of interactive technologies can use this work to test for embodied interactions by measuring the level of attention to different elements in virtual environments.

1.7 Document Organization

This dissertation is structured as follows: Chapter 2 presents the literature review with relevant background in both the fields of psychology and human-computer interaction. Chapter 3 will present study 1 with an overview of the study method, design, and implementation and results. Chapter 4 will present the tool embodiment framework and a novel measurement of virtual embodied interaction. Chapter 5 presents the details of study 2 using the tool embodiment framework. This chapter will also provide the results of study 2 and design implications for human computer interaction research. Chapter 6 will present study 3, which provides an empirical investigation of embodied interactions with broken tool. Chapter 7 will discuss the implication of this dissertation. Finally, chapter 8 will provide an overall conclusion of this research with contributions, limitations, and future work.

Chapter 277

Related Work

Through people's interaction with the world, their understanding of each object and tool changes. Starting by holding a tool to discover its properties, later using this tool proficiently to accomplish directed tasks. For example, reaching for a favorite coffee mug without looking and knowing its exact location. The aim of this research is to leverage what is currently known about this process of developing tool proficiency in order to understand how it applies to digital technology.

There is a strong literature presence in the field of philosophy discussing different ways that people perceive the world and their body within that world (De Vignemont, 2011). This dissertation did not focus on the philosophical perspective but rather used this perspective to enrich this investigation to understand the embodiment phenomenon and help construct a tool embodiment framework. This investigation of tool embodiment is empirical and based on quantitative evidence. Therefore, some of the following background sections will discuss a philosophical understanding of tool embodiment and others will focus on the empirical investigation on motor learning using tools.

The following sections will first discuss the relevant research areas in psychology (Gestalt, sensory perception, and visual and human performance) and second discuss studies in human-computer interaction (natural user interfaces, and virtual reality). The following section will focus on the relevant research on embodied cognition; specifically, a discussion about how the perception of the physical environment is part of human cognitive development and how people's perception is closely connected with the physical world. Then, relevant research in human-computer interaction will be discussed. Finally, a discussion of how different interactive technologies are currently measured will show how the presented research can contribute to the field of human-computer interaction.

2.1 Embodied Cognition

Embodied experience in the past had not been considered to influence cognition. Epistemological perspectives doubted the existence of the body that started from Descartes' work, and early cognitive scientists' perspectives considered the body as a sensory input for cognitive computation (Gibbs Jr, 2005a, p. 5) . However, these viewpoints changed with new empirical evidence in recent studies. For example, studies that investigated mental and motor imagery rotation tasks (Gibbs Jr, 2005a, p. 124) or the use of language for embodied language use (Gibbs Jr, 2005a, p. 158), among other examples (Dally & Towles, 2004), shed some light into how interaction in the world affects people's cognition. This section will present the related work for embodied cognition, particularly how physical objects and tools shape our perception of the world.

Embodied cognition literature debates how interacting with the world is part of people's cognitive development. The way people perceive the environment depends on learning how to navigate the physical world. By exploring the physicality of shapes, skills begin to develop that allows for a better understanding of how to use these objects and tools. These objects and tools change people's perception when they start actively using and interacting with their surroundings. Gibson (1966, 1979) has characterized the way people perceive these objects and tools as *affordances* and suggested that this interaction is governed by these affordances. For example, a flat surface affords walking on it, a chair affords sitting on it, a door handle affords opening. This suggests that the environment provides a set of possibilities or ecological information to do possible actions. Gibson introduced a new discipline called ecological psychology devoted to the understanding and studying of visual perception. Gibson also discussed the *ecological self*, where "awareness of the persisting and changing environment (perception) is concurrent with the persisting and changing self (proprioception in any extended use of the term)" (James J Gibson, 1982, p. 418). Gibson believed that the processes that require thinking about an action and the action itself both act in the physical environment, so they are "co-perceived". These activities then depend on the actions taken in the environment when people are engaged in the tasks on a daily basis (Gibbs Jr, 2005a, p. 22).

Perception is dependent on the way people actively engage in their environment. Merely touching an object, without exploring its contours and texture, will give little information to the explorer (James J Gibson, 1962; Streri, Spelke, & Rameix, 1993). Using the object, on the other hand, will allow even more complex information to be known, such as estimating its correct length. For example, People who use a rod over long periods of time are able to estimate its length correctly (Turvey, Solomon, & Burton, 1989). Gibson (1968) suggested that this awareness also happens in situations where there is no direct connection with the object that one manipulates (James J Gibson, 1968). For example, when using a hammer or a screwdriver there is no direct contact with the screw, but people would still sense the object (the screw) and the information it provides. Several other studies have demonstrated that people are relatively accurate when haptically exploring an object with a tool or a hand, and that direct or indirect information about the object or the tool is picked up by the user (Barac-Cikoja & Turvey, 1993; Lederman & Klatzky, 2001).

As people interact in the physical environment, the way they notice their body boundaries will change their perspective of their bodies. A study conducted on how people relate to their bodies in a variety of situations showed that people can be aware of different emotional states (Pollio, Henley, Thompson, & Thompson, 1997). For example, people reported being aware of their bodies when in pain, presenting the body to others when in different garments, or being aware of strong emotions. This study conducted interviews that also showed three major themes people identify with their bodies: experience of engagement, experience of corporeality, and experience of interpersonal meaning. Interestingly, experience of corporeality deals with how people understand the physicality of their body in the world and how it acts as an object and as an instrument to accomplish a specific task. Although, these themes are often experienced together, and it would be difficult to identify one theme specifically. For example, taking the activity of exercising, the body will be engaged in an activity in the world and at the same time will be used as an instrument to achieve that goal, like moving one's legs or arms in a certain way.

Other studies have investigated a more detailed description of the embodied experience by defining distinct body representation. Body schema and body image for example are two different body representations that deal with how people perceive their bodies in the environment. Body schema, on one hand, deals with the how people integrate body posture and position in the environment (Gibbs Jr, 2005a, p. 17). This effect does not happen on a conscience level and it is regulated by the proprioceptive system. Proprioception integrates and coordinates the movement of countless muscles and joints to construct the body schema (Gallagher & Cole, 1995). For example, when walking normally and holding a heavy case, the proprioceptive system makes several adjustments to the body to function properly, making sure that nothing will fall. Body schema was also investigated to demonstrate the perception of other people's movement when it replicates their own (Reed & Farah, 1995), estimating one's arm length differently when in a closed space or open space, and overestimating one's arm length when asked to point to objects (Tiffany, Shontz, & Woll, 1969). Body image on the other hand, deals with how people represent their body experience as emotions and attitudes (Cash, 2004; Gallagher & Cole, 1995). Often people self-identify these experiences like healthy/not healthy, pleased/displeased, or hidden/shown on 19-item questionnaires. These two different body representations also have been discussed in terms of different types of embodiment. Body image is linked to perceptional embodiment when people's perception changes with holding or feeling an object. Body schema however is linked to motor embodiments when people hold and use a specific tool (De Vignemont, 2011). These two embodiment categories; however, were not empirically investigated to make a strong connection to different body representation and embodiment types.

In summary, embodied cognition shows the effect of the environment on people's sensory experience. How people make decisions, feel objects, and use tools depends on this tight relationship between perception and action in the physical world. The next section will talk about sensory and active perception.

2.2 Sensory Perception

2.2.1 Perceptual Organization in Touch

Since the late 1800's, Gestalt psychology was introduced and has been used to discuss the way people perceive information in the world, particularly how people organize the amount of information presented to them daily. People's brains perceive a huge amount of information from their surroundings, but only retain what is relevant to the situation at hand. For example, when walking to the bus stop, one pays more attention to the time and will not be able pay significant attention to their surroundings. Substantial amounts of information in the environment can be missed when one only focuses on being late to the bus stop for example. The following section will discuss some of the research that relates to the effects of different interactive modalities in perceptual organization and how people perceive visual and haptic information in the environment.

Perceptual organization principles such as completion, proximity, similarity, or good continuation have been discussed extensively with visual perception but several examples have also tested these principles in haptic modality (touch) (Kahneman, 1973). The completion principle completes parts of the visual object when they are missing or occluded. This effect occurs when a circle or a square is drawn with dotted lines with empty space between these lines. Looking at shapes like these, the individual's mind will continue the circle or the square in what is known as good continuation or "closure" (Kanizsa & Gerbino, 1982; Kanizsa & Kanizsa, 1979). Few studies also demonstrated the principles of completion in touch which presented participants with a vibrotactile stimulus (Kitagawa, Igarashi, & Kashino, 2009). This stimulation was interrupted with vibrotactile noise at specific intervals. Participants were able to feel this tactical information as one continuous stimulus. Another study (Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969) looked at a tactile-vision substitution system for visually impaired participants.

These devices would be placed on the person's back and other body parts to stimuli tactile visual experiences, similar to watching television. Participants were able to recognize and perceive complete images using this device, which suggested that the principal of completion could be simulated by such tactile simulation (BACH-Y-RITA, 2004, 2004; Bach-y-Rita et al., 1969). Also, in another study, the tactile image was made bigger and participants responded by jumping backward (Bach-y-Rita, 1972). By enlarging the image participants felt the need to respond as if something was getting closer. Finally, in a more recent study on the principle of good continuation of touch, participants were presented with visual and haptic displays and asked to group different elements in these display into as many groups as possible (Chang, Nesbitt, & Wilkins, 2007). Both visual and tactile displays were used, and participants were able to incorporate elements of the haptic display as continuous lines indicating that perceptual organization also occurs with touch. Moreover, Chang (2007) also demonstrated the principles of proximity and similarity with haptic perception (Chang et al., 2007). For example, Spence (2007) explored a haptic layout while being blindfolded. Participants were using their hands and reported on the number of groups that they perceived in this layout (Auvray, Gallace, Tan, & Spence, 2007).

These studies show how different perceptual modality affects people's perception in a similar way. One modality like touch affect another like visual and visa versa. This also indicates that interacting with an object haptically, for example, affects more than the haptic perception but a combination of visual and haptic sensory modalities.

2.2.2 Active Perception

Perception cannot exist without an action. Both are necessary to perform the simplest task or explore the shape of an object. When looking at a specific object or when using a tool, an individual immediately thinks of possible ways that this object or tool can be used. Numerous studies have demonstrated this effect where people were able to associate the objects with the possible actions carried with them (Klatzky, Loomis, Lederman, Wake, & Fujita, 1993). In this study participants were able to identify several commonly used objects while blindfolded with high accuracy. This object identification also works when there is not direct contact between the body and the object explored. Gibson (1968) showed that, when using a hammer, people do not directly contact the nail, but still are able to reasonably know when the nail is in the wall (James J Gibson, 1968). This active exploration of objects leads to relatively accurate information about the environment.

A more recent endeavour to explain the connection between perception and action could be found in the work of O'Regan (2001) with sensorimotor contingency theory (O'Regan, 2001). Sensorimotor contingency theory describes that, for a particular action, one does not perceive that action as a separated experience, but rather a set of sensorimotor contingencies that are picked up through interacting with the environment. So, the act is what defines the perceptual experience, not something that resides in the brain. "Mastery of sensorimotor contingencies may be neurologically encoded, but this mastery does not itself reside in the brain" (O'Regan, 2001). For example, when driving a car, if an oncoming car becomes bigger, that means it is getting closer. Using this knowledge to operate the car would indicate familiarity of sensorimotor contingencies that are needed to drive without crashing. Sensorimotor theory also proposes the idea that the outside world acts as a memory. Since people's brains cannot store a visual representation of the whole world, the focus of attention would be on the important events in the environment. So, introducing a change in the environment would sometimes go unnoticed, unless a person is attending to that change. Several studies have demonstrated such an effect with change blindness (Suma et al., 2011) and inattentional blindness (Jensen, Yao, Street, & Simons, 2011). These studies demonstrate that visual attention capacity is limited and, even with large changes, people may miss these changes when not attending.

Several studies have also demonstrated that people perceive objects by imagining possible ways of using these objects (Newton, 1996; O'Regan, Rensink, & Clark, 1999). For example, observing a table, one would think of what can be put on it, or looking at a game joystick, one would think about how to hold it. Therefore, people's perception does not only use visual information to imagine the interactions with the object but also all multisensory information available about the action and the environment

(Ellis, 1995). In other words, anticipating the bodily movement or action that can be performed with a specific object is part of our perception.

Other studies have examined the way people estimate the dimensions of the physical environment that they had previously interacted with (Warren, 1984). For example, Warren (1984) asked subjects to judge the height of stairs that could be climbed. Participants were accurate in their judgment because they had performed similar actions before. Others have demonstrated the ability to judge object measurements through grasping physical objects (Van Leeuwen, Smitsman, & van Leeuwen, 1994), perceive other people's actions and affordances (Stoffregen, Gorday, Sheng, & Flynn, 1999), judge different surfaces (Burton, 1992), catch a fly ball (Ojemann, 1994), or design and understand virtual reality (Smets, Stappers, Overbeeke, & Van der Mast, 1995).

Both Sensorimotor Contingency Theory and Gibson's theory share the ideology that our perception is not an internal mechanism in the brain, but rather a dynamic system of give and take between the person and the physical environment. Sensorimotor contingency theory describes an important connection between how one behaves and perceive the physical environment, and how some events go unnoticed when one focuses on a specific task.

2.2.3 Attention

Part of people's interaction in the world is paying attention to the most important elements in the environment which contribute to neglecting others. People pay more attention to the task at hand when using a tool instead of observing the tool that is being used. Most of the research regarding attention was conducted in the visual field, but there have been studies conducted in haptic attention. People's attention has shown to increase when stimulated using touch compared to visual cues (Gallace & Spence, 2014). Several studies have showed this latency in the visual attention, demonstrating that attention could be directed to a specific perceptional modality, such as touch in this case (Vibell, Klinge, Zampini, Spence, & Nobre, 2007). Other studies also investigated the effect of body posture on tactile attention. For example, attention is shown to improve the location where the body is moving toward, pointing, or directing (Baldauf & Deubel, 2009; Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011). Other studies also investigated the difference between eye movement and hand movement in response to a stimulus. This study demonstrated that participants were able to respond faster when a hand movement was required to point at a location (Gherri & Eimer, 2008).

Attention can be enhanced when processed through touch, but it can also be narrowed by a cognitively loading task or occlusion in the visual field. Change blindness for example effects how people perceive the visual sense by introducing some distraction. Many studies have demonstrated that people fail to detect a change between one visual scene and the next when a distraction is introduced in between (Gallace & Spence, 2014, p. 80). In change blindness studies, participants are presented with one picture followed by a distraction, then another picture which contains the change. These changes are often hard to perceive after the distraction has been introduced. Change blindness also has been studied with haptic attention. For example, Auvray et al. (2007) have shown evidence that people fail to detect simple changes presented through vibrotactile patterns. In this study the distractor is a temporal one where after 110 seconds participants were not able to detect changes presented on their body (Auvray et al., 2007).

Another type of lack of attention is inattentional blindness, which is affected by cognitive load. This type of blindness occurs when participates are engaged in a cognitively loading task that requires counting or visually following a target. In the famous Gorilla experiment (Chabris & Simons, 2010) participants were asked to visually follow a ball and count the number of times it has been passed between one player of the same team. During a short video where participants were engaged with the task of following the team, a man wearing a black Gorilla suit would pass by for few seconds and stand in the middle of the scene. About 70% of participants would fail to notice the Gorilla as they were engaged in following the counting task. This dual task mechanism demonstrated that concentrating on the task would filter some of the other unimportant information in the visual scene.

Another example of attentional influence on haptic perception is the cutaneous rabbit illusion (Geldard & Sherrick, 1972). This illusion occurs when participants receive several haptic taps along their arm. Participants reported feeling one continuous tap alongside the arm after the stimulus. Participants perceived these taps as one continuous line if it was performed within 70-150 ms (Geldard & Sherrick, 1972). This illusion can also be observed when holding a physical object where the effects of the haptic stimuli would include objects, like a cube. In a study conducted by Miyazaki et. al. (2010), they showed that when participants received a tap through a stick that was laid on their index fingers, they would report a continuous line of dots along the stick (Miyazaki, Hirashima, & Nozaki, 2010). This illusion demonstrated that people are able to integrate external objects into their body schema when paying attention to a specific stimulus, in this instance, taps on the hand and the stick.

People have limited ability to notice their surroundings therefore, they will focus on the important element that are need at the moment. For example, when someone write with a pen one would only focus on the activity of writing and not the physical attributes if the pen. Measuring this limited capacity of attention would help identify where people focus their attention when actively using tools or holding objects. This work will used attention in study 2 and study 3 to understand changes in attention for goal directed behavior.

2.2.4 Memory

Memory is an important part of our embodied cognition. Memory can be enhanced by how one remembers and interacts with the external environment (Gallagher & Cole, 1995). Memory and motor skills also play an important part in people's task performance. Scribner & Beach (1988) conducted a study on bartenders, observing how in a very busy and noisy environment they can still remember the orders of several clients. Bartenders would use different glass shapes to remember different orders and recall these cues when presenting the drink (Scribner & Beach, 1993). Another study was conducted on climbers and the different recall mechanisms they used for distinct climbing holes (Boschker, Bakker, & Michaels, 2002). Experts in this case, would focus more on the functional distribution of climbing holes whereas novices would recall the structural distribution. This indicates memory representation of the physical environment changes with different motor skill levels.

The effects of working memory on overt body movement also have been investigated. Working memory is a temporary short-term memory that is needed to accomplish a particular task (Gibbs Jr, 2005a, p. 144). For example, Quinn (1994) has conducted a study where participants need to recall an imaginary path. Participants in one condition had to move their hand randomly before attempting to recall the path, and in the other condition the experimenter would move subjects' hands (Quinn, 1994). Results demonstrated that participants were able to recall the line more effectively when they did not have control of their hand compared to when they moved their hand on top of the table. Other studies on the effects of working memory include recalling information from mental images (Kosslyn, 1988) and recalling a path on a four-by-four matrix with or without holding a physical object in their hands (Baddeley, 1983). This illustrates how physical movement affects people's ability to remember particular information that was presented. This further demonstrates the connection between using our bodies and the effect of people's working memory in accomplishing tasks.

Haptic memory changes also could be used as a measure of embodied interactions. For example, study 1 used after effect on haptic memory to observe changes when entering with physical and virtual objects.

2.3 Human Motor Performance (Motor Learning acquisition)

Classic views on motor learning acquisition theories consider an internal mechanism that describes the process of acquiring motor skills. Both Adams' (1971) and Schmidt's (1975) represent this view of motor learning acquisition. The work of Adams' (1971) proposed a closed loop theory of motor learning acquisition that consists of two states of memory representation. The first one was memory trace, which is responsible for selecting and starting the movement. The second was perceptual trace, which is the desired movement image based on prior experience. These two memory states would act together to perform a coherent movement in a closed loop system one for movement initiation, and one for evaluation and correctness. Adams' (1971) theory also consisted of two motor learning stages: the verbal stage and the motor stage. The verbal stage requires an understanding of the motor activity and typically occurs while practicing. The motor stage is where the motor activity becomes autonomous and begins to enhance performance (Adams, 1971). Moreover, Schmidt's (1975) work considered schema to explain the motor learning acquisition process. Schema is a set of general rules or steps that describes the relationship between variables that are needed to perform the motor activity. In order to construct such schemas, one should be exposed to goal-oriented tasks that must be performed several times. Schmidt's (1975) theory consisted of four stages: 1- initial movement and condition, 2- parameters, 3- outcome of the movement, and 4- intrinsic sensory feedback. These four stages are essential to produce movement. Schemas also consisted of two sections that are similar to Adams' theory of two different memory types (Schmidt, 1975): recall schema and recognition schema. Both theories provided an internal representation of the learner motor activities. Both Adams' closed loop theory and Schmidt's open loop theory represent a classical view of motor learning skill acquisition; however, they both do not provide a practical understanding of how people use tools as part of the motor learning skill acquisition.

Another classical view on motor skill acquisition is the work of Fitts and Posner (1967). Their work divides skill learning into three stages: the cognitive stage, the associative stage, and the autonomous stage (Fitts & Posner, 1967). The cognitive stage is the first step taken by a learner of a particular skill. More attention is dedicated to every aspect of the learning process, which at the later stages will go unnoticed. In this stage the movement of limbs becomes dominant and the learner pays more attention to body parts that are performing the action. The second stage, associative stage, connects what was acquired in the first stage as individual components into one experience with many errors. This stage is the same activity practiced several times to reach a certain point of mastery of the skills. For example, typing on the keyboard is not an easy task to achieve proficiently. It is necessary to perform repeatedly until a state of mastery. At this stage, the practice component of the task is very important to achieve the final goal of mastery over the task. The third and final stage is the autonomous stage. This stage of motor skill learning requires less attention, and movements to perform the task are automatic in nature. The person performing the activity at this stage exerts less cognitive load performing the task and may not notice the particular body movement that is involved in accomplishing the task. For example, a pianist would not be looking at his or her individual fingers while playing the piano. This act would probably disrupt the flow of achieving the task and playing the piano. The autonomous stage has been supported by Bahrick, Noble, & Fitts (1954) where participants were asked to report a sequence of lights in one condition, and in another condition this sequence was randomized (Bahrick, Noble, & Fitts, 1954). At the same time, participants were to perform an arithmetic operation orally to the experimenter. With less practice, both conditions performed similarly, but as more practice was administered, the group that had been given a normal sequence of numbers was performing better on the arithmetic task. This demonstrates that part of the task that becomes autonomous after a period of practice would be performed without interfering with the second given task. Fitts and Posner's (1967) work shows a practical view of the motor learning acquisition compared to Adams' and Schmidt's work where they only described a specific internal mechanism of the motor learning activity.

2.4 Human-Computer Interaction (HCI) and Natural User Interfaces (NUI)

The most comprehensive work about embodied interaction in HCI is Dourish's "Where the Action Is" (Dourish, 2004), where natural user interfaces are represented as being embodied with the digital world. Dourish (2004) discusses embodiment and embodied interaction where interactive technologies can be developed to leverage properties of the physical world in virtual environments. The phenomenon of 'embodiment' is used in a general sense, drawing from multiple philosophical ideas that apply, not only to objects or people, but also to phenomena in their most general sense. An object can be embodied in at least two different ways: through a physical presence (physical embodiment) or through a visual representation in a display (virtual embodiment). HCI literature has also discussed embodiment of people, for example, when represented in the virtual world (Benford, Bowers, Fahlén, Greenhalgh, & Snowdon, 1995), or when parts of their bodies are extended into displays (Nacenta, Pinelle, Gutwin, & Mandryk, 2010a; Tang, Neustaedter, & Greenberg, 2004). Embodiment here is represented as being part of the virtual world and to act in that virtual world as naturally and intuitively as the physical one.

