Bodily Resonance: Exploring the Effects of Virtual Embodiment on Pain Modulation and the Fostering of Empathy toward Pain Sufferers

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Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

in the
School of Interactive Arts and Technology
Faculty of Communication, Art and Technology

SIMON FRASER UNIVERSITY

Spring 2021

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Abstract

Globally, around 20% of people suffer from chronic pain, an illness that cannot be cured and has been linked to numerous physical and mental conditions. According to the BioPsychoSocial model of pain, chronic pain presents patients with biological, psychological, and social challenges and difficulties. Immersive virtual reality (VR) has shown great promise in helping people manage acute and chronic pain, and facilitating empathy of vulnerable populations. Therefore, the first research trajectory of this dissertation targets chronic pain patients' biological and psychological sufferings to provide VR analgesia, and the second research trajectory targets healthy people to build empathy and reduce patients' social stigma.

Researchers have taken the attention distraction approach to study how acute pain patients can manage their condition in VR, while the virtual embodiment approach has mostly been studied with healthy people exposed to pain stimulus. My first research trajectory aimed to understand how embodied characteristics affect users' sense of embodiment and pain. Three studies have been carried out with healthy people under heat pain, complex regional pain syndrome patients, and phantom limb pain patients. My findings indicate that for all three studies, when users see a healthy or intact virtual body or body parts, they experience significant reductions in their self-reported pain ratings. Additionally, I found that the appearance of a virtual body has a significant impact on pain, whereas the virtual body's motions do not.

Despite the prevalence of chronic pain, public awareness of it is remarkably low, and pain patients commonly experience social stigma. Thus, having an embodied perspective of chronic pain patients is critical to understand their social stigma. Although there is a growing interest in using embodied VR to foster empathy towards gender or racial bias, few studies have focused on people with chronic pain. My second trajectory explored how researchers can foster empathy towards pain patients in embodied VR.

To conclude, this dissertation uncovers the role of VR embodiment and dissects embodied characteristics in pain modulation and empathy generation. Finally, I summarized a novel conceptual design framework for embodied VR applications with design recommendations and future research directions.

Keywords: chronic pain; virtual reality; virtual embodiment; sense of ownership; sense of agency; empathy

Dedication

To all my family members and friends.

To all my colleagues in the Pain Studies Lab at Simon Fraser University.

To all the people longing for light as they struggle with pain in the dark.

With much love to:

my mother and father, who always support what I do;

my husband, who encouraged me throughout my doctoral journey;

and my son, who inspires me to be a better person.

To all those who have blazed the trail before me,

those in the trenches alongside me, and

those who will follow in my footsteps.

Acknowledgements

I would like to express my deepest gratitude to all the people who made this Ph.D. dissertation possible.

First and foremost, I would like to thank my senior supervisor, Dr. Diane Gromala. You're a strong and wise woman, and you're my role model for life. Words really can't express how grateful I am for your unflagging commitment to my scholarship and to everything else as well. The time you've spent with me and my work has been a wonderful gift, and your intellectual and creative pursuits have shaped my life in ways you can't imagine. Thank you.

I'm also very grateful to my other two supervisors, Dr. Chris Shaw and Dr. Dave Fracchia. Your interest, care, and support have made my work infinitely better. Chris, your sharp mind gave me commentary that repeatedly cut right to the point. Thank you. Dave, you've been very supportive and considerate of my research topics, and your invaluable feedback motivated me to improve my dissertation. Thank you.

To my other academic mentors and exemplars, Dr. Kunlin Wei, Dr. Yuanchun Shi, Dr. Chun Yu, Dr. Qiong Wu, and Dr. Yansong Cui. Thank you all for letting me be a part of your labs; working with you inspired me to pursue a Ph.D. and motivated me to keep moving forward. I want to thank Henan Diao, Shaolin Zeng, Xinxing Wang, Pegah Kiaei, Bhairavi Warke, Gary Li, and Zahrah Ofoghi for being supportive colleagues and helping me conduct my research. I want to especially thank Paul Carlucci for his help in proofreading this dissertation. Thank you.