Natural user interfaces (Wigdor & Wixon, 2011) strive to present the user with intuitive human-computer interaction. Graphical user interfaces (GUI) have provided us with an easier way to interact with computer systems via a mouse to control graphical objects on the screen (Blankenberger & Hahn, 1991; Engelbart, 1968). NUIs are another step forward into the evolution of such interactions. NUIs remove the barriers that stand between the interactive technology and user interaction, providing more seamless medium to control the environment and accomplish tasks.

Although many interactive technologies could be categorized as NUIs, a few have emerged in the last decade that promise to provide that naturalness and intuitiveness of interaction. Tangible computing uses a combination of physical objects and virtual ones. Users might be interacting with physical cubes for example, and different virtual information would be presented to them through this cube (Ishii, 2008). Tangible computing (Ullmer, Ishii, & Glas, 1998) provides a bridge between the physical properties of objects with the virtual presentation of information. Such interfaces have been considered a more natural and intuitive way to interact. Touch screens (Weiser, 1993) also provide a direct medium of manipulation of virtual objects in the digital world, and are also considered more intuitive and natural. These and other interactive technologies like mid-air gestures (Harrison, Benko, & Wilson, 2011), augmented reality (Milgram, Takemura, Utsumi, & Kishino, 1995), and virtual reality (Rheingold, 1991) provide different sets of possible interactions that can mimic the physical world in some ways. For example, virtual reality uses some of the same sensory motor experience as the physical environment, and mimics them in the virtual one, thus providing a more natural experience (e.g., turning to the left will change the field of view accordingly). These NUIs promise to be closer to the physical world by applying the same physical properties of that world but there is little quantitative evidence from HCI that these modes of interaction actually result in interaction that is more natural or intuitive.

2.4.1 Measuring Intuitiveness and Naturalness

A missing piece in HCI research has been in finding an effective way to measure how an interactive technology is or is not similar to the real world. Although several studies looked at ways to evaluate different types of interactions (Ingram, Wang, & Ribarsky, 2012), little work has been dedicated to understanding intuitiveness or naturalness of these interactions. The few examples of previous work that attempted to measure intuitiveness have focused on performance measures, self-reports, and behaviour observation.

Performance measures of interactive technologies and different interactive modalities often include a variety of hardware and software that affect people's performance. Hardware has been evaluated by varying screen size (Ryall, Forlines, Shen, & Morris, 2004), display coordination effects on perception of 2D graphics (Wigdor, Shen, Forlines, & Balakrishnan, 2007), and the evaluation of 3D graphics on people's perception (Weiser, 1993). Software has been evaluated by looking at different aspects of the presented information on the screen, including menus (Guimbretiére & Winograd, 2000a; Leithinger & Haller, 2007), data visualization (Mikulecky, Hancock, Brosz, & Carpendale, 2011), and 2D and 3D virtual object manipulation (M. S. Hancock, Carpendale, Vernier, Wigdor, & Shen, 2006; Kruger, Carpendale, Scott, & Tang, 2005; Reisman, Davidson, & Han, 2009; Shen, Vernier, Forlines, & Ringel, 2004). The evaluation of using performance measures mostly considers speed and accuracy to assess the interactive technology.

Other research has considered people's expectations when using interactive technology, by creating user-defined gestures (Morris, Wobbrock, & Wilson, 2010a; Wobbrock, Morris, & Wilson, 2009). In these studies, users are shown an interaction, and then asked to select gestures to perform that task in an attempt to discover what is most natural or intuitive. Other studies have considered affect, task load, and motivation when using touch and tactile interaction (Watson, Hancock, Mandryk, & Birk, 2013). This methodology uses validated scales to measure the experience of using an interactive system.

Alternatively, other work makes use of observational studies to investigate how people appropriate territory when working in groups around multi-touch tables (Scott, Carpendale, & Inkpen, 2004), and others have extended this work to an exploration of territoriality in public (Azad, Ruiz, Vogel, Hancock, & Lank, 2012) and private locations (Rogers et al., 2006) to understand tactile input interaction. Other observational studies have been conducted in the wild to evaluate touch interaction technology (Hinrichs & Carpendale, 2011; Hinrichs, Schmidt, & Carpendale, 2008; Hornecker, 2008; Peltonen et al., 2008).

Despite the vast work exploring natural user interfaces, evaluation of interactive technology so far has not provided a direct measure of embodied interactions.

2.5 Virtual Reality (VR)

Virtual reality (VR) has become increasingly commonplace in the last few years with the variety of hardware and software that enhances the immersion experience. With a combination of haptic gloves, more advanced controllers and full body sensation, VR systems have become more realistic in mimicking the physical environment.

VR provides a tremendous opportunity to test full body illusions in virtual environments. For example, in a study conducted by Ehrsson (2007) on 'out of the body' illusion showed promising results. Participants would use a VR headset and would be seated on a chair. They would then see in the headset a view of their back via a camera placed 2 meters behind them. The experimenter would touch participants with a plastic tool on their chest out of view, but subjects would be able to see this touch with the VR headset on an artificial body (Ehrsson, 2007). This research reported a physiological reaction in form of a skin conductance response to a threat (hitting by a hammer) which shows that people are able to experience out-of-body illusions using this simple technique in VR. Moreover, Petkova and Ehrsson (2008) followed this research by placing the camera on a mannequin. Participants were able to see the mannequin body in their headset from the first-person perspective (Petkova & Ehrsson, 2008). They were also able to see how the mannequin was being touched for some time and then would see a threat approaching. Skin conductance response to the threat also showed appropriate physiological reaction. Finally, Guterstam and Ehrsson (2012) conducted a study that adopted the same previous techniques of using the VR system for disownment of a participant's body (Guterstam & Ehrsson, 2012). By placing the body in a different physical location, results show that participants disown their body and no longer perceive it as part of themselves. These different illusions show the potential of using VR to experimentally test in a controlled virtual environment.

VR and AR systems attempt to mimic the physical world by providing the same sensorimotor experiences of the physical environment (Slater, 2009). physiological responses and illusions that can affect people in the physical environment can also be mimicked in a VR environment. For example, public speaking anxiety can be reproduced in a VR environment (Slater, Pertaub, Barker, & Clark, 2006). A general sense of presence when navigating through the VR environments has also been explored (Barfield & Weghorst, 1993; Held & Durlach, 1992; Sanchez-Vives & Slater, 2005; Sheridan, 1992, 1996). These responses show how people's reactions in the physical environment can be replicated virtually.

Numerous studies have explored people's experience in VR to design a better system and enhance the interaction. These studies have largely considered self-report questionnaires or performance measures to evaluate the effectiveness of VR interaction. These measures give information about the system usability, but do not link directly to specific elements of the environment that was embodied with the users. For example, using a virtual tool in VR might produce high performance measures and level of satisfaction, simply because of the novelty factor, even if the technique was "poor" or did not allow for embodied interaction. This could lead the experimenter to conclude that the system is optimal without considering other factors. A VR study that looked at the sense of embodiment with the virtual body affected by a temporal shift forward or backward, was evaluated only using self-reported questionnaires (Kasahara et al., 2017). Another study that evaluated real-world training and compared it to VR training for a complex motor activity was also evaluated on self-report questionnaires and performance measures (Sigrist, Rauter, Riener, & Wolf, 2013). Various studies also use qualitative analysis in combination with self-report questionnaires to evaluate user experience in VR (Geszten et al., 2015). While these studies provide useful data to explore performance and first impressions of VR, this thesis explores a more in-depth measure of embodied interaction in this space to investigate whether people can focus on their task and forget about the tool.

VR environments can simulate the physical world experience where people feel like they are somewhere else. One study used virtual reality to manipulate dimensions of participants' fully-tracked virtual hands to investigate its influence on the perceived size and shape of virtual objects. Participants provided a verbal estimate of the virtual object size. This experiment demonstrated increases in the perceived sizes of objects as a function of decreases in the size of one's virtual hand. Presumably, these influences are a result of using the body and its action capabilities as "perceptual ruler" to which perceived sizes and distances are scaled (Linkenauger, Leyrer, Bülthoff, & Mohler, 2013). Another study (McDonnell, Scott, Dickison, Theriault, & Wood, 1989) focused on the length of the arms in the virtual world using similar measures to the one used in rubber hand illusions, proprioceptive drifts. This measure, however, is difficult to implement with technology. Specifically, when different virtual tools in the VR environments would not produce a proprioceptive drift measure similar to the rubber hand illusions measure.

A question that has not yet been addressed in VR is how such a system can induce these illusions, anxiety and presence. These psychosocial and physiological effects occur without using a VR system, and some of these effects can also be induced using indirect measures when subjects watch a regular screen with the same visuals (Slater, 2009). Little work has been conducted to evaluate VR in terms of measuring embodied interaction. For example, using stories and narratives as a test of embodied interaction. A study was conducted that supports spatial perspective-taking, where tangible blocks in VR were tested and compared to a keyboard and mouse (Kasahara et al., 2017). Performance was measured, and the tangible VR interaction showed significant results, which is an indication of improved perspective-taking using stories.

VR provides an enormous opportunity to test embodied interactions in the virtual world. Specifically, the experimenter could control and manipulate various aspects of this VR world like different sensory stimuli (e.g. visual, or haptic). Study 3 of this dissertation tested tool embodiment with different inputs alternative in the VR world.

2.6 Summary

This chapter introduced the concept of embodied interactions in both experimental psychology and human-computer interaction. This thesis focuses on identifying a direct quantitative measure of embodied interaction in virtual environments. In the first section of this chapter, the concept of embodied cognition was introduced. In the second part, theories on active perception, attention, memory, and motor performance were discussed. In this chapter, this literature review revealed a gap in identifying a direct measure of embodied interactions that can be used with different technologies. The next chapter will use after effect as a measure of object interaction with both physical and virtual objects.

Chapter 3

Study 1: Kinesthetic Figural After Effects (KFAE) Using Haptic Memory as a Measure of Embodied Interaction

The literature review (Chapter 2) revealed a gap in attempting to evaluate virtual objects interaction with a quantitative measure. Embodiment of people has been discussed when represented in collaborative virtual environments (Benford et al., 1995) , or when parts of people's bodies are extended into displays (Nacenta, Pinelle, Gutwin, & Mandryk, 2010b; Tang, Neustaedter, & Greenberg, 2004). These studies that relates embodied interactions with technologies would describe the phenomena in a general sense drawing from multiple philosophical backgrounds. However, there is lack of understanding how to adapt these phenomena as a measure of virtual object embodied interaction. Thus, this study designed, developed, and evaluated a quantitative measure of virtual object embodied interaction on a multi-touch screen.

According to Arzy and colleagues (2006), embodiment is the innate ability to perceive the localization of one's body within one's body outlines (Arzy et al., 2006). This property is often extended beyond the body and includes other physical objects in contact with our body, such as clothes, tools, or prosthetic limbs. De Vignemont (2010) posits that an object becomes embodied only when its properties are processed in the same way as one's body (De Vignemont, 2011) or, in other words, when an object becomes part of our body schema (Ullmer & Ishii, 2000) . There are multiple studies that test variants of how embodied an object is in this sense. For example, several studies have measured that using a tool extends one's own 'personal space' (Churchill, 1965; Petrie, 1967), and that the length of one's arm is overestimated after using a prosthesis or a grasping tool (Platt, Holzman, & Larson, 1971). The famous 'rubber hand' illusion also illustrates how people can be made to believe that an artificial object is part of one's body, both by using tactile (Botvinick & Cohen, 1998) and purely visual stimulation (James Jerome Gibson, 1966).

Although the haptic and limbic systems are mostly credited with maintaining the sense of proprioception, it is remarkable that visual manipulations such as the rubber hand illusion (Botvinick & Cohen, 1998), or the mere lack of visual feedback (Kelvin, 1954) can produce systematic distortions in proprioception. From these phenomena we could therefore conceive of the possibility that embodiment is created, not only through the haptic properties of its physicality, but also through visual representations. Perhaps visuals and simpler tactual experiences (e.g., those from touch screens) could be perceptually equivalent to physical embodiment.

As a first step, the phenomenon of figural after effects (FAE) was chosen as a measure for object embodied interaction. FAE occurs when changes in human perception resulting from grasping or holding physical artefacts which affects haptic memory and the next object that one holds. This phenomenon is well-studied in psychology and used in a controlled laboratory experiment to observe whether the effect applies to virtual object interaction accessed through multi-touch screens. This work was co-authored and published in the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (Alzayat, Hancock, & Nacenta, 2014).

3.1 Background

In this study, the phenomenon of figural after effects (FAE) was used as a measure of object interaction. FAE was discovered by the great visual perception pioneer James J. Gibson and refers to alterations of the perception of certain visual patterns after seeing other patterns (James Jerome Gibson, 1966). FAE was mostly researched in the visual field with visual patterns; however, following Gibson’s work, Köhler and Dinnerstein (1947) conducted several experiments to observe after effects for the sense of touch, which we refer to as Kinesthetic Figural After Effects (KFAE). In Kohler and Dinnerstein’s experiments, participants were blindfolded and instructed to hold a long cardboard piece between their thumb and fingers and run their hand alongside it for some time. Then they were asked to report the width of a different (wider or narrower) cardboard piece. Kohler found that people overestimated the width of the narrower piece and underestimated the wider piece. This over and underestimation did not take place for a control group who never touched the initial object, providing evidence that the touch of a previous object affects subsequent touches.

FAE is a very reliable phenomenon, and it has since been replicated many times (Churchill, 1965; Heinemann, 1961; Platt et al., 1971) and used to correlate with and validate a wide range of psychological phenomena, including pain resistance (Petrie, 1967), gender differences (Phelan, Brooks, & Brashears, 1970) and personality variables (Kidd & Beere, 1968). We make use of this reliable phenomenon in our comparisons of touch experience with physical and virtual objects.

3.2 Study Design (Methodology)

While there is an abundance of literature in psychology that explores the idea of embodiment, this study focused on the kinesthetic figural after effect for two reasons. First, this effect suggests a psychophysical response from direct interaction with physical artifacts. Thus, it seems in line with the notion in existing HCI literature and it is expected to have similar effects on human perception with direct interaction on touch screen. Second, the FAE phenomenon is linked to touching objects, which is something that we can reproduce with hands and fingers on a multi-touch device. The FAE experiment has been reproduced in the literature many times, and pilot studies revealed the reproducibility of these results.

Thus, in order to begin to understand the effects of direct touch interaction on one's physiology, a pair of experiments was conducted. The first experiment's purpose was to confirm that FAE phenomenon from previous work can provide a baseline measure for the effect. In the second experiment, the physical setup of the first study was replicated as closely as possible in a digital table with a virtual object, in order to determine whether this effect transferred to the digital space.

3.2.1 Experiment 1: Verifying Figural After Effects

This study adopted the procedures from Petrie (1967), with some modifications, to verify that this effect can be reproduced (Petrie, 1967). The essence of the experiment is the same as in Köhler and Dinnerstein's study (1947): participants were asked to estimate the width of wooden blocks with and without a previous exploration of another physical block. The expected result was that being primed with this exploration would result in different perceived widths than not being exposed.

3.2.1.1 Experiment 1: Participants

Nineteen right-handed participants (6 female, 13 male) between the ages of 22 and 37 (*Mdn* = 26) participated in this experiment. Participants were recruited from on-campus graduate mailing lists and paid with $10 gift certificates to a local coffee establishment.

3.2.1.2 Experiment 1: Task and Procedure

The study involved an interleaving of two phase types: inspection phases and measurement phases. In inspection phases, participants were asked to tactually explore a physical block of wood. The expectation was that this inspection would lead to perceptual changes over time. In the measurement phase, participants were asked to determine the width of a physical block of different size, having either been primed with an inspection phase, or not. The expectation in this phase was that their measurement of the block would be biased by the inspection phase. The order of trials was as shown in Figure 3.

R	M	I_{90}	M	I_{90}	M	I_{120}	M	R	M	I_{90}	M	I_{90}	M	I_{120}	M
Condition 1								Condition 2							

Figure 3: Each participant performed this trial sequence. R = rest, M = measurement, I_x = *x*-second inspection.

Rest Period (R). After the participant was seated and blindfolded, they were asked to keep their hands in an upward position, wherever it was comfortable for them to keep for ten minutes. They repeated this rest period before the second condition and block of trials.

Inspection Phase (I). In this phase, participants were given a specific time to inspect the object through touch. During this time, participants were instructed to move their left hand and feel the full length of a long block (the inspection block, see Figure 6) laid parallel to the long straight end of a semi-circular table. The right (dominant) hand was not used in this phase and participants were asked to hold their hand comfortably, without touching anything else with their fingers. To feel the full length of the block they needed to walk back and forth parallel to the length of the table. As shown in Figure 3, inspection phases occurred after the first measurement phase and before each subsequent measurement phase. The first measurement phase was therefore always free from the influence of an inspection phase. The time allowed for inspecting the object was 90 s for the first inspection phase, 90 s for the second, and 120 s for the last phase. Participants were blindfolded.

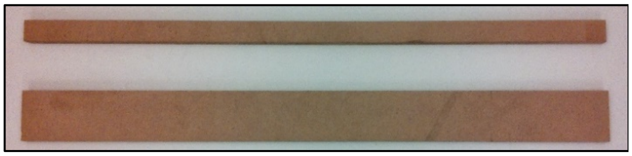


Figure 4: The 3 cm (top) and 7 cm (bottom) blocks used in the inspection phase.

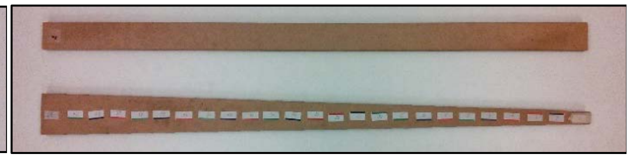


Figure 5: The 5 cm (top) and notched measuring (bottom) blocks used in the measurement phase.

Measurement Phase (M). In this phase participants were still blindfolded and were asked to compare the test block—a wooden block similar to the inspection block of the inspection phase but with a different width—to a measuring block. The measuring block, unlike the inspection and test blocks has different widths along its length (notches), which change width gradually in steps (Table 1, see details in section 3.2.1.2), and was laid on a symmetrical table to the participants' right. Participants moved between two tables holding the test block with their left (non-dominant) hand and the measuring block with their right hand (Figure 6). The participant was then asked to walk between the tables (Figure 6), sliding their

Figure 6: The setup in Experiment 1. Participants inspected blocks on their left (left image: near table) and measured the block with the measurement tool on their right (left image: far table).

fingers along both the test block and the measuring block until they felt that the widths of both sides were equivalent.

Notch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Width (cm)	2.28	2.62	2.85	3.07	3.29	3.52	3.72	4.00	4.25	4.48	4.69	4.89	5.11	5.35	5.55	5.75	5.94	6.16	6.35	6.56	6.75	6.95	7.14	7.40	7.61

Table 1: The measured widths of the notches on the measurement tool, using callipers.

Each measurement phase took between 300 s and 450 s. Because participants were blindfolded, the experimenter helped them to start a trial by asking them to stand with their hands held in a position avoiding touching anything with their fingers and affecting their kinesthetic memory. The investigator then took the participant's left hand, placed it on the test block, then their right hand and placed it on the measuring block. Participants were instructed to feel the full length of both blocks (which required walking from one end of the tables to the other) using exclusively their thumb and index finger before settling on a judgment (a particular notch). For each trial, the participant provided the estimated width four times. After settling on a particular notch in the measurement device, participants had to again feel the full length of the block and make another judgment for a total of four measurements per phase. This was done to increase the reliability of the measurements.

As shown in Figure 3, there were four measurement phases in each condition, the first being the control, with three following inspection phases. Participants performed two consecutive blocks of these phases, one with a small inspection block, and one with a large inspection block.

3.2.1.3 Experiment 1: Apparatus

The two parallel tables were placed approximately 55 cm apart to allow participants to move freely between them (Figure 6). A chair was placed at the end of the space between both tables for the rest phases. The tables were 120 cm long on the participant's edge and 77 cm tall.

Inspection and Test Blocks. Köhler and Dinnerstein's configuration (1947) was used for the physical blocks, with the exception that these blocks were made from medium-density fiberboard, not cardboard. Two inspections blocks were used with 3 cm and 7 cm widths. The test block used in the test phases was always 5cm wide. Each block was 1 m in length and 1 cm tall (Table 1).

Measuring Block. The measuring block is a notched measuring device that varied in width by an average of 2.22 mm at each notch (Figure 5) starting at 2.28 cm, for 25 notches. After cutting the measuring block, the widths of each step were measured using callipers (Table 1), as the manufacturing technology did not allow for extremely precise widths. The distance between each step was 4 cm. The material is smooth enough that participants could not sense irregularities in any of the blocks to use as landmarks. The measuring block was again 1 m long and 1 cm tall, and each step was annotated to allow the experimenter to easily record the width measured by the participant.

3.2.1.4 Experiment 1: Factors and Design

A 4 (measurement phase) × 2 (size) within-participants design was used. Specifically, a comparison was made between measurements after the inspection of a small block (3 cm) to those after the inspection of a large block (7 cm). The size factor was counterbalanced, and sequence of trials was as shown in Table 2.

The differences in size between each of the inspection blocks and the test block were the same as what Köhler and Dinnerstein (1947) used in their experiment (Köhler & Dinnerstein, 1947). Overestimation of the test block width after inspecting the small 3 cm wide block and an underestimation of the test block after inspecting the large 7 cm wide block was predicted.

3.2.1.5 Measures.

The measure used was the difference between the recorded size and the actual size (5 cm). Thus, positive values indicate overestimation, negative values underestimation, and zero a perfectly accurate measurement.

Participants (N)	Condition 1	Condition 2
10	Small (3cm)	Large (7cm)
9	Large (7cm)	Small (3cm)

Table 2: Participants across conditions in Experiment 1.

3.2.2 Experiment 2: Physical vs. Virtual Object After Effect

The second experiment approximately replicated the physical setup of Experiment 1 using a digital table and a virtual object instead of the physical table and the physical object. Note that, in the studies that we modelled Experiment 1 after, participants were blindfolded. Since interaction on a multi-touch screen would not provide awareness of a virtual object without the visual sense, we also used our second study to verify that figural after effects would still occur with physical objects when participants were not blindfolded in the inspection phase of the procedure.

3.2.2.1 Experiment 2: Participants

Twenty-one participants (12 female, 9 male) between the ages of 21 and 28 (Mdn = 24), 17 of whom reported being right-handed, participated in this experiment. Participants were recruited and paid as in Experiment 1. All except one were naive to the experiment, as this one participant had taken part in the first. Due to the time period between the two experiments (6 weeks) and the low-level nature of the effects being measured, we chose to include this participant's data in our analysis, and do not believe that it impacted the results.

3.2.2.2 Experiment 2: Task and Procedure

The task and procedure used in this experiment mirror exactly what was done in Experiment 1, with the following exceptions. In the inspection phase, instead of varying the size of blocks, we varied whether they were presented in the physical world (i.e., as in Experiment 1) or on a digital table. The inspection phase (I) with the physical block mimics Experiment 1 with the difference that participants were not blindfolded and were instructed to look at the object repeatedly when necessary. The inspection phase (I) with the virtual object was performed in the same manner (participants were not blind folded). The reason that the inspection phases were not blindfolded is to reproduce situations in the physical world, where objects are simultaneously grasped and seen. Additionally, it would not be possible for people to perceive the virtual blocks without the visual sense. Although this represents a departure from previous studies, in which participants were blindfolded throughout the whole experiment, it is still a valid manipulation, because both conditions included the visual sense, and provides a more ecologically valid task. Participants were still blindfolded in the measurement phase (M), which was thus identical to Experiment 1.

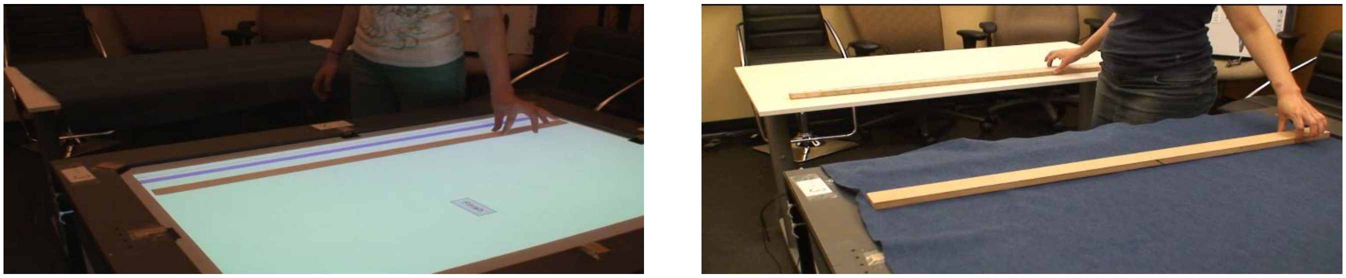


Figure 7: The setup in experiment 2. Participants inspected blocks on their left (near table in the image) and measured block with the measurement tool on their right (far table).

3.2.2.3 Experiment 2: Apparatus

The distance between tables in the second experiment was again 55 cm. However, the dimensions of the table were slightly different at 120 cm long, 80 cm wide, and 88 cm tall. In the second experiment, one of the two tables was a multi-touch digital table (Figure 7), so that the inspection phase could be done with virtual objects. We used a 1920 × 1080-pixel rear-projected screen that could detect touches by detecting reflections from diffuse laser infrared illumination, with a Sony PS3 camera. Camera data were processed using CCV and sent using the TUIO protocol to a Java program described below. In the physical condition in the second experiment, the table was covered with cloth.

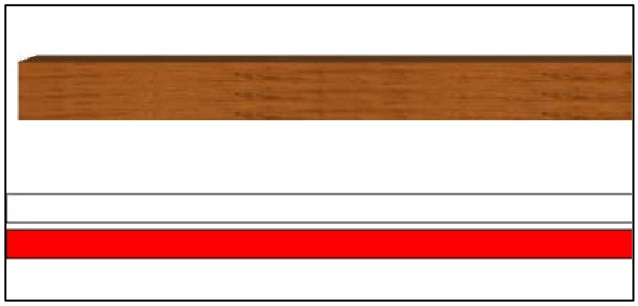


Figure 8: A screen capture of one end of the virtual block during the inspection phase. The bottom red bar indicates that the participant is not touching both sides of the block. This switches to the top bar turning blue when they are.

Virtual Inspection Block. Only one virtual object was used that mimics the 3 cm physical block. The object was developed in Processing[1] and presented on the laser table. The virtual block was designed to appear with the same length (1 m) and width (1 cm) as the 3 cm long inspection block that we used in the Experiment 1, and in the other condition of this experiment. Participants were asked to not touch anything on the touch table except the digital block and were shown a 3D representation of the block before starting the inspection (Figure 8). The investigator was able to rotate the block on its long axis to show participants the edges of the block; this was important because participants were not able to rotate the block themselves. Visual feedback was provided through two lines: a blue line indicated that the object was being "held" by the participant for the inspection, otherwise an adjacent red line was visible (Figure 7). These lines were the same length as and separated from the virtual block, so that the visual appearance of the block did not change, and the feedback did not require looking too far from the virtual block itself.

Participants (N)	Condition 1	Condition 2
11	Physical (3cm)	Virtual (3cm)
10	Virtual (3cm)	Physical (3cm)

Table 3: Participants across conditions in Experiment 2.

[1] Processing. http://processing.org. Last retrieved: Jan 2014.

3.2.2.4 Experiment 2: Factors and Design

A 4 (measurement phase) × 2 (interaction type) within-participants design was used. In this experiment, measurements after the inspection of a small physical block (3 cm) to those after the inspection of a small digital block (also 3 cm) was compared. The interaction type factor was counterbalanced, and the distribution of participants was as shown in Table 3.

Again, the expectation was to see an overestimation of width after inspection of small physical blocks. This investigation hoped to answer two questions: would looking at the object during the inspection period interfere with the kinesthetic figural after effect, and would the virtual object reproduce the same error in judgment after inspecting it?

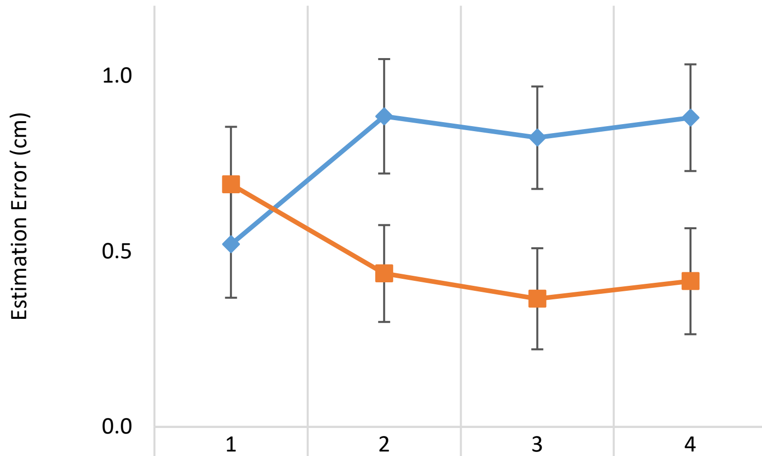
3.3 Study Results

Study results section will be organized as follows. First the results of the experiment 1 will be discussed, which focused on testing KFAE with physical objects only. Next the results of experiment 1 will be discussed, this experiment focused on testing KFAE with both physical and virtual object interaction.

3.3.1 Experiment 1 Results

A repeated-measures ANOVA with measurement phase and size as within-participants factors and order as a between-participants factor was performed. Bonferroni corrections were used in post-hoc analyses. There was a significant main effect of size ($F_{1,17} = 15.7, p = .001, \eta_p^2 = .48$), with participants estimating higher after small inspections (*M* = 0.78 cm, *SE* = 0.15 cm) than after large inspections (*M* = 0.48 cm, *SE* = 0.14 cm). Note that these means include both the control phase and the subsequent measurements and are therefore better interpreted as an interaction.

Estimation Compared to Control. There was a significant interaction between size and measurement phase ($F_{3.51} = 11.4, p < .001, \eta_p^2 = .40$). Figure 9 shows that the pattern of over- and underestimation



	1	2	3	4
small	0.52	0.89	0.82	0.88
large	0.69	0.44	0.37	0.42

Figure 9: Interaction between size and measurement phase.

relative to the control (phase 1) was as expected. Pairwise comparisons revealed that, when participants inspected the small block (blue diamonds in Figure 9), their estimation in phase 1 was significantly smaller ($p < .02$) than all three subsequent measurement phases (indicating overestimation). Phases 2-4 were not significantly different from each other ($p > .999$). When participants inspected the large block (orange squares in Figure 9), their estimation in the control phase was not significantly different from the other three phases ($p > .15$), nor were the subsequent three phases significantly different from each other ($p > .84$).

Nonetheless, the means in the large condition demonstrate the expected pattern of underestimation relative to the control measurement phase; however, these estimates were unexpectedly overestimates (positive), rather than underestimates (i.e., all positive values, rather than negative as was expected).

The main effect of measurement phase was not significant ($F_{3,51} = 0.5$, $p = .65$, $\eta_p^2 = .03$). There was also no significant interaction between size and order ($F_{1,17} = 0.2$, $p = .68$, $\eta_p^2 = .01$), nor between size, block, and order ($F_{3,51} = 1.8$, $p = .17$, $\eta_p^2 = .09$).

3.3.1.1 Order Effect and Between-Participants Analysis

There was a main effect of order ($F_{1,17} = 8.5$, $p = .01$, $\eta_p^2 = .33$), with participants inspecting small blocks first measuring blocks in all conditions higher (*M* = 1.02 cm, *SE* = 0.19 cm) and participants inspecting large blocks first measuring blocks in all conditions lower (*M* = 0.23 cm, *SE* = 0.20 cm). This order effect suggests that the changes that resulted from inspection in the first condition may have carried over to the second.

We thus performed a second repeated-measures ANOVA with size as a between-participants factor (discarding data from the second condition) and measurement phase as a within-participants factor. This analysis revealed the same significant effect of size ($F_{1,17} = 17.4$, $p = .001$, $\eta_p^2 = .51$) and significant interaction between size and measurement phase ($F_{3.51} = 6.4$, $p = .001$, $\eta_p^2 = .27$). Though, with significantly reduced power, the post-hoc comparisons only revealed significant differences between the control phase and the second phase (*p* = .04) for the participants who inspected small blocks, with all other pairwise differences being not significant (*p* > *.08*). The main effect of measurement phase was again not significant ($F_{3,51} = 1.2$, $p = .31$, $\eta_p^2 = .07$).

3.3.2 Experiment 2 Results

A repeated-measures ANOVA with measurement phase and interaction type as within-participants factors and order as a between-participants factor was performed. Bonferroni corrections were again used in post-hoc analyses. The main effect of interaction type was not significant ($F_{1,19} = 0.3$, $p = .57$, $\eta_p^2 = .02$), nor was the interaction between interaction type and measurement phase ($F_{3,57} = 2.3$, $p = .08$, $\eta_p^2 = .11$). There was a significant main effect of measurement phase ($F_{3,57} = 4.5$, $p = .01$, $\eta_p^2 = .19$); however, post-hoc analyses did not reveal any pairwise significant differences between these phases (*p* > .13).

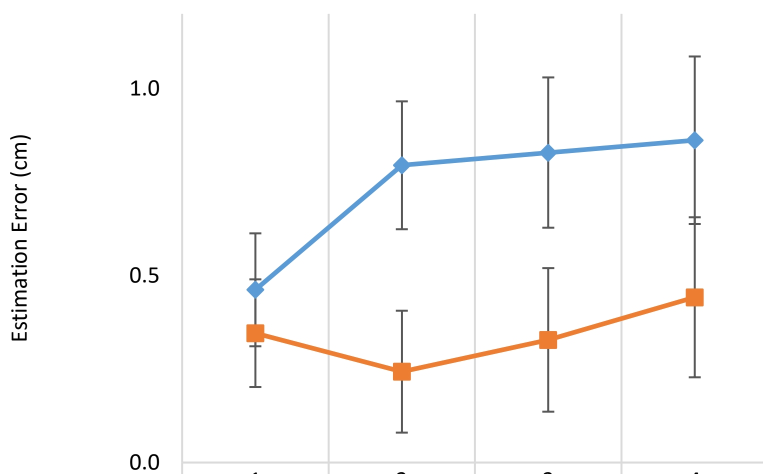
3.3.2.1 Order Effect

There was, however, a significant interaction between order and interaction type ($F_{1,19} = 8.6$, $p = .01$, $\eta_p^2 = .31$). Post-hoc pairwise comparisons revealed that, in the virtual condition, participants who inspected virtual blocks in the first phase estimated more accurately (*M* = 0.34 cm, *SE* = 0.17 cm) than when they had already inspected physical blocks (*M* = 0.87 cm, *SE* = 0.18 cm), and this difference was significant (*p* = .046). Participants overestimated when inspecting physical blocks, and the order did not significantly affect this overestimation (*p* = .41). Thus, again, the overestimation due to physical block inspection may have carried over into the virtual condition.

3.3.2.2 Between-Participants Analysis

Thus, we again performed a second ANOVA of only the first phase of the study, with interaction type as a between-participants measure, and measurement phase as a within-participants factor. This analysis revealed a main effect of measurement phase ($F_{3,57} = 3.8$, $p = .02$, $\eta_p^2 = .17$), but again, post-hoc comparisons revealed no pairwise significant differences between measurement phases (*p* > .09).

However, there was a significant interaction between measurement phase and interaction type ($F_{3,57} = 3.3$, $p = .03$, $\eta_p^2 = .15$). Figure 10 shows that the pattern of overestimation relative to the control (phase 1) was as expected for the physical block, and mirrored results from Experiment 1, but did not appear to manifest for the virtual condition. Pairwise comparisons revealed that, in the physical condition, the



	1	2	3	4
physical	0.46	0.80	0.83	0.86
virtual	0.35	0.24	0.33	0.44

Figure 10: Interaction between interaction type and measurement phase.

control phase (phase 1) was significantly smaller than phase 2 (p = .04) and phase 4 (p = .049), and marginally smaller than phase 3 (p = .051), and that phases 2-4 were not significantly different from each other (p > .999). For the virtual condition, no pairwise differences between measurement phases were significant (p > .26).

3.4 Experiment 1 Discussion

The results of this study show that the figural after effect can be reproduced, but that this effect was more easily reproduced with a small inspection phase leading to overestimations. Specifically, we found that the pattern of overestimation was as predicted for small block inspection, with size estimation prior to this inspection being more accurate than after inspection and estimates after inspection being significantly higher than this baseline. Additionally, we also identified an order effect that suggests that inspections in the first part of the experiment may impact estimations in the second, despite participants having a rest period in between these conditions. Thus, a between-participants design may be more appropriate for this type of study.

The results of this study were used for two purposes. First, we got assurance that the chosen effect was reproducible with our own setup. Although this might seem trivial, we recommend HCI researchers to take this approach first, since not all phenomena from the psychology literature is equally easy to reproduce, and sometimes the modifications required to test it for an HCI application can significantly weaken the effect. Second, the results directly informed the design of the second study, which involved a comparison of this physical phenomenon to the inspection of physical blocks without blindfolding participants and virtual blocks on a multi-touch table. For example, due to the effect being more obvious for the small blocks, we decided to only test small blocks in the second experiment. Although we expected that a within-participants design may again lead to cross-over effects in the second phase, we opted to again use a within-participants design, as the collection of this data was straightforward, and a between-participant’s analysis was still possible by discarding data from the second half of the study.

3.5 Experiment 2 Discussion

The results of this second experiment reveal that the kinesthetic figural after effect from the physical condition is difficult to detect in virtual environments. Specifically, while the inspection of physical blocks again led to overestimation in measurement phases 2-4, this same overestimation did not occur after inspection of virtual blocks, and instead resulted in very close to accurate estimations. We must highlight that the KFAE was present for the physical condition even though in Experiment 2, unlike in Experiment 1, the task was bimodal (visual in addition to tactile). This demonstrates that tactile experiences can have after effects, even for tasks that include a visual component.

3.6 General Discussion

The results of the experiments show that the kinesthetic figural after effect, a psychological phenomenon that has been replicated multiple times in the context of the perception of tactile physical objects, does not appear (or is attenuated to be too small to measure) when the grasping of the physical object is replaced by its equivalent in a multi-touch interface. These results further show that there is at least one fundamental difference between the experiences of touching a physical object and interacting with a similar virtual object through a multi-touch interface. This provides quantitative empirical evidence that interacting with physical objects through tangible interfaces (Ullmer & Ishii, 2000) and interacting with virtual objects through the multi-touch interfaces (Buxton, 2007) are fundamentally different from each other; thus, proving a measure of touch experience. Finally, a practical implication for the design of interfaces that can be derived from this study using KFAE as a measure of embodied interaction. Since the KFAE represents a distortion of our actual perception of objects, interfaces that require or can benefit from accurate perception of the dimensions of 3D objects (e.g., CAD applications) might benefit from the KFAE-free perceptions with a multi-touch interface.

This study is the first to show that the KFAE can be present in tasks that include a visual component. This is relevant for two reasons. First, it contributes to the body of knowledge in multi-modal perceptual effects and how different modalities integrate and compete with each other, showing that the visual aspects of the task do not necessarily override other senses completely. Second, because the KFAE still appears when visual information of the task is available, this makes the previous literature in KFAE relevant to a wider set of practical situations that are far more common than tactile-only ones. Assuming that the KFAE is strictly tactual and will not appear in the presence of visual information seems to unnecessarily constrain its relevance to people with severe visual impairments or for scenarios where visual attention needs to be engaged elsewhere (e.g., drivers and pilots).

Study 1 also showed that KFAE is hard to detect with virtual object interaction. This investigation is considered one of the first steps to attempt to measure embodied interactions in the virtual space using a quantities measure that affects people's haptic memory. This study would provide the needed feedback to further investigate other embodied interactions and the necessary information to construct a comprehensive framework.

3.7 Limitations and Future Work

Although this study provided some of the first quantitative evidence of differences in people's perception of the embodied interaction with physical vs. virtual objects, further experiments are required to find an alternative measurement that can be detected in virtual environments. Because KFAE depends on measuring haptic object interaction, the application of this phenomena with virtual technologies presents a challenge. Virtual environments are mediated generally by visual interactions and virtual objects are not tactile in nature in virtual environments; therefore, a different measure of embodied interactions could provide a more precise and clear evaluation of virtual environments.

3.8 Summary and Further Exploration

This chapter presented a sequence of studies that first verifies the existence of perceptual changes that result from handling physical objects (specifically, a figural after effect), and then show that these changes are difficult to measure in virtual environments with virtual objects. This chapter also discusses the implications of this finding to the understanding of multi-touch interaction and its ability to provide embodied interaction with virtual objects on a large display. Moreover, the results of this study provide some of the first evidence that suggests that the psychophysical effect of interacting with virtual artefacts is different than interaction with physical objects, despite the ability to directly interact similarly with both. This study compared the effects of holding both physical and virtual objects on haptic memory, which revealed that KFAE is stronger with physical objects (contribution 1). This study can provide a small piece of a larger understanding of the role of embodied interaction with virtual objects through multi-touch devices.

Chapter 4
An Evaluation Framework for Measuring Tool Embodiment

The analysis in Study 1 revealed that embodied interaction with objects is difficult to detect when using a touchscreen, specifically when KFAE is used as a measure of change in haptic memory. This may be due to the haptic nature of physical object interaction, which primarily depends on the tactile sensation of touch. Also, because virtual objects on a touch screen depend on visual stimuli, using a haptic sensation as a measure of virtual interaction may not be practical. Object embodiment is only a small piece of a larger puzzle. Many of the elements of embodied interaction that are of interest include the feeling of the technology “disappearing” or being incorporated into one’s body, and this chapter is about developing a framework that incorporates these ideas. While object embodiment is still relevant (after effects may help partly explain this “disappearance”, as objects become incorporated into the body schema), the use of tools is more central to this research investigation and more relevant in the context of measuring embodied interactions. While the effects of holding/grasping objects on our perception of body schema are relevant, a more canonical example of this “disappearing” is in the use of tools. Moreover, interaction with both physical and virtual objects is often mediated by physical or virtual tools. Tools are objects themselves that serve as intermediaries between our bodies and other objects that we intend to modify (e.g., we can use a stick in our hand to topple a vase that is out of our reach or use a virtual grabber to pick up objects that are out of reach). Thus, the next investigation will focus on a measurement of tool embodiment in virtual environments.

Embodied interaction has been discussed at length with the introduction of natural user interfaces (Wigdor & Wixon, 2011) and tangible user interfaces (Ishii, 2008) research. These methodologies have often discussed embodied interactions in the digital world by providing a bridge between the physical properties of objects and the virtual presentation of information and have been measured in many different ways. For example, using performance measures to evaluate different aspects of technology like hardware (Ryall et al., 2004, Watson et al., 2013) or software (Leithinger & Haller, 2007). On the other hand, other studies have considered affect, task load, and motivation when using touch and tactile interaction (Simons & Levin, 1998; Watson et al., 2013). This methodology uses validated scales to measure the experience of using an interactive system. These methodologies, however, do not provide a practical model that can be used as a measurement framework to test interactive technology. Finally, models from psychology, like *learning*, might be able to explain some aspect of embodied interaction with tools; however, measures of "learning" do not provide an explanation of tools "disappearing" and to what extent they can be made to "disappear". Therefore, a measurement framework to test interactive technology was constructed in this chapter to identify different aspects of using a tool in a virtual environment.

As a first step, an investigation of the use of attention as a measurable phenomenon that can help identify whether a person is embodied with a tool was conducted. This investigation revealed that people's attention would shift from the tool to the task when the tool is being used and therefore becomes embodied with the user. This chapter describes this measurement framework, which was then tested first for whether there was a measurable difference in attention to the tool vs. attention to the task (chapter 5) and second under what circumstances which might alter a person's experience of tool embodiment—when the tool breaks (chapter 6).

4.1 Framework Development

The aspect of forgetting a tool when skilfully using it was introduced by Heidegger in his discussion "Being and Time" in 1927. This characteristic of "invisibility" is often associated with technology being described as "natural" and "intuitive". For example, when using a tool like a hammer skillfully, people's attention becomes focused on the nail being hammered and the tool seems almost invisible. Heidegger (1996) and Dourish (2004) describe this phenomenon as "ready-to-hand". Therefore, we propose the following definition for tool embodiment:

Tool embodiment is a characteristic of skilled action in which the attention shifts from the manipulation of the tool to the goal action itself.

Heidegger (1996) described people's interactions with the world as skillful manipulation of the environment that consists of three states: ready-to-hand, unready-to-hand, and present-at-hand. Unready-to-hand describes when the tool is not functional or not working properly; attention will be focused on the tool and not the task at hand. Present-at-hand describes a state where the user observes characteristics of the tool or the object like its color or shape. Finally, ready-to-hand describes when a tool becomes "invisible" during an action. This effect of invisibility shifts the user's attention from the tool to the task at hand.