I also owe a huge debt of gratitude to my family. First, I want to thank my parents, who always agree with my choices and give me freedom to pursue my dreams. Caesar, thank you for giving me the support and always being there to listen to all my ideas. And thanks to my parents-in-law for babysitting Louis while I frantically finished up my dissertation. Thank you.

To Simon Fraser University, you supported and funded my scholarly research through different fellowships and awards throughout all my graduate studies. I owe special thanks to Dr. Carman Neustaedter, dean of the Faculty of Communication, Art and Technology (FCAT), for always being helpful and providing insightful feedback on my research. I also want to thank Dr. Halil Erhan, the graduate chair, Dr. Cheryl Geisler, and Lisa DaSilva and Tiffany Taylor, the graduate program assistants at SIAT, for providing support and assistance. Further, I want to give my gratitude to my internal examiner, Dr. Owen Williamson, and my external reviewer, Dr. Mel Slater. Dr. Slater and his colleagues' work builds a solid foundation for this dissertation, and I started my work on their shoulders. Thank you.

Last but not the least, to all my study participants, especially the patients who are struggling with pain and the many challenges it creates. Without your participation, this dissertation would not have been possible. Thank you.

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List of Acronyms

ACC	Anterior Cingulate Cortex
AR	Augmented Reality
BIBS	Body Image Body Schema
BPA	Brachial Plexus Avulsion
BCI	Brain Computer Interface
CRPS	Complex Regional Pain Syndrome
EC	Embodied Cognition
EEG	Electroencephalogram
EMG	Electromyography
fMRI	Functional Magnetic Resonance Imaging
FoV	Field of View
GSR	Galvanic Skin Response
GCT	Gate Control Theory
HADS	Hospital Anxiety and Depression Scale
HCI	Human Computer Interaction
HMD	Head-Mounted Display
HR/HRV	Heart Rate/Heart Rate Variability
IASP	International Association for the Study of Pain
MT	Mirror Therapy
ME	Motor Execution
MR	Mixed Reality
NRS	Numerical Rating Scale
PLP	Phantom Limb Pain
PNI	Peripheral Nerve Injury

QoL	Quality of Life
RHI	Rubber Hand Illusion
RCT	Randomized Controlled Trial
SCR	Skin Conductance Response
SoC	Standard of Care
SoE	Sense of Embodiment
SoO	Sense of Ownership
SoA	Sense of Agency
SF-MPQ	Short-Form McGill Pain Questionnaire
VAS	Visual Analog Scale
VHI	Virtual Hand Illusion
VE	Virtual Environment
VR (IVR)	Virtual Reality or Immersive Virtual Reality

Glossary

In this section, I briefly introduce the reworded definitions of the technical terms that are mentioned frequently in this dissertation. The selection criteria of the following definitions are from the most cited and accepted research papers adopted the same research methods or in the same fields where my research falls under.

Anterior Cingulate Cortex	is the frontal part of the cingulate cortex that resembles a "collar" surrounding the frontal part of the corpus callosum. It lies in a unique position in the brain, with connections to both the "emotional" limbic system and the "cognitive" prefrontal cortex (Stevens et al., 2011).
Augmented Reality	is the experience of actual environments that is supplemented by digital information in the form of images, sounds, and texts (Sumadio & Rambli, 2010).
Avatar	in this dissertation, avatar refers to an electronic image or 3D model that represents and may be manipulated by a computer user (as in a game) (Definition of avatar, 2020).
Body Image and Body Schema	body image is a conscious image or representation, owned, but abstract and disintegrated, and appears to be something in-itself, differentiated from its environment. In contrast, body schema operates in a non-conscious way, is pre-personal, functions (Gallagher, 1986)
Brain-Computer Interface	is a computer-based system that acquires brain signals, analyzes them, and translates them into commands that are relayed to an output device to carry out a desired action (Shih et al., 2012).
Brachial Plexus Avulsion	A brachial plexus avulsion occurs when the root of the nerve is completely separated from the spinal cord. This injury is usually caused by trauma, such as a car or motorcycle accident. More severe than ruptures, avulsions often cause severe pain. Because it is difficult