There are several studies that looked into the invisibility aspect of people's interaction in the environment. Change blindness is a well-known phenomenon that describes how people miss large changes presented to them (Ma, Xu, Wong, Jiang, & Hu, 2013). Large changes in people's surroundings can go unnoticed when this change is introduced between a black or white blink (Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997), mud splash on that specific change (O'regan, Rensink, & Clark, 1999b), or other distractors (Hochberg, 1986). Change blindness does not only affect visual perception but also can affect hearing, touch, and even multiple sensory modalities (Auvray, Gallace, Tan, & Spence, 2007b) where vision, touch, and hearing can be affected. Another phenomenon that affects our attention is *inattentional blindness*. An important distinction between change blindness and inattentional blindness is that the latter requires a cognitively loading task to induce lack of attention (Mack, 2003). These effects hint at a mechanism in the brain that filters unwanted or unimportant objects in the visual scene when concentrating on a task.

Attentional shift from near the hand to near the action is central in understanding how interacting with a tool affects people's perception. Previous studies have reported that attention near the hand is stronger when a tool or the hand is held stationary (Reed, Betz, Garza, & Roberts, 2010) or the tool is moved near the targeted stimuli (Abrams, Davoli, Du, Knapp III, & Paull, 2008). However, this research did not include a situation where a tool is used to skilfully manipulate other objects in the environment. For example, a study by Adam et al. (2012) compared two main conditions of a stationary tool and a dynamic tool—where a tool was moved forward and backward near the stimuli measured. This chapter concentrates primarily on how attention is affected during skillful use of the tool, which indicate a ready-to-hand state as proposed by Heidegger (1996) and Dourish (2004).

4.2 Locus of Attention Index (LAI)

Since the main interest of this research is in the relationship between detection rates in task and tool that provide an operationalization of the concept of ready-to-hand and unready-to-hand, this section proposes the *Locus of Attention* index (LAI). LAI is a simple measure of the relationship between detection rates in the hand and in the tool, calculated as follows:

$$LAI = \frac{DR^{Task} - DR^{Tool}}{DR^{Task} + DR^{Tool}}$$

Where DR stands for the detection rate (changes that take place in the *task* or in the *tool* gives us the *number of noticed changes in the task* and the *number of noticed changes in the tool*) divided by total changes in the task or the tool. LAI can potentially vary between +1 (all changes detected are in the task) and -1 (all changes detected are in the tool), with zero indicating that attention is equally likely to be on the task or on the tool. The LAI ignores the base rates of detection, i.e., it obviates whether the detection rates are low or high (which could vary between individuals) and focuses on which area (task or tool) has the dominant detection rate.

4.3 Framework Testing

The presented framework was based on Heidegger's three states of interaction with the world: ready-to-hand, unready-to-hand, and present-at-hand. First, the framework was tested for whether there was a measurable difference in attention to the tool vs. attention to the task (chapter 5) using the attentional shift measure. Second, under what circumstances a person's experience of tool embodiment can be altered—when the tool breaks (chapter 6).

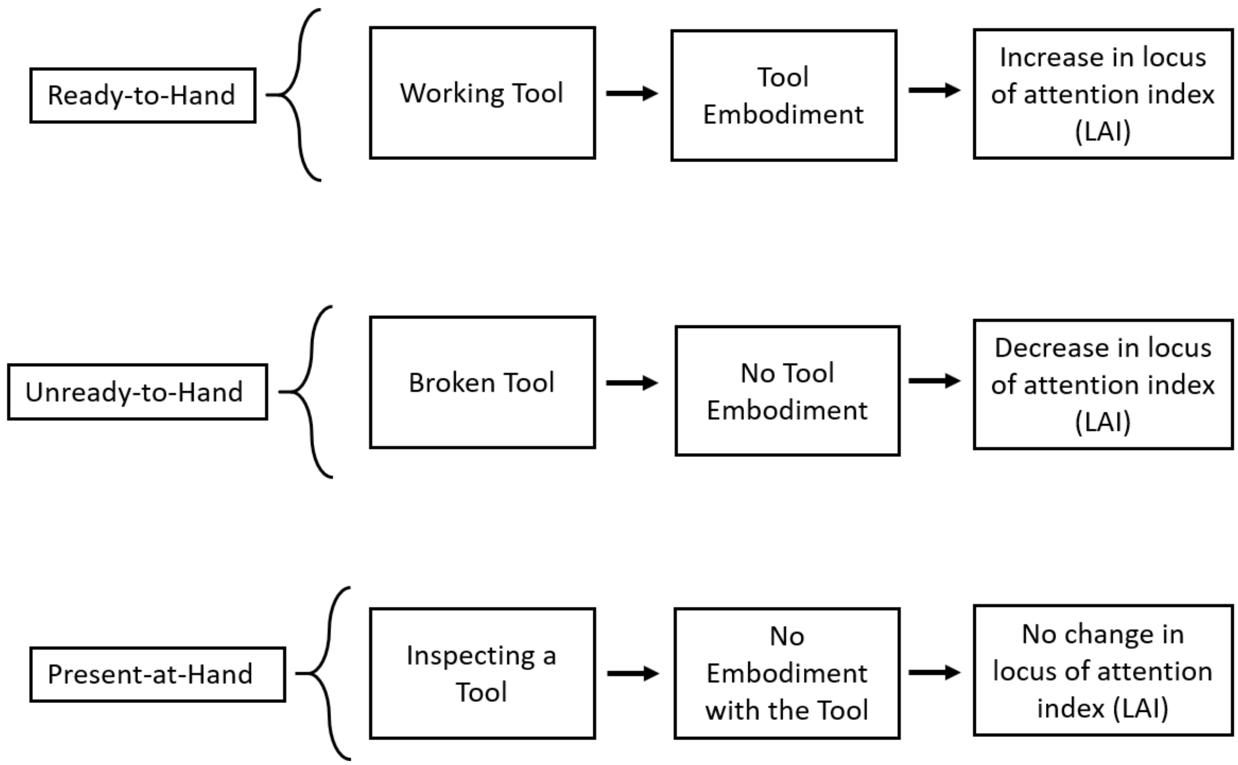


Figure 11: Tool Embodiment Framework that decomposes the three states of interacting with a tool as proposed by Heidegger (Ready-to-Hand, Unready-to-Hand, and Present-at-Hand).

Study 2 focused on the tool which was divided into two sections: near the hand and near the action. When a person is performing a skillful action with the tool (i.e., ready-to-hand), attention is directed toward the task and away from the tool. More specifically, this would lead to a lack of attention near the hand (e.g., the handle of a hammer) and more attention near the action (e.g., the nail being hammered). To measure attention near the hand we considered theories that measure *lack* of attention. For example, when we use a tool like a pen to write some notes, we do not pay attention to the tool but we pay attention to the task at hand. The same effect of invisibility proposed by Heidegger in readiness-to-hand when using a tool could therefore potentially be measured through this lack of attention.

Study 3 looked more specifically at two changes in attention to test the framework, tool breakage measured by the LAI and shift of LAI. The main goal of study 3 is to validate an operationalization of a measure of embodiment based on the ready-to-hand and unready-to-hand concepts with the introduction of tool breakage with different inputs. In the unready-to-hand situations, there were two types of breakage: a pickup failure and a drop failure. In the case of the block pickup failure the block would simply be dropped, even if the pressure applied to the tool or controller trigger, or the distance between the two fingers of the hand was correct. On the next try it would work again, and then again not after. In the drop failure the cube would stay stuck to the tool even if the triggers were release or the finger points were separate. By introducing tool breakage, the level of tool embodiment can be observed using the LAI measure for working and broken tools.

4.4 Framework Implications

The framework presented can be used to compare interactive technologies as a measure of readiness-to-hand and unready-to-hand situations. Particularly, this framework presents a direct measure of touch and tangible interaction using virtual tools with different inputs. Other interactive technologies could be tested in a similar way given that the following elements are present:

- The tool: a tool is an essential part of our framework. In this framework, the tool must act as an intermediary between a person and the task (e.g., a wrench, hammer, etc.)
- The action (Task to be accomplished): just holding a tool in one's hand will not affect attention. A tool must be used skillfully to measure attention.
- The stimuli: A stimuli on the tool and the action is also required. Augmenting the tool and the task with these stimuli in a separate locations.

Another interesting implication for the presented framework is the connection that this framework has with classic views on motor learning acquisition literature. The work of Adams (1971) and Schmidt (1975), for example, presents a different model of motor learning acquisition that describes an internal mechanism in the brain for accomplishing a motor activity. These models often describe a learning stage or a trial and error stage before engaging in the motor task activity which is associated with tool embodiment after accomplishing the learning stage. To reach the level of embodied interaction with the tool, learning how to use the tool must be accomplished fist. In both ready-to-hand and unready-to-hand situations, the user have reached a sufficient level of proficiency. Moreover, trial and error described by these classic views also can be observed in the tool embodiment framework in the unready-to-hand situation. When interacting with a broken tool a level of adjustment would occur which can also be seen as learning how to interact with the tool differently. Furthermore, another classical view on motor leaning acquisition that has been used in sports psychology defines three distinct stages: cognitive stage, associative stage, and autonomous stage. These stages also relate to the tool embodiment framework and future research can empirically test the effects of these stages on the presented framework. However, some connections can also be made, for example, in the cognitive stage, when user starts to theoretically learn how to use the tool and possible ways of using the tool. Next the associative stage would allow the user to make the connection between what was learned and how practically apply it with trial and error. These two stages are similar to present-at-hand where interacting with the tool is about observing its characteristics. Final autonomous stage requires little attention from the user to skilfully operate the tool which can also be similar to the ready-at-hand situation. This chapter focuses on a practical framework to test tool embodiment with virtual tools by using these three stages of interactions proposed by Heidegger.

4.5 Conclusion

This chapter presented a tool embodiment framework that was constructed based on Heidegger's phenomenon. This framework describes the three stages of interacting with the tool: ready-to-hand, unready-to-hand, and present-at-hand. The design of this framework for measuring tool embodiment in physical and digital media and the creation of the Locus of Attention Index (LAI) can be used to measure the level of tool embodiment by comparing attention to the task to attention to the tool (contribution 2). The next chapter will conduct a study to apply the tool embodiment framework and to compare a tangible user interface to a touch interface for a "wrench" tool in a ready-to-hand state (working).

Chapter 5

Study 2: Measuring Readiness-to-Hand through Differences in Attention to the Task vs. Attention to the Tool

Study 1 focused on using KFAE to measure haptic change with objects presented in the physical environment or on a digital surface. However, using KFAE as a measure presents a challenge for two reasons: 1- KFAE depends on measuring the tangible sensation of objects and 2- a variety of interactive technologies dependence primarily on visual interaction. Body schema, people's perception of their body boundaries, can be affected by haptic memory changes measured by KFAE which can also be affected by a combination of visual manipulations and actions. Performing a task skillfully requires both of these manipulations of visual perception and action. Several studies have labeled this combination as "sensory-motor contingency" which discusses how action and perception is an integral part of people's interaction in the world (Gibbs Jr, 2005b; O'regan, 2001). For example, using a physical tool, like a pen, requires knowing specific physical properties of that pen (e.g., a rigid object) and a set of actions to use that pen in the world (e.g., used vertically, used on paper). This skilful use of a tool changes how people perceive their body boundaries (body schema) (O'Regan, 2001). Several studies have demonstrated updates in the body schema by extending personal space (Cardinali et al., 2009; Maravita & Iriki, 2004) and estimating one's arm length differently (Maravita & Iriki, 2004; McDonnell et al., 1989). This chapter extends the concept of body schema updates to situations where a tool is actively used in a task. This chapter uses attention changes as a measure of tool embodiment in the physical and virtual environments.

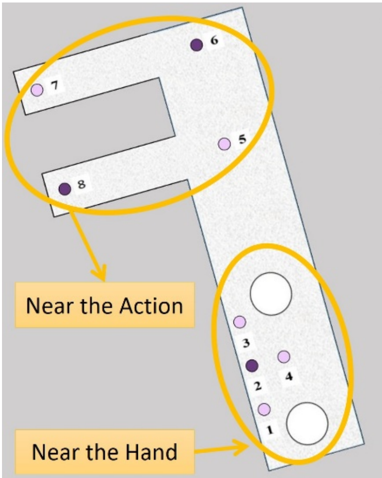
This novel measurement is based on the phenomenon described by Heidegger (1996) and Dourish (2001) that, when tool use is natural and intuitive, the tool becomes "invisible". When using a tool like a hammer skillfully our attention becomes focused on that task and less attention will be dedicated to the tool itself. Heidegger (1996) and Dourish (2001) describe this phenomenon as "readiness-to-hand". While Dourish (2001) discusses many different ideas of embodied interaction, there is a distinction between embodiment as a general phenomenon and being embodied with a tool. This chapter investigates these concepts using physical and virtual tools.

A missing piece in HCI research has been in finding an effective way to measure concepts like embodied interaction in virtual environments. Although several studies have looked at ways to evaluate different types of interaction like direct touch (Ingram et al., 2012), little work has been dedicated to understanding virtual tool embodiment. On the one hand, many researchers have designed interaction with the intention of creating natural and intuitive techniques (Guimbretiére & Winograd, 2000b; M. Hancock, Ten Cate, & Carpendale, 2009; Harrison et al., 2011; Wigdor & Wixon, 2011a), and techniques such as elicitation studies (Morris, Wobbrock, & Wilson, 2010b; Nielsen, Störring, Moeslund, & Granum, 2003; Wobbrock, Morris, & Wilson, 2009b) and consideration of the "continuum of knowledge" in the design process (Blackler & Hurtienne, 2007) have allowed for the creation of gestures that are familiar, and therefore perhaps more embodied. However, summative evaluations of these techniques have primarily used performance (Hespanhol et al., 2012) and self-reports (Grandhi et al., 2011) as measures. Consequently, there is a gap in our understanding of how to measure these complex, nuanced phenomena. In this chapter, we focus on a more direct measure of tool embodiment using a novel measurement of attentional shift.

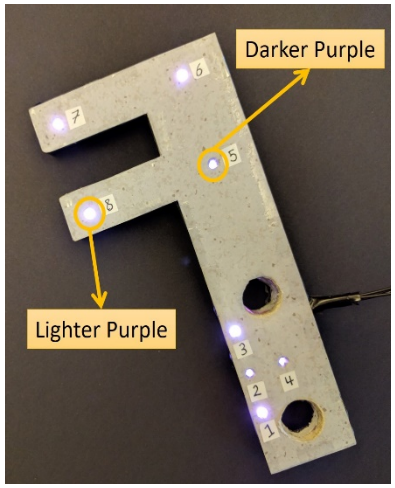
This chapter focuses on using attention as a measure of tool embodied interaction with physical and virtual tools. This part of the dissertation is a necessary part to test the tool embodiment framework as an evaluation technique for different virtual technologies. Finally, researchers can use this framework as guideline to design other novel technologies with embodied interactions.

5.1 Study Design

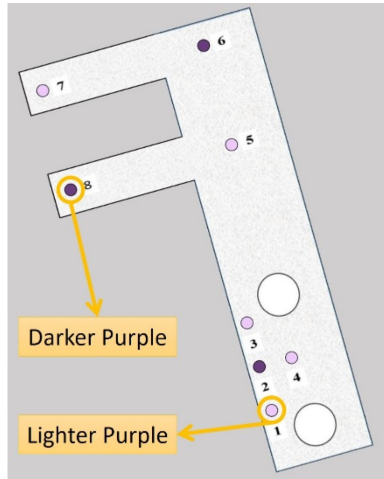
This study explores changes in attention when using both physical and virtual tools. More specifically, this study will concentrate on Heidegger's (1996) and Dourish's (2001) work in applying the phenomenon of "readiness-to-hand" to measure difference in attention between two tool locations: near-hand and near-action. Study 2 only tested "readiness-to-hand" which is the state that describes using a



a.



b.



c.

Figure 12: Shows two different tool types: b. physical tool, and c. virtual tool. a. shows two the secondary task stimuli: near the hand and near the action.

non-broken tool skilfully in a task, as described in the tool embodiment framework shown in Figure 11. This study was conducted using two main tool types: physical and virtual. “readiness-to-hand” was used as a main indicator of tool embodiment where attention is shifted from near the hand to near the action location of the tool.

5.1.1 Apparatus

For this study, a comparison of two similar tools was explored, with physical and virtual versions of a “wrench” tool and a “bolt” to be twisted, which were both usable on a two-dimensional surface as shown in Figure 12. This two-dimensional design was used because of the virtual environment’s limitation. For that reason, the physical tool (Figure 12b) was designed and controlled in a similar manner to the virtual tool. Designing the way the tool was to be controlled and used presented a challenge berceuse of the virtual environment’s two-dimensional design. A traditional wrench would be hold with a grip but in this study controlling the wrench would be used by the thumb and index fingers as shown in Figure 12. During the design process considering a different holding position was tested, for example holding the virtual and physical wrenches with a gesture using all fingers on one side and the thumb on the other. Piloting of this holding configuration proven to occlude more of the near hand stimuli that was on the tools. Therefore, this study used only the thumb and index fingers to control the both tools to minimize obstruction of the near hand stimuli. Since the main investigation of this study is to show differences in attention to stimuli to different tool locations, this holding configuration design was prioritized over other holding configurations that might be closer to the natural way people use the wrench. Through piloting the chosen holding configuration did not show any difficulties with subjects when using the wrench. The physical setup was also designed to make holding much easier with the thumb and index fingers. The first design that was piloted used a vertical surface where the tool was placed. Subjects reported difficulty and fatigue after few minutes of interaction. Therefore, a horizontal surface was chosen to better assists subjects interacting with the tool. The final design for this study was carefully considered to make the interaction as comfortable as possible, subjects did not report any issues during training. The main two aspects of using the tool for this study were making the tool comfortable to use and minimize any occlusion to the stimuli. The final design of this study provided a balance of these two aspects.

Physical Tool. The physical tool consists of several layers of cardboard foam (Figure 12) and is similar in appearance to a monkey wrench (a.k.a. gas grips) but is not adjustable. The tool had two holes for the index finger and thumb to be able to move and rotate the "wrench" to fit over a square piece of cardboard on a pin that allows it to swivel (Figure 12), which represented a bolt.

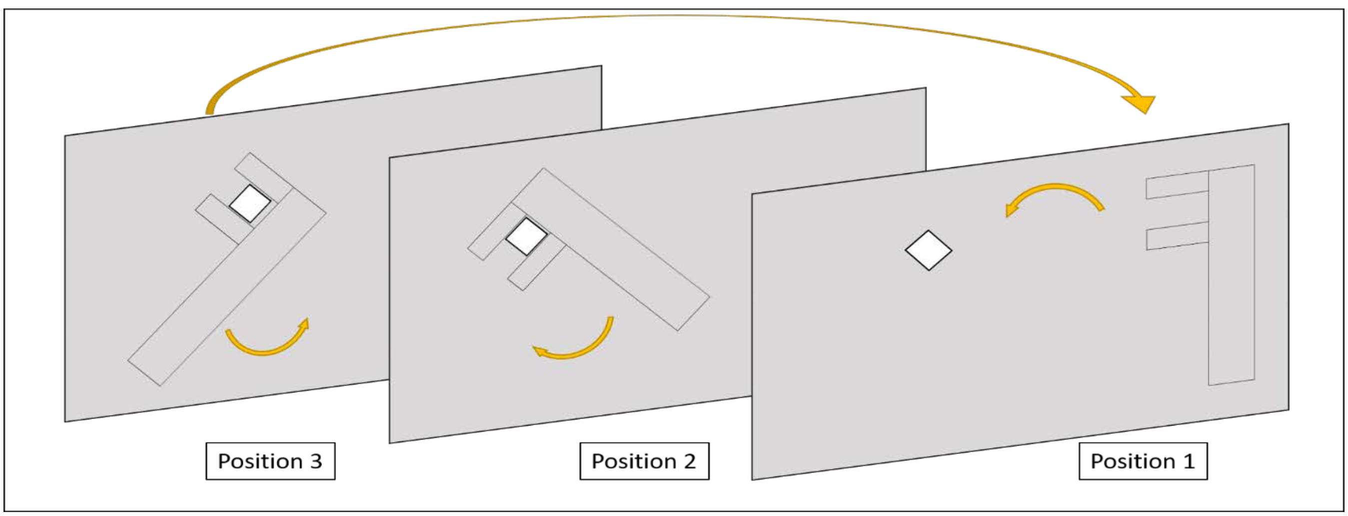


Figure 13: A. Shows Different Tool Positions in the Study.

As shown in Figure 12, two screens were used in both conditions. In the physical setup, we created a mock screen from cardboard foam that was firmly situated on top of a regular screen. In order to present stimuli on the tool, wired lights (Flora RGB Smart NeoPixel v2) and wires were placed in the middle layer of the tool and controlled by an Arduino board.

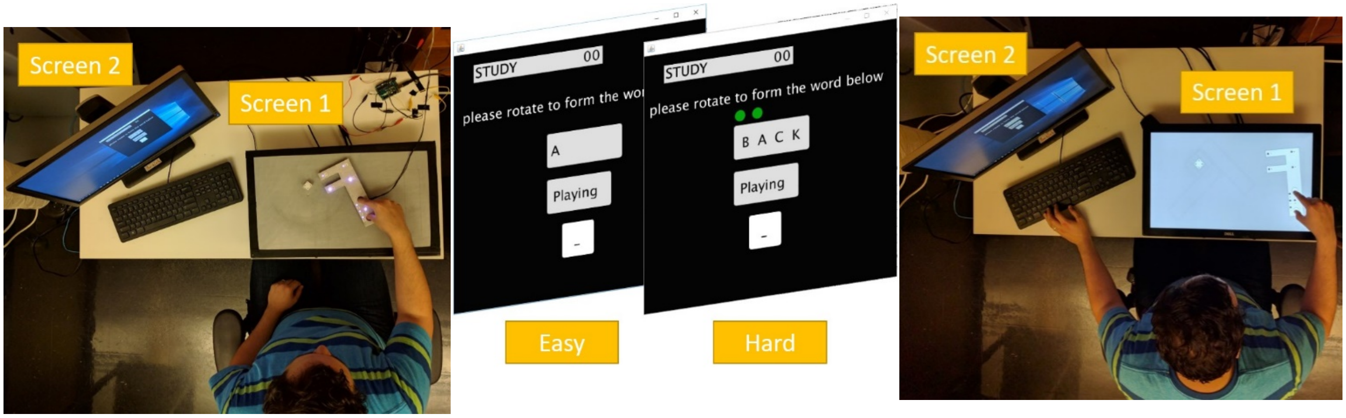
Virtual Tool. In the virtual setup (Figure 14c), the physical setup was closely mirrored, using white circles to represent the holes for the index finger and thumb, which could be used to move and rotate the tool to fit over a virtual white square representing the “bolt” that could only rotate. The virtual tool and object were developed in Processing using Java. Procesing2D was used as a physics engine to take touch input and simulate movements of the tool and the object. The Simple Multitouch Toolkit[2] was used to record touch points and enable touch interactions.

Screen Setup. Two 21-inch screens were placed on a 120 cm × 60 cm table (Figure 14, a and b). The table’s surface was 65 cm above the floor. Participants were seated on a chair where it was most comfortable for them to interact with screen 1 (Figure 14, a and c). Screen 1 was used to interact with either a physical or virtual tool and screen 2 provided feedback about the task. Screen 1 was placed horizontally and screen 2 was placed vertically. A keyboard was also available on the table for participants to provide input.

5.1.2 Task

We introduced a novel task of using either a virtual or physical tool in nearly similar conditions. Participants were asked to complete a primary spelling task and a secondary stimulus task during the experiment. The primary task was intended to be the focus of attention, with the secondary task as a means to measure shifts in attention.

[2] (http://vialab.science.uoit.ca/smt/)

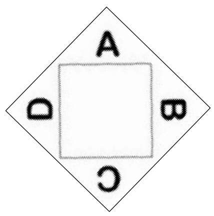


a. b. c.

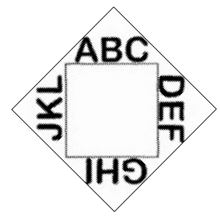
Figure 14: Study Location Setup. a. shows the physical study setup with a participant holding the physical tool. b. shows the second screen for the primary task. c. shows the virtual study set up with the participants holding a virtual tool.

Primary Spelling Task. Participants were asked to use either a virtual (Figure 12 c) or physical (Figure 12 b) tool to rotate a square “bolt” object (Figure 13) until a target letter was facing upward (only clockwise rotations were allowed). In the easy condition, the square object had 4 letters located on each corner (Figure 15 a) and participants were always asked to go to the “next” letter (i.e., one clockwise rotation). In the hard condition, the object had 12 letters, 3 on each corner (Figure 15 b), and participants were asked to spell a four-letter word, so the next letter was determined by the next letter in that word. After each letter, participants would return to the starting position. Thus, as shown in Figure 13, to complete an easy task the sequence was: Position 1, Position 2, Position 3, and return to Position 1 (starting point). To complete a hard task, the sequence always started in Position 1, then had one or more repetitions of Position 2, Position 3 (to get to the right letter), before returning to Position 1 (to indicate that letter was selected).

The second (vertical) screen showed the target letter/word and, in the hard condition, a green dot was used to indicate the current letter (Figure 14b). This feedback was initiated by the experimenter, who would press a button to advance when the participant returned to position 1. In the hard task, when the required letter was already facing up (e.g., when going from “A” to “B” in “ABLE”), participants were asked to make a full rotation of the object (4 rotations). The words used in the study were: ache, bail, bike, chef, dice, file, gild, held, idle, leak (physical condition); and able, back, bide, cage, deal, face, glad, half, idea, lack (virtual condition). Participants were instructed to complete as many spelling tasks (letters/words) as they could in a 432 second interval.



a. Easy "bolt" object



b. Hard "bolt" object

Figure 15: Object of manipulation "bolt"

Secondary Stimulus Task. Participants had to report any change that occurred on the tool (Figure 12) while completing the primary task. Both tools had 8 coloured circles/lights divided into near-the-hand and near-the-action sections (Figure 12 a) — this division was not known to participants. Participants were instructed to report any changes on the tool regardless of location. Half of the circles/lights (randomly selected) were a lighter purple colour and the other half a darker purple colour. The experimental system creates a change by shifting the colour from lighter to darker or vice versa. Changes took place 6 seconds apart, and only one change happened at a time. Participants were only aware that changes would occur (not how many, when, or where), and they were instructed to report changes that they noticed as soon as possible by pressing the space bar and then typing the number of the changed light and then "enter" to resume the letter/word completion task. In each condition, 36 near-hand stimuli and 36 near-task stimuli were changed ($2 \times 36 \times 6$ seconds = 432 seconds). Pressing space to report the change also paused the primary task timer.

S/I	Virtual						Physical				
	ToT	TT	VE	TT	VH	B	ToT	TT	PE	TT	PH

Figure 16: The order of trials was counterbalanced first by tool type (virtual/physical) and then by difficulty (easy/hard). This figure shows the order (1 of 4) with virtual-easy (VE) first, and the actual tasks are highlighted in orange (VE, VH, PE, PH).

5.1.3 Procedure

The experiment follows a within-participants design with two factors: tool type (physical vs. virtual) and task difficulty (easy vs. hard). We counterbalanced first by tool type, then by difficulty and so participants were assigned to one of four orders and either performed all physical trials first (both easy and hard), or all virtual trials first (both easy and hard). Figure 16 shows one of four orders used by participants.

Start (S). After participants were seated, study details were explained. Participants were reminded of the procedure after finishing each condition and wherever they needed help.

Ishihara Color Blindness Test (I). In this phase, participants completed the Ishihara Color Blindness Test (Ishihara, 1918). Because of the use of colores in the tool stimuli this test would screen participants for color blindness.

Tool Training (ToT). In this phase, participants were given 10 minutes to interact with a physical tool (Figure 12 b) or a virtual tool (Figure 12 c). Each participant was instructed to use their thumb and index fingers in the allocated position on the wrench-like tool (Figure 12) to rotate a square bolt-like object (Figure 15).

Task Training (TT). In this phase, participants were given 2 minutes to use the tool and practice completing the main task (VE, VH, PE, or PH).

Virtual Condition (VE and VH). In this phase, participants interacted with a virtual tool (Figure 12 c) to accomplish either an easy (VE) or hard (VH) task.

Physical Condition (PE and PH). In this phase, participants were asked to interact with a physical tool (Figure 12b) to accomplish either an easy (PE) task or a hard (PH) task.

Break (B). In this phase, participants were asked if they needed a break. Although breaks were allowed at any time when requested, longer breaks were more common (3-5 min) for a few participants.

5.1.4 Participants

Thirty-two participants (16 female, 16 male) aged 18 to 31 (*Mdn* = 22) took part in our study. Participants were screened for handedness (all reported to be right-handed), color-blindness (all passed the Ishihara Color Blindness Test (Ishihara, 1918)), and English proficiency (self-rating from 1-10; *M*=8.7). Participants were recruited via on-campus mailing lists and given $15 gift certificates to a local coffee establishment.

5.1.5 Measures

For the primary spelling task, the experimenter manually recorded task completion time and number of tasks completed. The number of rotations required to complete the task was computed using the letter sequence. For the secondary stimulus task, attentional shift was measured based on the reported changes noticed by participants. A percentage of missed stimuli was used for study analysis (recorded separately for near the hand and near the action). We also recorded the timing between stimuli presentation and space bar presses.

5.1.6 Hypotheses

Our study is designed to identify an attentional shift from the tool being used toward the task being done, and so our primary hypothesis is as follows:

H1: Participants will experience tool embodiment with both the physical and virtual tools, which will lead to an attentional shift in the secondary task from stimuli presented near the hand to stimuli presented near where the primary task is taking place (the action). This effect will lead to more missed stimuli and longer reaction times in the secondary task for stimuli near the hand.

Based on this attentional shift, we can further investigate the degree of embodiment by looking at the size of the difference between what happens near the hand vs. near the action. Thus, our secondary hypotheses relate to the size of this attentional shift, measured by the difference in number of lights missed and reaction times near the hand vs. action:

H2: As difficulty of the primary (spelling) task increases, participants will become more embodied with the tool, and therefore have a larger attentional shift.

H3: Due to its tangible, physical nature, participants will be more embodied with the physical tool and therefore have a larger attentional shift with the physical tool than the virtual.

We also had a hypothesis for our primary task measure:

H4: Due to its tangible, physical nature, we expect performance (number of tasks completed) to be increased when using the physical tool than the virtual one.

5.2 Results & Discussion

Because the measure of main interest in our study was the comparison between what happened near the hand and near the action in the secondary stimulus task, we report these findings first. We then report findings of the primary spelling task, followed by a correlational analysis between the number of rotations in the primary task and the overall number of missed lights in each task.

5.2.1 Secondary Stimulus Task

For secondary task measures (missed changes, reaction time), we performed a repeated-measures ANOVA with tool type (physical vs. virtual), difficulty (easy vs. hard), and location (near hand vs. near action) as within-participants factors. We also included order as a between participants factor to enable further investigation of order effects. Bonferroni corrections were used in all post-hoc analyses.

5.2.2 Missed Changes

There was a significant main effect of location ($F_{1,28} = 22.9$, $p < .001$, $\eta_p^2 = .45$), with participants missing more near the hand ($M = 60.7\%$, $SE = 3.7\%$), than near the action ($M = 50.4\%$, $SE = 3.1\%$). This finding supports the presence of attentional shift throughout all conditions (H1).

There was a significant interaction between tool type and location ($F_{1,28} = 8.1$, $p = .008$, $\eta_p^2 = .23$). Post-hoc analyses revealed pairwise significant differences between missed changes near the hand and near the action for both tool types ($p < .05$); inspection reveals that the difference was smaller for the physical tool (7%) than the virtual one (13%), which runs contrary to H3 (Figure 17). However, there was a significant tool type × difficulty × location interaction ($F_{1,28} = 5.9$, $p = .02$, $\eta_p^2 = .17$) which helps shed light on this finding (Figure 17). Post-hoc analyses revealed pairwise significant differences between missed lights near the hand and near the action ($p < .05$) for all except for the physical easy condition ($p = .18$). Thus, for the hard task, both physical and virtual had similar-sized attentional shifts (i.e., differences between

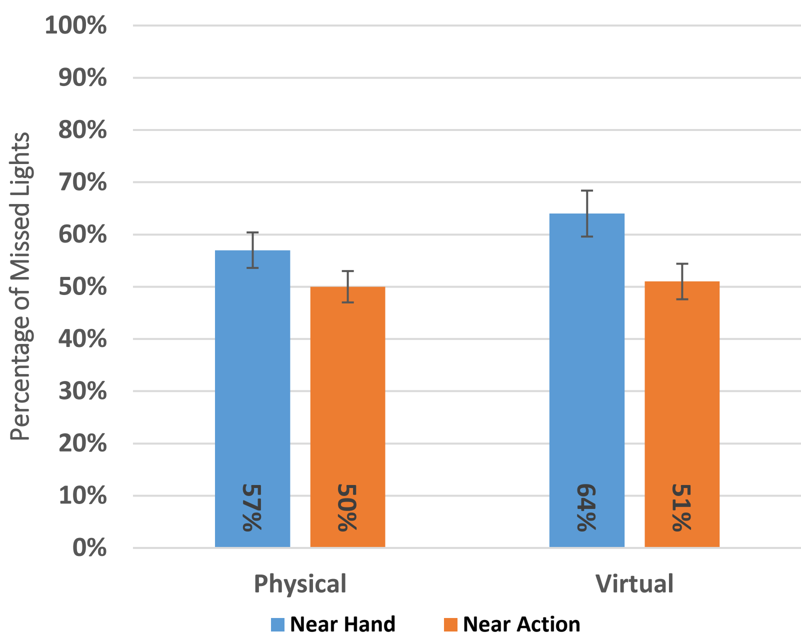


Figure 17: A 2-way Interaction (Tool Type and Location) of Missed Lights Measure. This indicate the strength of the national shift.

near-hand and near-action means), and the change in attentional shift is only larger for the virtual tool in the easy condition. We expect this is because the virtual tool generally required more effort, and so even in the easy condition, participants were more embodied with the tool (i.e., had to pay more attention to the primary task). Nonetheless, we cannot confirm H3 (larger attentional shift for physical), but this finding does provide partial support for H2 (larger attentional shift for difficult primary tasks).

There was also a significant main effect of difficulty ($F_{1,28}$ = 26.1, p < .001, η_p^2 = .48), with participants missing fewer stimuli in easy (M = 52.3%, SE = 3.4%) than in hard tasks (M = 58.8%, SE = 3.2%). This finding is unsurprising given the pattern of missed changes in the 3-way interaction, but may indicate that cognitive load was lower, leading to fewer missed lights. There were no other significant main effects or interactions. In particular, there was no main effect of order, nor interactions that involved the order factor.

5.2.3 Reaction Time

There was again a significant main effect of location ($F_{1,27}$ = 7.2, p = .01, η_p^2 = .21), as participants were slower to report changes that occurred near the hand (M = 2.16 s, SE = 0.09 s) than near the action (M = 1.93 s, SE = 0.09 s). This finding again supports the presence of attentional shift (H1).

There was also a significant main effect of tool type ($F_{1,27}$ = 6.7, p = .02, η_p^2 = .20), with participants taking longer to report the stimuli in the virtual condition (M = 2.17 s, SE = 0.09 s) than in the physical condition (M = 1.92 s, SE = 0.10 s). This may again indicate that there was higher cognitive load in the virtual condition, but there were no other significant main effects or interactions (except with order, discussed below), and so this increased reaction time did not depend on whether the lights were near the hand or near the action, and thus there is no support for H2 or H3 from the reaction time analysis.

There was a significant interaction between tool type and order ($F_{3,27} = 3.4$, $p = .03$, $\eta_p^2 = .27$). Pairwise comparisons revealed that, with the virtual tool, orders 2 ($M = 2.5$ s, $SE = 0.2$ s) and 3 ($M = 2.6$ s, $SE = 0.2$ s) had significantly higher reaction times than orders 1 and 4 ($p < .05$), but no other pairs of orders were different ($p > .99$). Moreover, orders 1 and 4 in the virtual condition and all orders in the physical condition were in the range 1.8 s-2.0 s, and so it is likely orders 2 and 3 which were anomalous, and only for virtual-tool reaction times. The only pattern we can discern for these two orders is that order 2 began with virtual-hard and order 3 ended with virtual-hard, and so this condition may have had higher reaction times due to being either first or last in the experiment. We don't expect that this effect influenced our findings about location differences, but may influence reaction time findings regarding tool type, although these were already inconclusive (H2 and H3 are still not supported).

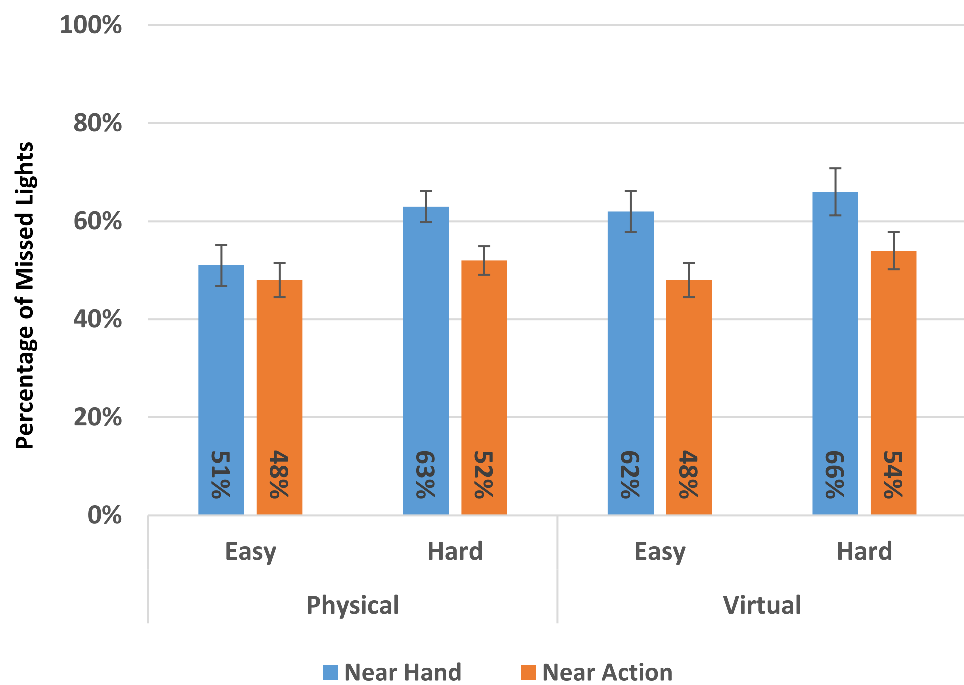


Figure 18: Shows a 3-way Interaction (Tool Type vs. Difficulty vs. Location) of Missed Lights Measure. Near the Hand Missed lights is Higher Indicating Attentional Shift.

5.2.4 Primary Spelling Task

We also analyzed measures from our primary spelling task using the same RM-ANOVA, without the location factor. Since participants completed as many tasks as they could in a fixed time, the number of tasks completed, and task completion time are perfectly correlated. Consequently, we present findings for number of tasks only. Bonferroni corrections were used for post-hoc analyses.

5.2.5 Number of Tasks Completed

There was a significant main effect of tool type ($F_{1,28}$ = 220.7, p < .001, η_p^2 = .89), with participants in the virtual condition completing fewer tasks (M = 26.7, SE = 1.1) than in the physical condition (M = 57.2, SE = 2.7), suggesting higher performance in the physical condition (H4). The main effect of difficulty was also unsurprisingly significant ($F_{1,28}$ = 316.1, p < .001, η_p^2 = .92), with participants completing more tasks in the easy condition (M = 57.1, SE = 2.5) than in the hard condition (M = 26.8, SE = 1.1). There was a significant interaction between tool type and difficulty ($F_{1,28}$ = 144.0, p < .001, η_p^2 = .84). Post-hoc analyses revealed pairwise significant differences between number of tasks for easy and hard conditions

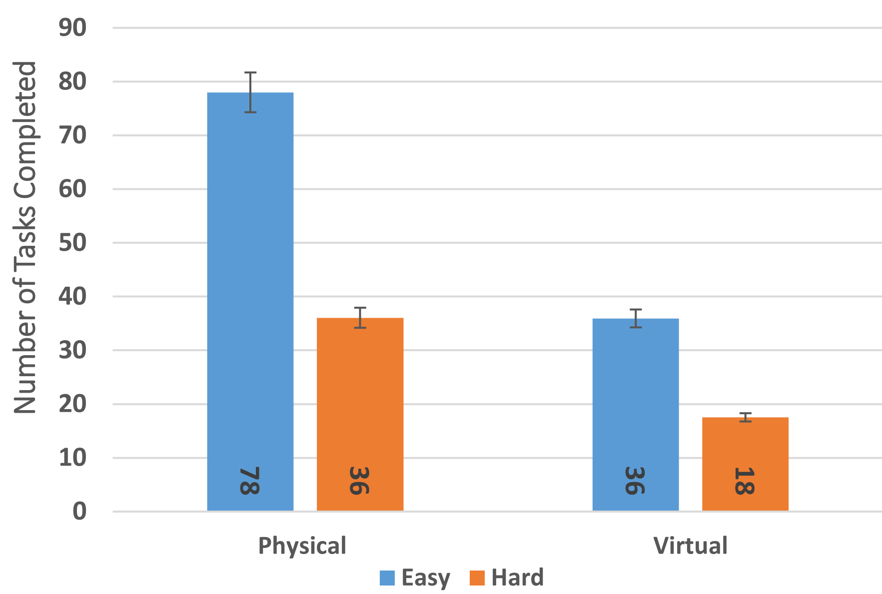


Figure 19: Tool type × difficulty interaction for number of tasks completed.

for both tool types ($p < .05$); inspection (Figure 19) reveals that the difference was smaller for the virtual tool (18) than the physical one (42). This interaction also suggests that performance was better in the physical condition (H4).

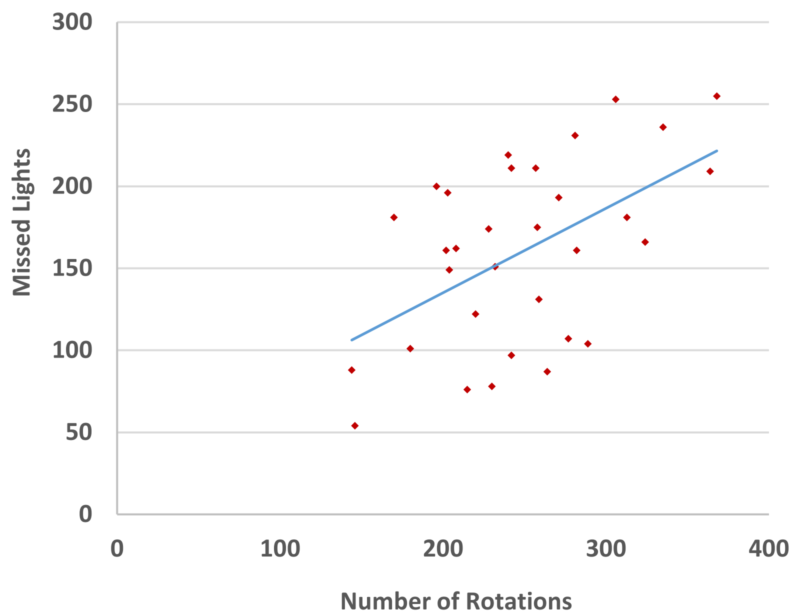


Figure 20: A positive correlation between the number of rotations and missed lights. This indicates how engaged participants were with the task.

There was a significant interaction between difficulty and order ($F_{1,28} = 11.8$, $p < .001$, $\eta_p^2 = .56$). Post-hoc analysis revealed that the only pairwise differences were between orders 1 and 4 in the easy condition (p = .048) and orders 2 and 3 in the hard condition (p = .04). This effect again seems to be related to when the virtual condition occurs, with the differences being exacerbated when the virtual easy is first (order 1) vs. last (order 4) or when the virtual hard is first (order 2) vs. last (order 3). This order effect is consistent with our hypothesis that people would perform better in the physical condition and does not interfere with our main findings.

5.2.6 Object Rotation Analysis

Due to the nature of our task, the number of tasks completed can be further dissected into the number of rotations performed within each task (i.e., to get to the subsequent sequence of letters—1 rotation per easy task, $M = 9$ rotations per hard task). Since the conditions were time-limited, the total number of rotations performed over the duration of each condition is an indication of how engaged participants were with the task. We suspected that this would be related more directly to how embodied they were with the tool, so we conducted a further correlational analysis using number of rotations as a measure and compared this to the number of lights missed overall in the secondary task to see if there was a connection between this measure and attention. There was a positive correlation between object rotations ($M = 248.4$, $SD = 55.7$) and total missed changes ($M = 160.0$, $SD = 15.5$), $r = .52$, $p = .002$, $n = 32$, as shown in Figure 20.

This relationship indicates that participants tend to miss more lights as the number of rotations they complete in the primary task increases (note that there were exactly 288 light changes for each participant, as these happened at regular intervals in a fixed time interval). Because the number of rotations only relates to the primary task, it is not possible to identify a relationship between increased rotations and lights missed specifically near the hand (to indicate attentional shift); however, this finding does suggest that higher engagement may be related to attentional changes in general.