	and usually impossible to reattach the root to the spinal cord, avulsions can lead to permanent weakness, paralysis and loss of feeling (Brachial Plexus Injury, 2020).
Chronic Pain	is a time-based definition, and refers to pain that lasts or recurs for more than 3 months (IASP, 2011).
Complex Regional Pain Syndrome	in 1994, the International Association for the Study of Pain (IASP) entered the condition into its taxonomy as a diagnostic entity. The hallmarks of CRPS as defined by IASP include the following: (a) specific injury or noxious stimuli, which may include surgery; (b) continued pain that is disproportionate to the noxious stimuli or injury, including allodynia and hyperalgesia; (c) changes in localized skin, including edema and changes in blood flow and coloration of the skin; and (d) no specific dermatomal or nerve pattern (IASP, 1996).
Embodied Cognition	the emerging viewpoint of embodied cognition holds that cognitive processes are deeply rooted in the body's interactions with the world (Wilson, 2002).
Functional Magnetic Resonance Imaging	is a class of imaging methods developed in order to demonstrate regional, time-varying changes in brain metabolism. It depicts changes in deoxyhemoglobin concentration consequent to task-induced or spontaneous modulation of neural metabolism (Glover, 2011).
Field of View	the extent of the observable environment at any given time, or the range of what a user can see (Jerald, 2016).
Gate Control Theory	The Gate Theory of Pain, published by Ronald Melzack and Patrick Wall in Science in 1965, was formulated to provide a mechanism for coding the nociceptive component of cutaneous sensory input (Melzack & Wall, 1965).

Galvanic Skin Response	or electrodermal activity (EDA), is an “electrodermal” signature of the sympathetic nervous innervation of the skin (Nagai et al., 2019).
Head-mounted Display	is a display device, worn on the head or as part of a helmet, that has a small display optic in front of one (monocular HMD) or each eye (binocular HMD) (Sutherland, 1968).
Human-Computer Interaction	is a multidisciplinary field of study focusing on the design of computer technology and, in particular, the interaction between humans (the users) and computers (Carroll, 2003).
Mirror Therapy	is the use of a mirror to create a reflective illusion of an affected limb in order to trick the brain into thinking movement has occurred without pain. It involves placing the affected limb behind a mirror, which is sited, so the reflection of the opposing limb appears in place of the hidden limb. (Ramachandran et al., 1995).
Motor Execution	is the overt and volitional movement associated with body movement or activities (Raffin et al., 2012).
Mixed-Reality	is the merging of real and virtual worlds to produce new environments and visualizations, where physical and digital objects co-exist and interact in real-time (Jerald, 2016).
Numerical Rating Scale	is a subjective measure in which individuals rate their feelings or experience on a point-based numerical scale (ScienceDirect Topics, 2020).
Phantom Limb Pain	phantom limb pain (PLP) is defined as pain felt in the missing portion of the amputated limb following amputation (Limakatso et al., 2019).
Peripheral Nerve Injury	a peripheral nerve injury refers to destruction, damage, or crushing of the peripheral nerve which is a serious health