5.3 General Discussion

A summary of this study findings is as follows:

- Overall, there were more missed lights and reaction times were higher near the hand than near the action for both virtual and physical tools, indicating an attentional shift predicted by our framework (H1).
- We expected difficult tasks to lead to a greater shift in attention (H2); however, only the physical tool followed this pattern.

- We expected the physical tool to lead to a greater attentional shift (H3); however, this hypothesis was completely unsupported, and instead, the difficulty imposed by the virtual tool led to more attentional shift even in the easy condition.
- Participants performed (expectedly) better with the physical tool than the virtual one.
- There was a correlation between number of rotations (as a measure of engagement) and the number of lights missed, indicating a connection between engagement/performance and attention.

This study provides the first step in the development of a tool embodiment framework based on the measure of attention. Of particular note, this study indicated a clear performance difference between physical and virtual tools, and without the additional measure, an experimenter may be tempted to conclude that the virtual tool is less “intuitive” or “natural”. The measure presented can therefore augment these findings and provides evidence that tool embodiment occurs with both. Furthermore, interactions between tool type × difficulty × location can help elucidate these performance findings and demonstrates a more nuanced story that can help explain that the virtual tool requires more cognitive resources, despite still providing a high level of tool embodiment.

5.4 Limitations and Future Work

While this study provides some of the first evidence that tool embodiment can be measured independently from task performance, this study presented only two instances of a tool (physical and virtual). Further studies could help to corroborate these findings and support more nuanced analysis involving differences in attention between vastly different tool types. Moreover, the study presented in this chapter only tested ready-to-hand state of using the tool which provided the first step to test tool embodied framework. However, to paint a more complete picture of measures of unreadiness-to-hand an introduction of intentional tool malfunctioning would be required. As presented in the previous chapter of the framework (Figure 11) there are two main stages of actively using the tool, the next study will address the unreadiness-to-hand of the tool embodied framework. This will provide a more efficient analysis of the level of tool embodiment.

5.5 Summary and Further Exploration

This chapter presented an investigation of tool embodiment using Heidegger's readiness-to-hand phenomenon. This work is the first to directly measure attention as evidence of Heidegger's readiness-to-hand phenomenon using both physical and virtual tools. Other studies have identified Heidegger's readiness-to-hand phenomenon using a mouse (Dotov, Nie, & Chemero, 2010), in which the mouse controls a pointer on the screen but failed to show how the attention is directed during tool use. The results of this study showed that when using a tool skilfully people's attention concentrates more on the near task compared to near the hand locations of the tool. This further indicates that using attention can be an effective measure of virtual tool embodiment. This study also applied the tool embodiment framework to compare a tangible user interface to a touch interface for a "wrench" tool in a ready-to-hand state (working), which revealed that both tools reliably led to a change in attention, but that the tangible tool had a greater change (contribution 3). The next chapter will continue to explore the tool embodiment framework and bring together both readiness-to-hand and unreadiness-to-hand of Heidegger's phenomenon of interaction.

Chapter 6

Study 3: Quantitative Measurement of Embodiment for Virtual Reality Input Alternatives

Study 2 (chapter 5) investigated whether there was a measurable difference in attention to the tool vs. attention to the task. This investigation was a necessary step in providing evidence that different interactive modalities (physical vs. virtual) can affect people's attention similarly. This chapter will further investigate tool embodiment with two different tool states (working vs. broken) and with different input alternatives (hand, controller, and tool). Research in VR has a long tradition striving to reproduce the sensations, perceptions and experience of being elsewhere (this is often referred to as presence (Witmer & Singer, 1998), or immersion (Reed et al., 2010)). An important part of this presence is interaction; people in an immersive VR environment need to be able to interact realistically with the objects in the environment in order not to break the illusion of immersion in an alternative reality. Presumably, in order to produce high-fidelity interaction in immersive VR environments we also need an understanding of the issues of human physical interaction in the real world. This chapter will focus on testing tool embodiment in a VR environment with different input alternatives.

From research in psychology and philosophy we know that interaction with objects in the environment is mediated by the physicality of our own body (Dourish, 2004; Heidegger, 1996). In other words, interaction in this context is not only a matter of how an external object is perceived by the person's sensory mechanisms but, perhaps more importantly, involves how the human body itself affects the physical object and how the overall interplay between both the object and the body is processed by the brain. To make things more complex, interaction with both physical and virtual objects is often mediated by tools. Tools are objects themselves that serve as intermediaries between our bodies and other objects that we intend to modify (e.g., we can use a stick in our hand to topple a vase that is out of our reach). Tools are particularly interesting in the context of this thesis for two main reasons: first, VR interaction is often implemented through the use of input devices (e.g., controller), which themselves are presented in

VR as tools that mediate interaction with virtual objects. Second, from evidence in psychology and theories from philosophy we know that tools become, in some ways, extensions of our own body when sufficient proficiency with the tool has been achieved. For example, expert tool users often refer to their tools as “almost part of their own bodies”, and that psychologists have found evidence that tool use can produce changes in body perception (people’s body schemas are enlarged by the use of a tool (McDonnell et al., 1989)) and even extend the size of peripersonal space (Cardinali et al., 2009).

The influential philosopher Martin Heidegger discusses this kind of embodiment as a tool being “Ready-to-hand” as opposed to “Unready-to-hand” and “Present-to-hand” as describe in chapter 4. A tool is “present-to-hand” when it is being examined (i.e., when it is considered as an object) and “ready-to-hand” when it is used in a way that it is not even noticed (i.e., “embodied”). “Unready-to-hand” is an intermediate state meaning that the tool is broken, or the person is still trying to develop sufficient skill with it.

This chapter investigates an operationalization of these categories for measuring embodiment and apply it to measure embodiment for three different ways to interact in virtual environments: interaction with a controller, a physical tool, and the hand. We propose the use of the shift of a locus of attention index (LAI) as an indicator of embodiment, which measures, through a secondary task, whether attention is directed at the task or the tool before and after a tool is “broken”. This study provides a validation of the measurement and a comparison about the embodiment levels of these three common ways to interact with virtual environments.

6.1 Goals

The main goal of this study is to validate an operationalization of a measure of embodiment based on the ready-to-hand and unready-to-hand concepts. This measurement is described in detail in 6.2.4 section. As a secondary goal, this chapter will investigate differences in embodiment between several VR input alternatives, which are described in detail in 6.2.2 section.

6.2 Study Design

In this study, participants were introduced to three different inputs in the physical environment in which they control the same virtual tool to accomplish the task in virtual environments. This study also adapted a dual task paradigm to measure difference in attention to the task vs attention to the tool. using these methodologies, this study will further investigate Heidegger's (1996) phenomena of ready-to-hand and unready-to-hand.

6.2.1 Apparatus and Task

Participants were immersed in a virtual reality environment provided through a latest Oculus Rift Model[3] that uses a head-mounted display to deliver the visuals as well as two sensors to track the position of the headset. In addition to the Oculus Rift, the set up included a tripod-mounted display, set looking down from high above a horizontal table (121.5 cm wide by 61 cm deep, 73 cm high). Tripod and sensors rested on another table (121.5 cm wide by 61 cm deep, 73 cm high) at the same level of the other table in front of the participant, and the experimenter sat to the right side of the participant (Figure 21 and Figure 23). The virtual environment was built with the Unity 3D[4] game engine and programmed in C#.

The virtual environment presented a table in the same height and position as in the physical environment, and a series of virtual objects to accomplish the task: an information display, a bookshelf with virtual cubes, and placeholders for the cubes (Figure 23). The display was presented with the appearance of a monitor standing on the table and showed information and instructions of the experiment to the participant. Messages consisted of: welcome - next word - game paused time to report (when game is paused only) - 1 is reported ready to continue (when number 1 is reported) - game running. The bookshelf contained a set of nine cubes in three levels, each cube with a letter inscribed on it. Four placeholders for the cubes appeared on top of the table and in front of the virtual monitor. Each

[3] https://www.oculus.com/rift/

[4] https://unity3d.com/

placeholder showed a letter. All objects necessary for the task fitted within the typical field of view of the participant.

The individual trials were based on a dual-task paradigm (Kahneman, 1973). The primary task was a simple puzzle in which participants had to successively find letter cubes from the bookshelf and place them in the placeholders marked with the corresponding letter, to complete a “word”. Participants were not bound by any order to place the letter cubes. When a word was completed, another set of cubes appeared and the cubes on the placeholders disappeared, revealing a new word to complete. The four-letter words were drawn randomly from a word bank of 1000 words; the set of nine cubes always included the four-word letter cubes of the solution, with an additional five “distractor” cubes that had other letters. The cubes were grabbed and released using the hinged virtual tool shown in Figure 22. The details of how participants controlled the tool vary per condition and are therefore described in 6.2.2 section.

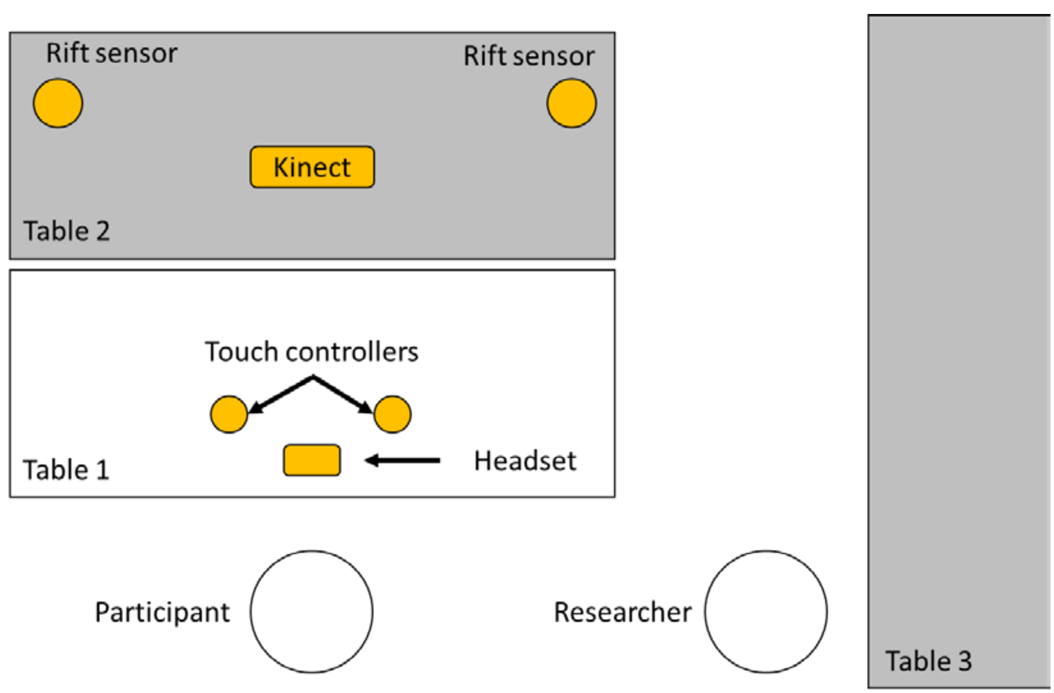


Figure 21: This figure shows the physical experimental set up. Table 1 will be represented in the virtual world.

The secondary task consisted of noticing and reporting the change of color of small visual dots placed in two locations: on the cubes (which we call the *task dots*), and on the tool (which we call the *tool dots*). There were two dots on each cube, located in the letter-side of the cube, for a total of 18 *task dots*. The location of the 12 *tool dots* is described shown in Figure 22. The dots could be green or red color at the beginning and changed at random intervals throughout the trial one change every 2 seconds, for a total of 150 changes during one 300 seconds trial (90 changes in task dots and 60 changes in tool dots). Participants were instructed to, while doing the primary task, pay attention to the dots and interrupt the primary tasks by clicking a button on their non-dominant hand as soon as they noticed a dot change. When this happened, numbers appeared besides the dots and participants reported verbally to the experimenter the number of the dot they saw changing, which the experimenter recorded. After this, the numbers would disappear, and the primary task could be resumed.

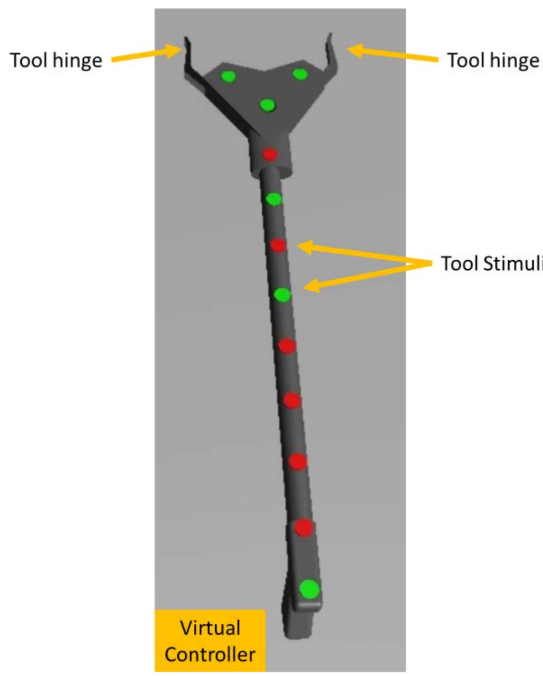


Figure 22: The Virtual Tool used in Study 3. This figure shows the tool and the colored dots that were used as a stimulus during the experiment.

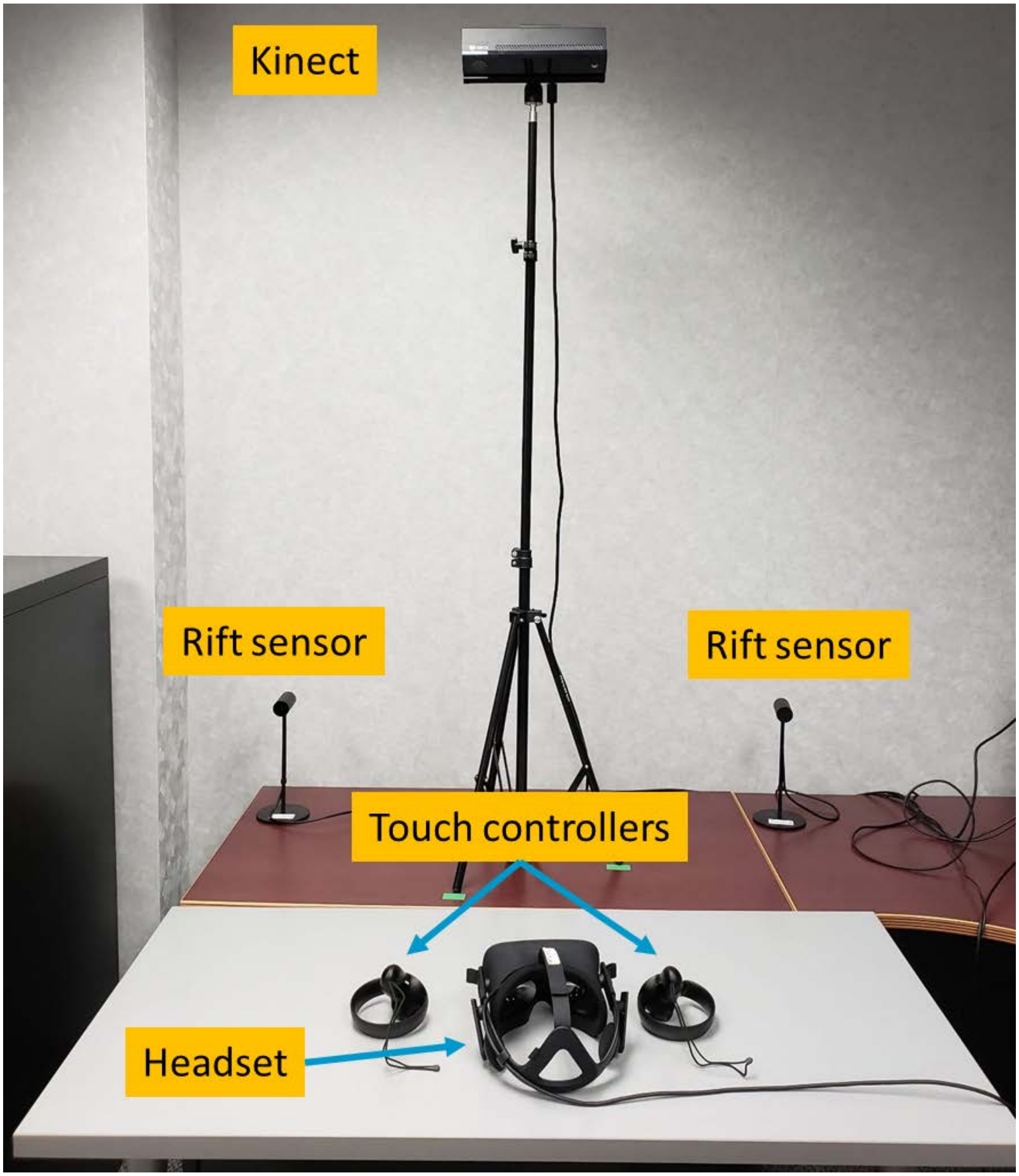


Figure 23: This figure shows the physical experimental set up and the location of Rift sensors and Kinect on the tables. Participants would not see this set up during the experiment but only will be exposed to the virtual set up.

6.2.2 Conditions

There are two main factors in the design of the experiment: the physical input (henceforth *input* for convenience), and the tool working state (henceforth *state*). We describe first the three input conditions and then the two state conditions.

6.2.2.1 Physical Grabber

In the physical grabber condition of the input factor (*grabber* henceforth) participants operated a grabber tool with the right (dominant) hand. The dimensions of the grabber are 45.7 cm × 10.2 cm × 2.5 cm and, without the controller, it weighs 136g. The tool was attached to the middle of the Rift right hand controller to track its position (the tool weighs 438g with the controller attached). Additionally, two infrared reflective markers made the tips of the tool visible to the Kinect sensor in order to detect the state

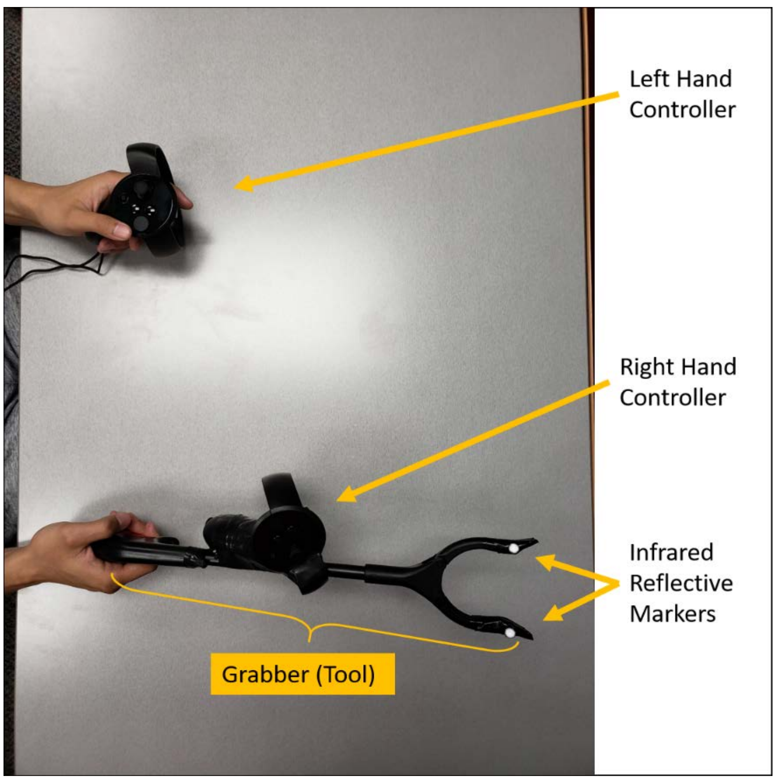


Figure 24: This figure shows the physical tool condition. Participant would be using the physical grabber to interact with the virtual environment. The right-hand controller will be also mounted in the physical tool for tracking purposes only.

of the tool (open or closed). On the left hand the participants held the Rift's left-hand controller, which allowed them to initiate the secondary task by pressing one of its buttons. Figure 24 shows the actual apparatus for this condition.

The grabber tool state is operated by a trigger mechanism, resembling that of a pistol. This mechanism is continuous (i.e., gradual pulling of the trigger results in gradual closing of the hinge, until the tool's tips touch each other). The virtual and physical versions of the tool are equivalent in dimensions in the real and virtual world respectively and similar in appearance (although the virtual tool has additional area to accommodate some additional dots).

When grabbing a cube, the distance between the markers determined whether the cube was in the process of being grabbed (maximum aperture to half aperture), held (half aperture to 80% aperture), or dropped (80% aperture to completely closed). These thresholds were determined to resemble physical behavior (closing the grabber too little would not allow to hold a cube sufficiently firmly, and too much pressure would result on the cube slipping from the tool). The physical tool has a spring mechanism (if the trigger is released the hinge opens to the maximum aperture), but it does not have any interface with the VR system to simulate additional resistance on closing (it is just a tool with controller and markers attached for pose tracking).

6.2.2.2 Rift Controllers

The second input condition uses the Rift's left and right controllers in the manner they are designed to be held. We refer to this condition as *controllers*. The hinge of the tool is controlled by the right-hand controller's trigger mechanism, which is also continuous. The left hand is used in the same way as in the physical tool condition as shown in Figure 25.

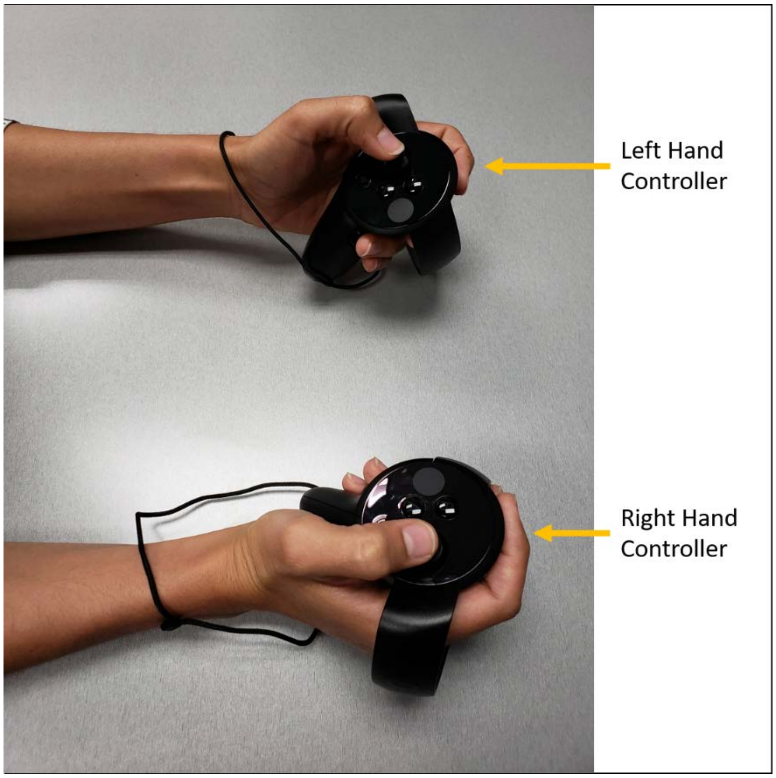


Figure 25: The oculus rift controllers that were used in study 3. The right-hand controller is used only in the controller condition and the left had controller is used thought out the experiment with all the conditions.