	problem that affects 2.8% of trauma patients annually (Hebl, 2007).
Quality of Life	is an overarching term for the quality of the various domains in human life. It is an expected standard level that consists of the expectations of an individual or society for a good life (Quality of Life, 2020).
Rubber Hand Illusion	the Rubber Hand Illusion (RHI) is a tantalizing illusion, where the feeling that a rubber hand belongs to one's body (feeling of ownership) is brought about by stroking a visible rubber hand synchronously to the participant's own occluded hand (Rohde et al., 2011).
Randomized Controlled Trial	is a trial in which subjects are randomly assigned to one of two groups: one (the experimental group) receiving the intervention that is being tested, and the other (the comparison group or control) receiving an alternative (conventional) treatment (Kendall, 2003).
Sense of Agency	refers to the sense of having ‘‘global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will’’ (Kilteni et al., 2012).
Sense of Ownership	refers to one’s self-attribution of a body. It has a possessive character and it implies that the body is the source of the experienced sensations. (Kilteni et al., 2012).
Standard of Care	a diagnostic and treatment process that a clinician should follow for a certain type of patient, illness, or clinical circumstance (Definition of Standard of Care, 2020).
Short-Form McGill Pain Questionnaire	the short-form McGill Pain Questionnaire (SF-MPQ) is a shorter version of the original MPQ, and was developed later in 1987. The pain rating index has 2 subscales:

	sensory subscale with 11 words, and affective subscale with 4 words from the original MPQ (Melzack, 1987).
Visual Analog Scale	is a measurement instrument that tries to measure a characteristic or attitude that is believed to range across a continuum of values and cannot easily be directly measured (Visual Analogue Scale, 2020).
Virtual Embodiment	sense of embodiment (SoE) in Virtual Reality. The capability of our brain of having a representation of our body results in a mental construction composed of perceptions and ideas about the dynamic organization of our own body, involving vision, touch, proprioception, interoception, motor control, and vestibular sensations. (Kilteni et al., 2012).
Virtual Hand Illusion	is an illusion that can be induced even in the absence of tactile stimulation, simply by manipulating the temporal delay between the participant's own movement and the movements of the virtual hand on a screen (Ma & Hommel, 2015).
Immersive Virtual Reality and Virtual Environment	is the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors. Virtual environment (VE) normally refers to the immersive and illusory environments rendered in VR (Jerald, 2016).

Chapter 1. Introduction

1.1. Overview of Research Problems

Chronic pain affects approximately 20% of people worldwide (Schopflocher et al., 2011). The International Association for the Study of Pain (IASP) defined chronic pain as pain that persists for longer than three months (IASP, 2020). In addition to the physical and psychological effects (pain, stress, depression, and distorted body images), the emotions and social environments of chronic pain sufferers are also severely impacted due to experiences such as stigma and social isolation (Dueñas et al., 2016). Therefore, clinicians have developed and tested other alternative treatments, such as yoga and Tai Chi, psychotherapy, cognitive behavior therapy, mind-body techniques (mindfulness-based stress reduction [MBSR], hypnosis), and virtual reality (VR) and augmented reality (AR) interventions (Turk, 2002).

Among non-pharmacological treatments, immersive VR has great promise for acute and chronic pain management (Mallari et al., 2019). Although the underlying mechanisms of VR pain modulation (or VR analgesia) remain unclear, two primary approaches to utilizing it for pain management have been widely studied: attentional distraction (directing attention inward to the pain or outward from the pain) and virtual embodiment (sense of embodiment in VR). The effectiveness of the attentional distraction approach has been validated with evidence from acute and chronic pain patients. For instance, many studies by Hoffman's and Gold's groups adopted an attentional distraction approach to pain alleviation in virtual environments (Gold & Mahrer, 2018; Hoffman et al., 2001a, b, c; Hoffman et al., 2011). Although most studies that adopted this approach showed significant pain reduction levels during the study period, very few studies followed up with the patients after the research in the long-term.

In other studies, the virtual embodiment approach has also resulted in pain alleviation in healthy study participants experiencing pain stimulus through the visual and motor feedback of a virtual body (Gilpin et al., 2014; Martini et al., 2014; Martini, 2016; Zanini et al., 2017).