6.2.2.3 Hand

The third condition of the input factor required participants to use their own right hand to grab and release virtual cubes with the index and thumb fingers. In order to track the fingers, the experimenter attached a reflective marker to the tip of the two fingers, which tracked them in the same way as the grabber tool's tips as shown in Figure 24 . The thresholds for cube holding were also the same as in the physical grabber and calibrated for maximum aperture at the beginning of each phase. In all conditions the virtual appearance of the tool was the same (as in Figure 26).

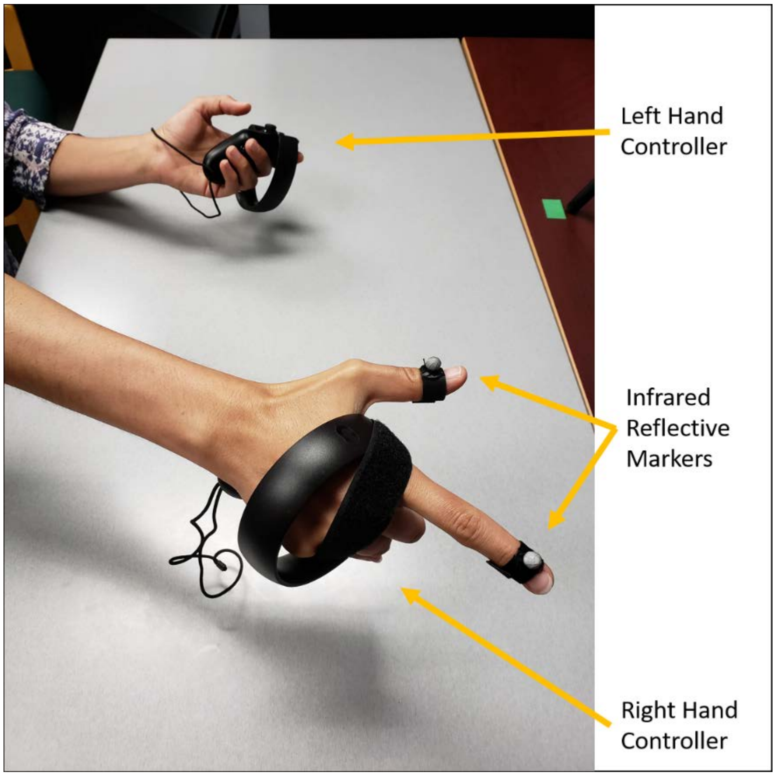


Figure 26: This figure shows the Hand condition. Participants used their thumb and index fingers to control virtual objects in the virtual environment. The controller on the right hand would be mounted for tacking purposed only.

6.2.2.4 Working

The first of the tool state factor's condition is the normal state, where everything works as it is described above.

6.2.2.5 Broken

The second tool state condition is the *broken condition*, in which the system simulates instances of tool failure at fixed intervals. There were two types of breakage: a pickup failure and a drop failure. In the case of the block pickup failure the participants would not be able to pick up the block, even if the pressure applied to the tool or controller trigger, or the distance between the two fingers of the hand was correct. Participants had to press the trigger several times to be able to pick up the block. Pick up failure operated with the following sequence: no pick up, pick up, no pick. In the drop failure the cube would drop with the following sequence drop, no drop, drop. Finally, participants were not aware that a *broken* phase would even exist. This small but necessary deception was addressed and approved in our Ethical application.

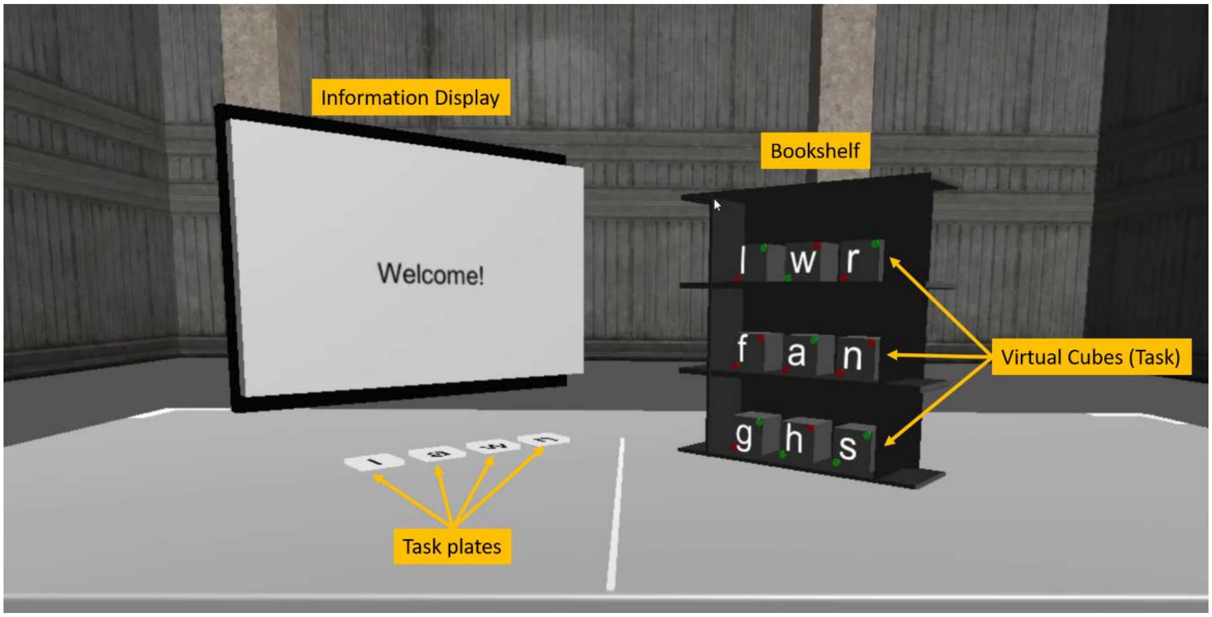


Figure 27: This figure shows the virtual experimental set up. On the right side the books shelf with 9 cubes would represent the task. On the left side the cubes must be moved to the task plats to complete the word.

6.2.3 Participants and Procedure

Sixty participants (32 female, 27 male, 1 undisclosed gender, 16 to 46 years old, age median 23) were recruited via on-campus mailing lists from the local university. Four additional participants took part but their data were excluded from the analysis due to technical difficulties with the VR apparatus. These difficulties occurred at the begging of the experiment and included some bugs in the game that were corrected. Participants were screened for handedness (all self-reported to be right-handed), and color-blindness (all passed the Ishihara Color Blindness Test (Ishihara, 1918)). Participants received $15 gift certificates for participating.

The study lasted approximately one hour and follows a mixed within-between-subjects design. The design is between-subjects for the physical input factor (*grabber, controllers, hand*), and within-subjects for the tool working state factor (*working or broken*). Participants were randomly assigned an input condition and a tool working state order, the latter to counterbalance possible order effects. Although we considered a within-subjects design for both factors, which would have resulted in better statistical power for the input condition comparisons we eventually decided for a between-subjects design in that factor because our pilots showed that there is a strong learning effect that could transfer between conditions and, more importantly, because to get good measurements in sufficiently long trials without training the participants too much or losing their interest would have been difficult if they had to carry out several hours of tests.

Participants gave first written consent, passed the Ishihara test, and underwent two phases of training. In the first training phase, they interacted with the VR environment by moving around the cubes (primary task). In the second training phase participants trained reporting the stimuli presented (secondary task).

The core of the experiment consisted of four trials described in Section 6.2.1 Apparatus and Task, alternating between working and broken two times, depending on the order assigned to participants (order 1: *working-broken-working-broken*—see Table 4). We refer to each half of the four trials as Phase 1, and the second as Phase 2. Each trial lasted exactly 300 seconds, in which participants would complete a variable number of puzzle task words but were always shown 150 changes. In the transitions between trials and at the end of the trials participants had a short break of approximately 5 minutes during which they also completed questionnaires about the previous trial.

	Phase 1		*Phase 2*	
Order 1	*Working 1*	*Broken 1*	*Working 2*	*Broken 2*
Order 2	*Broken 1*	*Working 1*	*Broken 2*	*Working 2*

Table 4: This table shows four trials that were assigned to participants during the study. Participants would start with either a working or a broken condition.

6.2.4 Measurements

This section describes the main measurements taken during the trials. There are measurements of attention, performance and engagement/presence.

6.2.4.1 Measures of Attention

The lowest-level measurement of attention in the experiment is the *absolute number of noticed changes* during a trial. Separating changes that take place in the *task* or in the *tool* gives us the *number of noticed changes in the task* and the *number of noticed changes in the tool*, respectively. Since the total number of changes actually happening was different for the task (90) and the tool (60) locations, it is meaningful and straightforward to normalize the detected changes by dividing the number of noticed changes by the overall number of changes, resulting in the *detection rate*, which can be applied to all changes, the task dot changes and the tool dot changes separately, for each type of trial.

Since our main interest is not in the base rates, but in the relationship between detection rates in task and tool that provide an operationalization of the concept of ready-to-hand and unready-to-hand, we propose the *Locus of Attention index* (LAI). LAI is a simple measure of the relationship between detection rates in the hand and in the tool, calculated as follows:

$$LAI = \frac{DR^{Task} - DR^{Tool}}{DR^{Task} + DR^{Tool}}$$

where DR stands for detection rate as described above (detected changes in the task or tool divided by total changes in the task or the tool). We obtain a LAI for each trial, resulting in four different LAI measurements per participant, two for each of the tool state conditions (working and broken). Notice that the LAI can potentially vary between +1 (all changes detected are in the task) and -1 (all changes detected are in the tool), with zero indicating that attention is equally likely to be on the task dots or on the tool dots, on average, across the trial. The LAI ignores the base rates of detection rates, i.e., it obviates whether the detection rates are low or high (which could vary much between individuals) and focuses on which area (task or tool) has the dominant detection rate.

The last measure of attention, which is also the measure at the highest level of abstraction is the *shift* of LAI between two consecutive working and broken trials (w-b) or vice versa (b-w). Depending on the order the participant has been assigned to, they might have two measures of $SLAI_{wb}$ and one of $SLAI_{bw}$ or vice versa. This second-order measurement intends to record, for a given interaction technique, how much changing the state of a tool (i.e., “breaking” or “fixing” it) affects the locus of attention. For example, a negative SLAIW−B (i.e., a decreasing LAI) would indicate that changing from a working to broken tool corresponds to detecting more changes on the tool, which may indicate a shift from ready-to-hand to unready-to-hand. Our calculations for the $SLAI_{wb}$ and $SLAI_{bw}$ follow the following formulas:

$$SLAI_{B-W} = LAI_{Working} - LAI_{Broken}$$
$$SLAI_{W-B} = LAI_{Broken} - LAI_{Working}$$

6.2.4.2 Performance, Engagement and Presence

Beside attention, we measured the number of words completed, which is inversely proportional to the time taken per word. Additionally, participants filled a Game Engagement Questionnaire (GEQ) (Brockmyer et al., 2009), and the *realism* part of the Presence Questionnaire (PQ) (Witmer & Singer, 1998) during the break after each trial. GEQ (Brockmyer et al., 2009) consists of 19 questions where each question in different categories have three answers: no, sort of, and yes. These questions are designed to produce a score between 19 to 57 where an increase in the GEQ scores represents more engagement with the game tested. These questions are meant to test different aspects of the game like immersion, presence, flow, and absorption.

Participants also filled the seven realism questions of the presence questionnaire (Witmer & Singer, 1998). This is because other questions are not relevant in our context (e.g., audio questions). Questions in the PQ are based on a 7-point Likert scale, with higher values indicating a more realistic experience.

6.2.5 Hypotheses

Generally, it is expected that the LAI measure shows differences between the working and broken conditions, as a reflection of the concepts of ready- and unready-to-hand. We were also interested in the comparison of LAI levels between the different devices. We expected that the tool input condition would show generally higher levels of LAI than the controllers, since it corresponds better with the virtual tool. We were not sure what to expect regarding the hand, since this could go both ways: if what is important for embodiment is that the VR visuals correspond to the physical reality, then we could expect LAI to be lower for the hand. If the LAI provides a measurement of how embodied we are with the tool, we would expect the hand to have the highest levels, since one cannot be more embodied than with their own limb. We also expected that the second-order measurement (SLAI) would become more pronounced for input conditions in which the LAIs are higher. In other words, if one is more embodied with a tool, it should become more apparent when the tool “breaks”. Finally, we expected the game engagement questionnaire and the presence questionnaire to follow roughly the same patters as LAI, with higher measurements for the working conditions, and different values for the different input conditions. However, due to the between-subjects nature of the experiment we would not be able to calculate correlations between the attention and questionnaire measures. The main hypotheses are encoded as follows:

H1. LAI is higher in the working tool state than in the broken tool state.

H2. Levels of LAI are different for the different input conditions.

H3. The physical input has higher levels of LAI than the controller condition.

H4. Shifts in the locus of attention between working and broken conditions (SLAI) are different for different input conditions.

H5(a/b). Levels of game engagement/presence are higher in the working than in the broken condition.

H6(a/b). Levels of game engagement/presence are different for the different input conditions.

The main hypothesis for this study is H1 where our main interested is in identifying that different levels of LAI corresponds to working vs. broken condition. All the other hypotheses were exploratory in nature.

6.2.6 Results

We address first the analysis of the data regarding the LAI (H1-3), as well as the absolute measurement of changes noticed. We then look at the shift of LAI, and the GEQ and PQ measurements. Finally, we include a section on non-planned or non-statistically testable observations. All analysis was run on IBM SPSS v.24. The data and the analysis scripts are included in the supplementary materials. All post-hoc comparisons between tools are corrected for multiple comparisons with Scheffe's procedure (Bohrer, 1967). Whenever the sphericity assumption is broken, we apply Greenhous-Geisser's correction Error bars in charts indicate 95% confidence intervals.

6.2.6.1 Locus of Attention Index Analysis

We run a mixed design repeated measures ANOVA with *input* (grabber, controllers, hand) as between-subjects factor and *state* (working vs broken) and *phase* as within-subject factors. The dependent variable is LAI. The ANOVA showed a main effect of the *state* factor ($F_{1,57} = 20.52, p < 0.001, \eta_p^2 = .265$). LAIs are lower (more attention on the tool) for the broken condition ($\mu_{LAI\text{-}broken} = .46$ and $\mu_{LAI\text{-}working} = .65$). Therefore, H1 is supported.

The ANOVA showed a main effect of the *input* factor ($F_{2,57} = 4.32, p = 0.018, \eta_p^2 = .132$). H2 is therefore supported by the collected data.

The post-hoc contrasts show that *Hand* is statistically separate from *Controllers* (p = 0.18), although none of the other two comparisons are significant. The average LAIs of the three input conditions (across both state conditions) are highest for the Hand ($\mu_{LAI\text{-}Hand}$ = 0.67) and lowest for Controllers ($\mu_{LAI\text{-}Controllers}$ = 0.44), with the Grabber in between them ($\mu_{LAI\text{-}Grabber}$ = 0.56). H3 is therefore not supported, although also not contradicted by the results of the analysis. Instead, if we interpret LAI as a measure of embodiment, Hand seems to be the most embodied type of input, and controllers the least, with the Grabber somewhere in the middle.

Phase had also a significant effect ($F_{1,57} = 8.51$, $p < 0.005$, $\eta_p^2 = .13$), with LAIs being higher in the first phase ($\mu_{LAI\text{-}first}$ = .61 and $\mu_{LAI\text{-}second}$ = .50). Since none of the other two-way or three-way interactions were significant, we do not perform a separate analysis per phase. Figure 28 shows the distribution of the indices split by input, state and phase.

To verify that *order* (working-broken, broken-working) did not interfere with the data we also run a parallel ANOVA that includes *order* as a between-subjects factor. None of the tests involving *order* were significant.

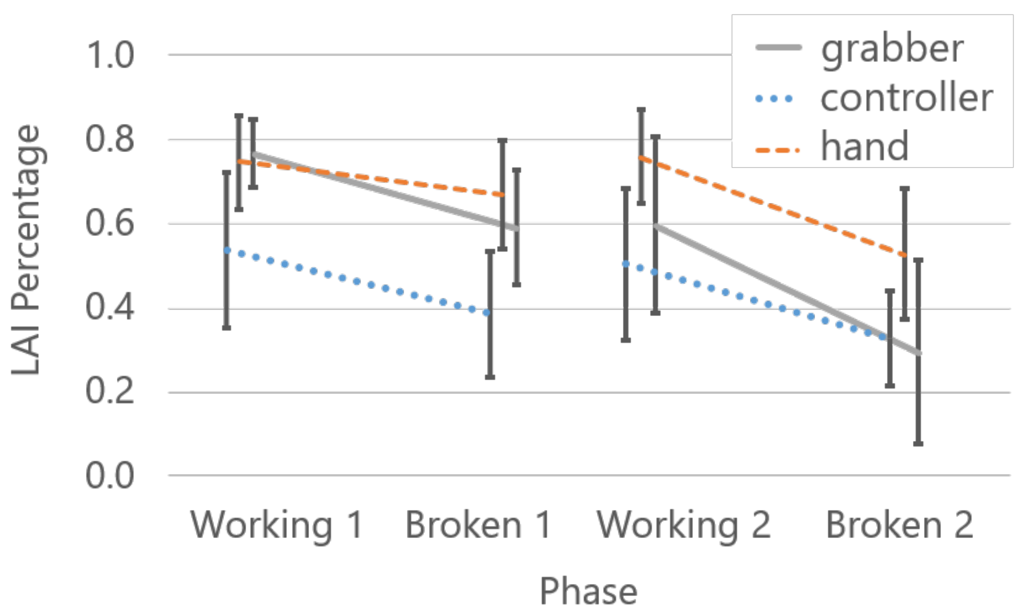


Figure 28: Average LAIs by state and phase, per tool.

6.2.6.2 Shift of Locus of Attention Index Analysis

To discern whether the SLAI measurements (working to broken and broken to working) can be a useful measure we calculated the two SLAI values for each participant and ran two ANOVAs with *input* and *order* as between-subjects factors. Although the average values are consistent with our expectations ($SLAI_{W-B}$ is negative on average and $SLAI_{B-W}$ is positive), neither of the two tests showed any significant main effects or interactions, leaving H4 without support.

6.2.6.3 GEQ/ Presence Questionnaire Analysis

We ran the same kind of ANOVA as in 9.1 with GEQ as the dependent variable. The only main effect was *state* ($F_{1,57} = 17.00, p < 0.001, \eta_p^2 = .23$). This supports H5a. The *input* test was not significant but came close ($F_{2,57} = 2.85, p < 0.066, \eta_p^2 = .09$), which means that there is not support for H6a. Figure 29 shows the distributions of the GEQ scores by input, state and phase. Similarly, the only main effect for the PQ dependent variable was *state* ($F_{1,57} = 83.66, p < 0.001, \eta_p^2 = .60$) (H5b supported), with none of the other tests being significant (H6b not supported).

6.2.6.4 Performance measurements

To complete the set of analyses, we ran the same kind of ANOVA described in the performance section (the count of words that participants were able to complete in the primary task). As expected, performance was affected by the state of the tool ($F (1,57) =758.89, p < 0.001, \eta_p^2 = .93$) as well as the phase ($F (1,57) =34.74, p < 0.001, \eta_p^2 = .38$), which essentially means that people get better in the second phase. There was also an interaction between state and phase ($F (1,57) =29. 40, p = 0.006, \eta_p^2 = .13$) that is of little interest to us.

More importantly, the between-subject input factor was not significant (F(2,57)=2.06, p = 0.137, ηp2 = .067), which suggests that, if the other measurements above showed some ability to discriminate between input tools, this is not because people performed better with one input type than the other; in fact, the performance averages are fairly closed and do not have the same ordering as the LAI measurements (μPerformance-Hand = 19.25 words, μPerformance-Controllers = 17.56, μPerformance-Grabber = 16.56).

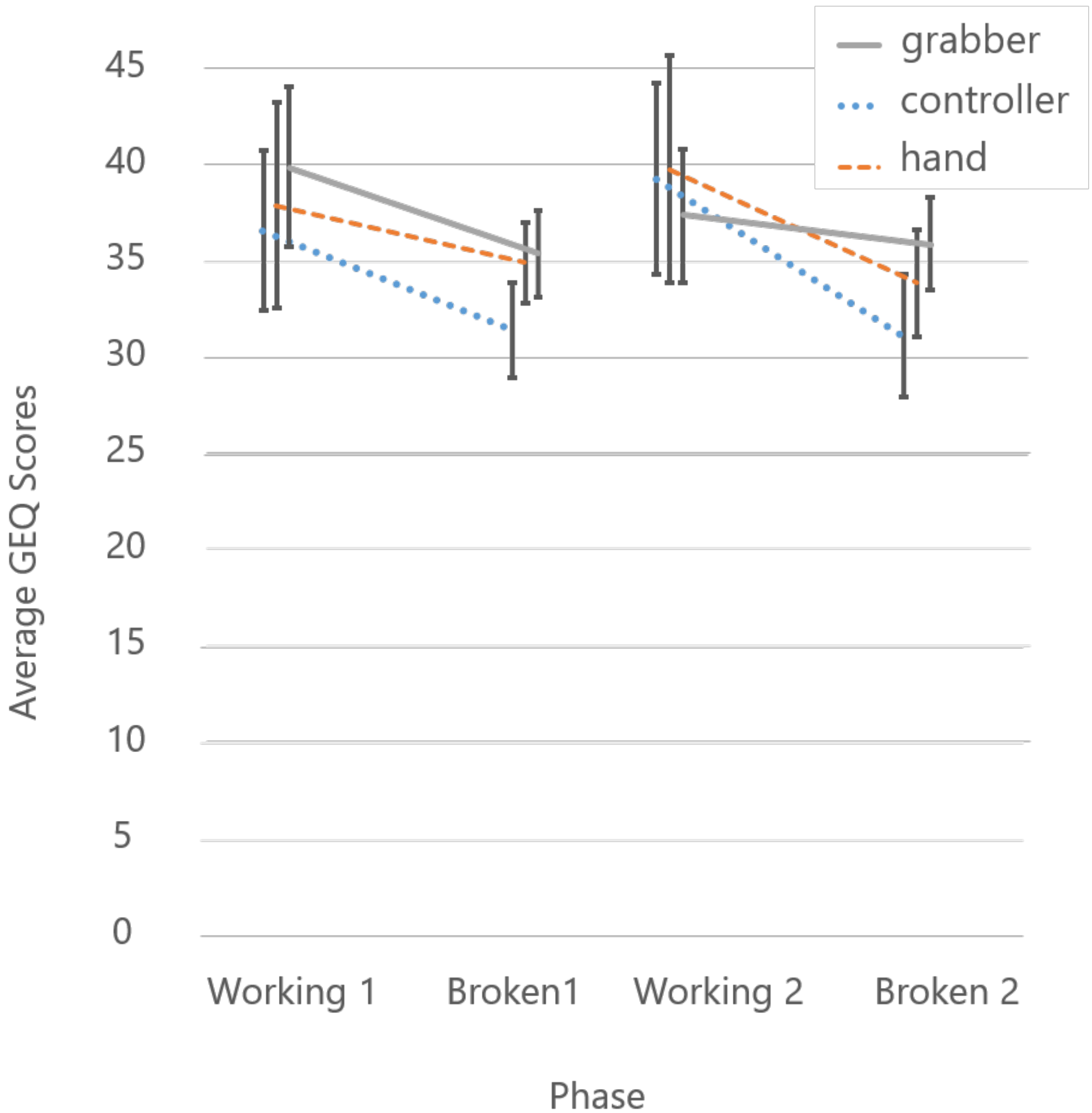


Figure 29: Average GEQ Scores by state and phase, per tool.

6.2.7 General Discussion

This work presents evidence of Heidegger's readiness-to-hand and unreadiness-to-hand in a virtual reality environment with three different controllers. A summary of our findings is as follows:

- The LAI measure was an effective way to measure embodiment-LAI was higher when the tool was working and lower when it was broken. This supports H1, indicating that, in the working condition, people pay more attention to the task and less to the tool, but in the broken condition, attention partially shifts from the task to the tool.
- Different interaction techniques had different LAI values, which supports H2.
- The hand had the highest LAI, followed by the grabber, and then by the controller; however only the hand and controller were significantly different, and therefore H3 was not supported.
- Our second-order SLAI measure did not reveal any significant differences, therefore H4 was not supported.
- The GEQ/presence questionnaires showed higher engagement/presence when participants used working tools than when they were broken, confirming H5a and H5b.
- While our performance measure (number of words completed) revealed, unsurprisingly, that participants performed better with working tools than broken ones and improved performance between phases, it was not able to discriminate between interaction techniques, indicating that our LAI measure provides a more nuanced understanding than performance measures alone.

Our study provides the first empirical investigation to support Heidegger's phenomenon of readiness-to-hand and unreadiness-to-hand using different interaction techniques in virtual reality. In particular, LAI can be used as a measure of tool embodiment showing different levels of the tool "disappearing" (i.e., attention shifting to the task rather than the tool) when a participant is engaged in the task. Notably, the LAI measure was higher with hand input when compared to the controller, indicating that hand interaction may be more embodied than current VR controllers (though this finding cannot currently be generalized beyond our specific designs for these techniques). More specifically, we can argue that participants were able to pay more attention to their task when using hand interaction than when using the Oculus controllers, despite there being no observable performance difference.

6.2.8 Summary

This study provides an empirical investigation Heidegger's readiness-to-hand and unreadiness-to-hand phenomenon. Particularly, H1 shows a clear difference between ready-to-hand and unready-to-hand situations which indicated the level of tool embodiment. Locus of attention was used as a measure of tool embodiment. This work presents the first strong evidence of directly measuring attention as evidence of Heidegger's readiness-to-hand and unreadiness-to-hand phenomenon. Other studies have identified Heidegger's readiness-to-hand phenomenon using a mouse (Dotov et al., 2010), in which the mouse controls a pointer on the screen but failed to link the tool directly. This study supports this dissertation contribution (4), where three different interaction techniques in a virtual reality (VR) environment (hands only, a physical prop, and a VR controller) in both ready-to-hand (working) and unready-to-hand (broken) states were tested. This further indicates that attention was focused more on the task when the tool was working but more on the tool when it was broken. This study contribution also helps to confirm the theoretical basis of the framework.

Chapter 7

General Discussion and Implications

This dissertation examined closely the phenomenon of embodiment with objects and tools and how to measure such phenomena. It was important for this work to identify a measurement for embodiment in the physical environment and then test the same measure in the virtual one. The ultimate goal of this dissertation was to start an investigation of virtual tool embodiment measurement that will assist designers to create interactive techniques that can break the barrier between the physical and virtual worlds.

This dissertation faced a challenge in bridging the experimental psychology literature with human-computer interaction literature. It was challenging to find an applicable phenomenon that can affect human perception with objects and tools which also be practical to test with virtual objects and tools. So, an exploratory approach was taken at the beginning of this work to find a phenomenon that can affect haptic and visual sensory perception. Several pilots were conducted to test the effectiveness of such phenomenon. After identifying several attributes that work well with interactive test in the virtual environment, a specific direction was taken. Tool embodiment was proven to be a more practical approach to test the phenomenon of embodiment in the virtual world. Study 2 and 3 concentrated on tool embodiment as a subset of the embodiment phenomenon.

The embodiment phenomenon as a terminology is used differently within different fields of study. In philosophy for example, embodiment discuss how bodily experiences as different from meta physical one (De Vignemont, 2011) and how people might experience out of the body sensations. Some of these effects have been reproduced using a VR system in the field of HCI (Ehrsson, 2007). The field of HCI, however, focuses on imperial investigation into the embodiment phenomena with different test methods like asking participants the level of embodied interactions or showing different performance levels with certain interaction. So, the field of HCI applies a more practical methodology to investigate embodiment or embodied interactions but lacks a strong measure to identify if such phenomena exists with each and different interactions.

There has been a lack of a unified theory that explains embodiment and this work does not pretend to provide one. However, this dissertation identifies first some of the pitfalls of objects embodiment in the virtual environment and second a practical methodology and a measure to test tool embodiment. This methodology and the measurement presented in this work could be the first pillar in completing a comprehensive framework for embodiment and embodied interactions.

This chapter will present the overall discussion and implication of the three empirical studies conducted. These studies have been a result of an identifiable gap in literature from both experimental psychology and HCI. In addition to philosophical work of Heidegger which was used to construct tool embodiment framework which was tested with study 2 and 3. The next section will first discuss the implications of this work with the field of experimental psychology and second will presented a discussion and implication of study 1, 2, and 3 to the field of HCI.

7.1 Body Schema

Body schema refers to how people perceive their body boundaries (Head et al., 1920). This concept has been tested with few empirical studies where using a tool would extend the personal space of the user, indicating tool integration into the body (Maravita & Iriki, 2004; McDonnell et al., 1989). This integration could also be referred to as embodiment. Body schema is something that people have perceived and developed over time therefore it is also possible to look at ways to change body schema. The change to body schema in this work is investigated as integrating new objects and tools into the body schema.

This dissertation builds on concept of body schema with a specific measure based on attention (LAI) that can be applied in physical and virtual environments. Finding an appropriate measure is instrumental in detecting body schema integration. Different perceptual modalities could be at work to detect body schema integration, this research only implemented haptics and visual changes in perception.

Chapter 2 of this dissertation cited some of the work that discuses different perceptual modalities and how they affect human experience. For example, the work introduced by Gibson in visual after effect showed the effects of a stimulus on visual perception (James J Gibson, 2014). Other work (O'regan, 2001b) also showed the vital connection between different sensory experiences. For example, feeling something on the skin could affect the visual sensation and vice versa. The amalgamation of these studies presents us with an interesting gap in terms of embodiment. This answers the question what the sensory modalities are being activated when it comes to embodiment and body schema integration. Therefore, having a measure for each sensory experience and test this measure with different objects and tools would be instrumental in understanding body schema integration. This work introduces this idea and a specific methodology to test different ways interaction using objects and tools.

Another aspect that effects body schema and sensory experience is the activity itself. Several studies in sensory experience research advocates the critical importance between perception and action. The activity of exploring objects or using tools to accomplish a task is part of people's daily life. This activity could be an exploratory activity like discovering the dimension of a shape or a goal directed activity like accomplishing a task with a tool. These two types of activity have been explored in this dissertation with Study 1 with objects and Study 2 and 3 with tools.

Object and tool embodiment in terms of body schema integration is still an ongoing research that have been implemented with physical objects and tools. This thesis investigates how virtual objects and tools can affect people's sensory perception similarly. HCI research can use this investigation to design interactive technology where the technology can seem invisible. This aspect of invisibility would help create interactions that are part of the user's physical world where holding a physical pen would be equivalent of holding a virtual pen to accomplish similar tasks. This dissertation with three studies strives to find measure of object and tool embodiment to investigate when technology disappears.

7.2 Object Embodiment (study 1)

Study 2 undertook the phenomenon of Kinesthetic Figural After Effect (KFAF) as a measure of object embodiment. After holding an object for some time people would experience an after effect when they hold another object. This after effect can be measured by the displacement in the reported experienced size of the new object after stimulation. This method was tested with both physical objects and virtual ones. So, in essence an effect is carried with the participants after stimulation and the user's experience would change. This relationship would influence people's judgment of physical object interaction very strongly as was observed in Study 1 results. Virtual object interaction, however, did not show any significant changes indicating a decreased reaction to virtual object stimulus.

In terms of body schema this study points out that the body's amenability is stronger with physical object integration. This impales that people can easily integrate physical object into their body schema, but this does not happen as easily with a virtual object on a table top screen. Moreover, this does not mean that virtual object has no effect on the human body, in fact the original research that tested for KFAE reported that it would enough to imagine holding a physical block to stimulate the after effect. Virtual object integration may require additional stimulus to approximate the experience to the physical block. For example, adding haptic cues in addition to the visual stimulation would most probably show a stronger effect.

Study 1 was an exploratory study that investigated ways to bring more quantities measure to the embodiment experience. With this start, this work realized some of the pitfalls of object embodiment and changed the direction into a more practical manipulation. In the next two section tool embodiment will be discussed that shows promising results in to the phenomenon of embodiment.

7.3 Tool Embodiment

Object embodiment was an interesting research direction to pursue that helps in understanding the phenomenon of embodiment and to start identifying a measure of body schema. However, measuring object embodiment presents few challenges like applicability to the virtual interaction and the type of measurement used in after effect phenomena. First, the aspect of applicability to the virtual world presents a challenge since most of the virtual interactions are completed using a medium (e.g. mouse, keyboard, touch screen) it is difficult to isolate what is the object that was integrated into the body schema in these scenarios. Although, it is not impossible to measure object embodiment in the virtual world but the lack of specific understanding of the phenomenon of embodiment makes it more challenging to identify specific elements of objects embodiment. Second, the type of measure that is taken with after effect phenomena depends on two phases; measurement phase and stimulus phases. This dependency is problematic since not all object interactions in the virtual world have a specific stimulus phase and the interaction is again delivered via a medium. For these reasons, tool embodiment was the next logical step to study and measure.

People's interaction with the world is often mediated by a tool of some kind. And although tools are objects themselves, they are not the object of manipulation in accomplishing the task at hand. Tools act as a layer that is needed to accomplish once task. For example, a golf player will need to use a tool to hit the ball to the right direction on the field. Tools in this context is just a medium and not the focus of attention. However, there are some examples where this relationship is difficult to identify. A pianist for example would use a piano as a tool but in the same time it is the object of manipulation to accomplish the task. Similarly, a football player kicking the football to the right direction also do not distinguish what is the tool and what is the object of manipulation. This work differentiates between these scenarios and others where a physical or virtual tool is need as a separate entity to accomplish the task at hand.

Another important aspect of using a separate tool is the measurement taken. Object embodiment, as was mentioned above, required two separate phases of measurement, where with tool embodiment measurement can be taken during the task itself. Study 2 and 3 implemented dual task paradigm when people would report changes while accomplishing the task.

Implementing tool embodiment with physical and virtual tools accompanied a construction of tool embodiment framework and a measure that depends on visual perception. The framework identifies three ways of interacting with the world. Heidegger (1996) presented a philosophical account of these three ways of integration, this work identified these three stages and tested two of them; ready-to-hand and unready-to-hand. although this work is phenomenological in nature, we drew a connection between ready-to-hand and embodiment. Embodiment, as we mentioned before, is generally still a philosophical construct and to test it an empirical measure is needed to identify the difference between these stages.

7.3.1 Study 2

Study 2 sought to investigate how people's visual perception changes when using a tool, virtual and physical. This step showed that selective visual attention in a dual task is a reliable measure with both virtual and physical tools. This study also shows that tool embodiment can be independently measured from performance measures. Although performance measures could correlate with tool embodiment; however; they alone can not explain tool embodiment accurately and directly. The results of this study presented a clear and significant distinction between visual attention to the tool and attention to the task. This indicates and help us understand that the aspect of forgetting the tool when using it can be one of the main factors that conclude changes in the body schema and ultimate be embodiment with the tool. study 3 in the next section will farther explore tool embodiment with a specific measuring of locus of attention index (LAI).

7.3.2 Study 3

Study 3 provides the first empirical investigation to support Heidegger's phenomenon of readiness-to-hand and unreadiness-to-hand using different interaction techniques in virtual reality. Heidegger's phenomenon of readiness-to-hand in this desertion is used in parallel with tool embodiment. In these situations when the tool used skillfully to accomplish a task the tool becomes part of the user's body and in essence disappear. Body schema can also be explained by readiness-to-hand situations where tool body integration occur which changes the body boundaries to include the tool at the moment of use. This investigation provides the first account of using selective attention as a measure to connect these concepts.

7.4 Implications of using LAI for HCI

The LAI measure provides a more direct method for measuring embodied interaction for interactive technologies. In Study 3, we used a controller, a hand, and a grabber in the physical world to control a virtual tool. The virtual tool and objects used in the study were identical in terms of the visual stimuli presented. This technique would allow other interactive technologies to use LAI to measure tool embodiment and embodied interaction. Our work can be applied as a measure provided these elements exists in the experimental setup:

- A tool: in order to measure embodiment with a tool, there must be some mediator between a person's body and the artifacts they are interacting with. This can be a virtual or physical tool.
- Dual-task paradigm: future experimenters must determine a primary task to complete with the interactive tool in question, and then can use our secondary task of detecting changes of some kind. In our study, this was a change of color, but to calculate LAI, there need only be a sequence of changes of any kind.
- Tool breakage: an important aspect of the LAI is having both working and broken states. It must be possible to have the tool malfunction in some controlled way by the experimenter.

The combination of these elements provides the necessary information to calculate LAI and begin to draw conclusions about a tool's level of embodiment.

7.5 Summary

This chapter summarized the findings and discussed implications of three studies presented in chapters 3 through 6. First, although object embodiment can be an interesting direction to investigate the phenomenon of embodiment and body schema integration, it proved to be difficult to apply to all virtual interactions. Furthermore, tool embodiment framework was constructed to reflect several phenomenological and psychological concepts presented in the literature. The next two studies (Chapter 5 and 6) had tested tool embodiment framework using selective attention as measure of readiness-to-hand. The investigation presented in this dissertation revealed some important aspects of the embodiment phenomenon with objects and tools, specifically how to measures these interactions in the virtual environment. Finally, this work brought together literatures from experimental psychology and investigated its applicability to HCI filed, by uniting these two fields this dissertation provides a first step to empirically investigate a unified framework of the phenomenon of embodiment in virtual space.

Chapter 8

Conclusion and Future Work

This dissertation has presented an investigation of possible ways to measure embodied interaction in the physical and virtual environments. The focus was first on identifying a suitable phenomenon that can be measured. Secondly, constructing a framework that can be used by designers to test for embodied interactions. Embodied interactions in virtual environments have not been directly measured. The literature review presented in Chapter 2 revealed a gap in finding a measurement of embodied interaction in physical environment that can be applied as a measure of virtual one. Moreover, measuring embodied interactions with tools also revealed some philosophical and epistemological discussion (Heidegger, 1996). New interactive technologies are increasingly being used in every aspect of people's daily life. However, existing work does not provide any direct measure of how natural and intuitive one interactive technology is over another. Furthermore, most of the research in the field of HCI on embodied interactions depends on performance measures, self-reported questionnaires, or measures like proprioceptive drift used in rubber hand illusion study. This dissertation presents the first step in providing insights into finding a reliable measure of embodied virtual interactions with virtual tools.

Study 1 (Chapter 3) was motived by the lack of applicable measure of object interactions. Through the literature review in the area of experimental psychology, a direct measure of a change in the haptic memory was identified. Kinesthetic Figural After Effects (KFEA) was used to test haptic memory changes when interacting with physical objects. The same test then was applied with virtual objects. The results of this study motived the design of a new measurement of tool interaction. Chapter 4 presents the framework for tool embodiment which was tested in study 3 (Chapter 6) with both physical and virtual tools. Chapter. Chapter 7 (study 3) tested a new measuring technique which shows the level of tool embodiment. The results of study 1 showed that the measuring technique was hard to apply with technologies and motivated the investigation of tool embodiment (study 2 and study 3). This allowed a more extensive analysis of the tool embodied phenomenon which demonstrated that the tool embodiment framework can be used to test virtual tools. Furthermore, these studies provided insights into how to better design new interactive technologies taking advantage of the physical world in virtual interactions.

8.1 Contributions

This dissertation presented three studies that investigated embodied interactions with objects and tools. Study 1 contributed to the general understanding of how to measure these phenomena in virtual environments and provided the necessary feedback for the next steps in the design of new measurement. Study 2 and 3 contributed to the design of the tool embodiment framework and tested this framework in physical and virtual situations. This section presents the contributions of this research.

8.1.1 A Study Comparing the Effects of Holding both Physical and Virtual Objects on Haptic Memory

The first study empirically evaluated haptic perception of physical and virtual objects via KFAE measurement. Using this measurement revealed that physical objects affect memory of haptic perception much stronger than virtual objects. These results suggested that interacting with virtual objects on a table top screen cannot be considered more natural than the physical world interaction. This study also provided further insight into improving the measuring technique of the embodied interaction with virtual tools.

8.1.2 The Design of a Framework for Measuring Tool Embodiment in Physical and Digital Media and the Creation of the Locus of Attention Index (LAI)

This framework describes the three stages of interacting with the tool: ready-to-hand, unready-to-hand, and present-at-hand. The design of this framework for measuring tool embodiment in physical and digital media and the creation of the Locus of Attention Index (LAI) can be used to measure the level of tool embodiment by comparing attention to the task to attention to the tool.

8.1.3 A Study that Applies this Measurement Framework to Compare a Tangible User Interface to a Touch Interface for a "Wrench" Tool in a Ready-to-Hand States

Tool embodiment framework was designed and tested in study 2 (chapter 5). Study 2 was the first step to investigate a general change in attention to the task vs to the tool. Through a laboratory study the tool embodiment framework was tested showing how physical and virtual tool can be measured via attention. The results of this study provided more insights into developing a better measuring technique to evaluate the tool embodiment framework with a broken tool with different input modalities.

8.1.4 A Study that Applies this Measurement Framework to Compare Three Different Interaction Techniques in a Virtual Reality (VR) Environment in both Ready-to-Hand (Working) and Unready-to-Hand (Broken) States

Study 2 tested tool embodiment further by introducing a locus of attention index (LAI). This index will serve as a direct measure of tool embodiment to test virtual tool with different inputs. This study also looked at different tool states (working vs broken) that directly links to ready-to-hand and unready-to-hand phenomena. Designers of different interactive technologies would be able to use the tool embodiment framework to evaluate technologies for embodied interactions. The LAI measure will help to identify the level of tool embodiment and assist in predicting the level of embodiment the user is exhibiting.

8.2 Limitations

Although the three investigations of this dissertation were fruitful and provided much needed insight into the embodied cognition phenomenon, these studies had several limitations. For study 1, the KFAE measure was not able to detect any effects with virtual object interaction. This presented a challenge in constructing an effective measure of such interactions with virtual technologies. Nevertheless, this study provided important design lessons and future directions of the next studies, looking at tool embodiment with physical and virtual interactions.

Tool embodiment framework in both studies was conducted in a laboratory setting to maximize control of the study factors. The framework requires several elements that needs to be included so that it can be used to measure interacting with technology. A tool to be held is required that should be actively used to accomplish a task. A stimulus, several distributed stimuli should be available on the tool and the task that are presented during active use of the tool. There should be an activity that engages users to accomplish a goal. All these three elements need to be present to have an effective evaluation of the interactive technology using LAI measure.

Finally, the concept of readiness-to-hand describes interaction with the physical world in a general sense where everything in the environment could be a combination of tools to accomplish a task. As Wigdor (2011) suggested in his example the keyboard, the mouse and the monitor are tools used to accomplish the task of writing on a word processor (Wigdor & Wixon, 2011b). This work, however, only looked at held tools by hand, physical or virtual, to accomplish a goal directed behavior.

8.3 Future work

Study 2 was the first attempt to test the tool embodiment phenomenon in the physical and virtual environments. The virtual environment was implemented using a touch screen. In study 3, however, the tool embodiment framework was tested in the VR environment with different inputs. A future work for the tool embodiment framework is to implement and test the framework with other interactive technologies. for example, augmented reality (AR) presents another opportunity to test tool embodiment. With a combination of physical elements with virtual objects and tools in the environment. Tool embodiment can be tested using augmented reality.

The measure used with the tool embodiment framework hinged on the amount of attention detected on specific areas in the environment. Finding other measures and correlating them with the presented framework would add more validity to the framework. For example, the tool embodiment framework does not consider the haptic perception of touching different physical tools and objects.

For study 3, one particular technology can be used to further analyze the data collected. Eye tracking can present another opportunity to specifically identify and detect where users are looking during active motor performance. A combination of attentional stimuli and eye tracking technology would allow for better detection of the tool embodiment measure. This combination would also allow for the development of live tool embodiment detection system. For example, a score with the level of embodiment using LAI measure and eye tracking can produce live results of tool embodiment.

8.4 Summary

With the increased availability of interactive technologies that uses several virtual tools, a direct and effective measure of these interactions is essential. The research presented in this dissertation investigated embodied cognition phenomena. Study 1 showed an understanding of haptic object interactions. The next two studies investigated the construction of a tool embodiment framework which was accompanied by an empirical investigation of a direct quantitative measure of attention. This investigation also opened further research questions. While the immediate work includes iterations on different physical and virtual tools, future work may consider applying them to different technologies with augmented reality interactions. More importantly, this research revealed the need for more examination into the embodied cognition phenomenon and the importance of using embodied measures to improve the evaluation of new interactive technologies.

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