Virtual embodiment research was initiated by cognitive scientists who believed rubber hand illusion (RHI), virtual hand illusion (VHI), or virtual body illusion (VBI) might explain the pain alleviation phenomenon (IJsselsteijn et al., 2005; Petkova & Ehrsson, 2008; Slater et al., 2008, 2010). RHI refers to the perception of owning a rubber hand similar to owning one's real hand, which was elicited by viewing a co-located rubber hand (Botvinick & Cohen, 1998). Similarly, VHI is the feeling of owning virtual hands in VR (Slater et al., 2008) and VBI is the feeling of owning the entire virtual body (Slater et al., 2010).

For instance, researchers found that different levels of embodiment and pain outcomes can be induced by manipulating the appearance and motion of virtual limbs, including their color (Martini et al., 2013), arms' shapes (realistic arms and abstract tubes) (Zanini et al., 2017), skin transparency (Martini et al., 2015), body sizes (Romano et al., 2016), and movement states (synchronized and asynchronized) (Martini et al., 2014; Zanini et al., 2017). However, most of the studies exploring manipulated avatar features were conducted by exposing healthy participants to pain stimulus. In a recent study, Matamala-Gomez et al. (2019) found that chronic pain participants and healthy participants' pain perception and sense of embodiment did not react similarly to the same avatar features. Patients with different types of pain also did not react similarly. For instance, increasing the skin transparency decreased pain in complex regional pain syndrome (CRPS) patients but did the opposite in peripheral nerve injury (PNI) patients (Matamala-Gomez et al. 2019). Further, though the movements of virtual arms can be manipulated to regulate the sense of agency (Martini et al., 2014; Zanini et al., 2017), only one research has analyzed the potential correlations between agency and pain (Käthner et al., 2019).

Therefore, this dissertation's first research trajectory focused on utilizing virtual embodiment for analgesia and aimed to (1) manipulate avatar features and evaluate how they affect pain and embodiment (the sense of ownership and agency); (2) further explore the correlations between virtual embodiment and induced pain with a focus on sense of agency (SoA); and (3) compare the effectiveness of the virtual embodiment approach in managing different types of pain, healthy participants' induced acute pain, and unhealthy participants' chronic pain.

Virtual embodiment also holds promise for eliciting empathy towards chronic pain too. Despite the prevalence of chronic pain, public awareness of it was remarkably low until the opioid crisis that began in the 2000s (Eriksen et al., 2006). Since chronic pain is a condition that does not necessarily include amputation, scars, deformities, or the objective evidence seen on imaging, it remains mostly invisible to the public. As a result, social stigma remains a problem for people who live with this condition (De Ruddere & Craig, 2016). Further, stigmatization might reduce patients' self-esteem and social support, leading to isolation; it may also cause negative emotions and issues with well-being, such as stress and depression (De Ruddere & Craig, 2016). Many researchers have been evaluating how digital media can impact the affective and perspective-taking aspects of empathy in both clinical and non-clinical settings. Evidence has also shown that VR applications (either environments or games) could stimulate a significantly higher level of empathy than videos or traditional media forms (Herrera et al., 2018). In this dissertation, VR environments refer to applications that don't have game mechanics implemented, but more for therapeutic purposes; while VR games refer to commercial titles that has game mechanics but weren't developed for therapeutic features. The immersive and convincing nature of VR has profound effects and may confer meaningful benefits to an individual's cognition or behavior (Slater & Sanchez-Vives, 2016). Despite the growing interest in using VR applications to motivate empathy, few studies have focused on empathy for people who live with chronic pain. Hence, this dissertation's second research trajectory examined the effect of embodied VR in facilitating non-patients' empathy toward chronic pain patients. Moreover, I was keen to explore potential design features and recommendations for empathy facilitation in embodied VR games.

In this chapter, I first introduce the background of my research on pain and VR and discuss my two research trajectories: (1) utilizing virtual embodiment for analgesia and (2) utilizing it to foster empathy toward pain patients. Next, I discuss the research questions that informed each trajectory and present an outline of this dissertation. Finally, I briefly discuss the contributions of my dissertation.

1.2. Research Background

1.2.1. Pain: An Unpleasant Sensory, Emotional, and Social Experience

IASP defined pain as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" (IASP, 2020). Since the 1800s, philosophers and psychologists have put forward formal theories, such as specificity theory and pattern theory (Moayedi & Davis, 2012), to explain how and why people feel pain. In the 1960s, Melzack and Wall (1965) published a paper proposing gate control theory (GTC) to explain the mechanisms of pain; the theory put forward a biological and physiological theory describing how pain signals are processed in the body and perceived by the brain. Then, Melzack and Casey (Casey, 1968) added emotional and cognitive aspects to the pain theory. Thirty years later, Melzack (1999) proposed the neuromatrix theory, a theory based on neural networks that incorporated GCT as well as emotional and cognitive feedback loops all together. More recently, Moseley's (2003) "pain matrix" (p.1) focused more on the holistic predictors of pain; this theory arrived late to the field because its development relied on advancements in neuroscience.

The two most important categories of pain are chronic pain and acute pain. Chronic pain is defined as persistent or recurrent pain that lasts longer than three months (IASP, 2011). Chronic pain affects 20% of people worldwide. Functional impairment, distress, and demoralization often accompany chronic pain, making it a significant source of suffering and economic burden (Breivik et al., 2013). In this dissertation, due to the scope of my research questions, I focus more on chronic pain than acute pain.

Similar to Melzack, Gatchel et al. (2007) proposed a biopsychosocial (BPS) approach for pain that suggests it is the result of dynamic interactions among physiological, psychological, and social factors. Gatchel's comprehensive BPS approach considers both the health and mental illness of the pain sufferers (Gatchel, 2004), and it has been especially influential and useful in contexts of chronic pain (Gatchel et al., 2007) and mental health conditions (Gatchel, 2005). Initially, it focused on both disease and illness and proposed that illness is a complex interaction of three factors: biological, psychological, and social (Gatchel, 2004; Gatchel, 2005). Later, Gatchel (2007) used this approach to specifically address chronic pain because it is the result of that type of dynamic interaction. Although the underlying mechanisms of pain have been frequently debated, the implication of GCT and other theories—specifically, the interaction between the psychological (or psychosocial) and physiological processes—has been widely accepted (Gatchel, 2007). In my research, I utilized Gatchel's (2007) BPS approach as an underlying theory for understanding the modulation process and potential impacts of chronic pain.

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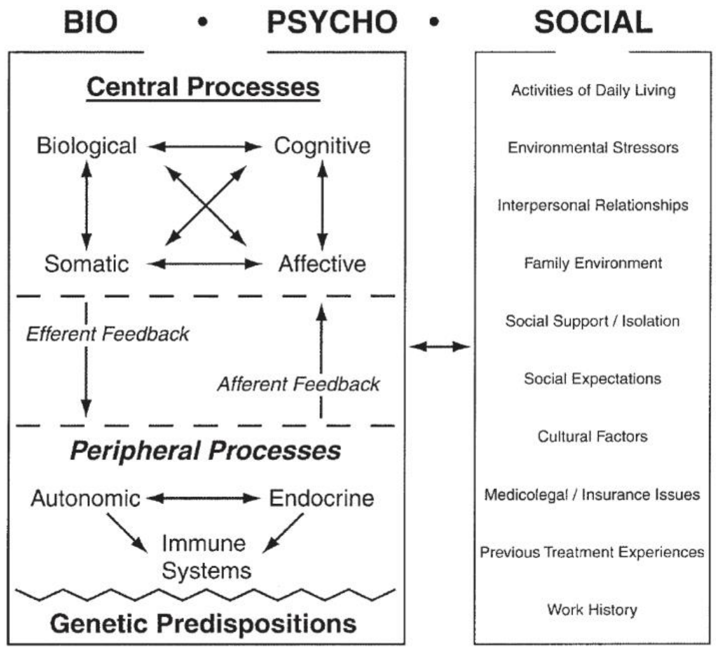

Figure 1.1.Conceptual approach of BPS interactive processes involved in health and illness (Gatchel et al., 2007).

1.2.2. Virtual Reality as an Embodied Technology and Virtual Embodiment

The term "virtual reality," first coined by Jaron Lanier (Wikipedia, 2020), is defined as an interactive simulated environment that can provide sensory stimuli that range from auditory and visual feedback to haptic feedback (Jerald, 2016). To precisely define the VR technology that was created for this dissertation, I differentiated non-immersive VR from immersive VR.

Immersive VR refers to 3D environments with immersive visual interfaces (Slater & Sanchez-Vives, 2016), such as VR head-mounted displays (HMDs), and immersive projections, such as the cave automatic virtual environment (CAVE) system (Cruz-Neira et al., 1992). While the former offer 3D graphics that reduce our awareness of the physical world, the latter use a 360° field of mapped projections of a room or a helmet, thus preserving the perspective of one's real body or the real-world. In this dissertation, I used the term VR referring to immersive VR.

Non-immersive virtual reality refers to computer-generated 3D environments that users can navigate in a virtual space to which their sense of awareness is tethered (Slater & Sanchez-Vives, 2016). Non-immersive VR is generally displayed through 2D interfaces, such as computer monitors, projectors, and TVs. Immersive 360° environments allow participants to feel as though they are inside the environment while non-immersive environments only allow participants to see the contents based on how the device in use – PC, smartphone, or tablet – is held and moved. According to Ventura et al. (2019), the difference between immersive and non-immersive VR can be better clarified through the concept of spatial presence, meaning “the sense of being in an environment” (Kober et al., 2012). See more in Chapter 2.2.2.1 for details about this presence illusion.

Because of the revolutionary development of hardware devices since 2000 (Jerald, 2016), VR has been widely adopted in multiple industrial and academic fields, including medicine and health, education and training, commercials, entertainment, art, and communication (Bailenson, 2018; Dyer et al., 2018; Grau, 2002; G. Riva et al., 1999; Sveistrup, 2004).

VR HMDs’ multisensory feedback and powerful technical properties can provide the users with a sense of presence. This is the sense of being there, which refers to people’s responses to their surroundings and their ability to take action to modify them (Slater et al., 2009). Researchers believe that presence is one of the most critical factors in VR environments’ elicitation or alteration of people’s perceptions in most VR HMDs. This sense of presence is what makes VR a novel medium that immerses all our senses and embodies our actions in a virtual world, changing us cognitively and psychologically.

According to Slater et al. (2009), the sense of presence consists of two primary perceptual illusions: place illusion (the sense of being in a place) and plausibility illusion (the sense that the depicted scenario is occurring). Later, Jerald (2016) offered a refinement of plausibility illusion, breaking it into *self-embodiment illusion* (the sense of embodiment or embodiment presence; the sense of having a body in the virtual world), the illusion of *physical interaction* (the sense of having physical responses that match the visual representations), and *social communication* (social presence; Jerald, 2016). Among the four illusions, embodiment illusion, or the sense of embodiment, is the only component that considers the impact of the virtual avatar or body (parts) on one’s perception. Prior research (Banakou et al., 2013; Bertrand et al., 2018; Gilpin et al., 2014) revealed that people could feel ownership or control of virtual avatars, thus allowing them to take the perspective of the virtual avatars. In this dissertation, I mainly focus on embodiment illusion and its impact on pain reduction and empathy facilitation.

When defining the phenomenon of sense of embodiment (SoE) in VR, some researchers have followed classic embodied cognition (EC) theory through a cognitive science lens (Kirsh, 2013). For instance, some of Bailenson et al.'s (2018) research focuses on how being embodied in an avatar results in perceptual or behavioral changes across a broad range of topics, including empathy toward a specific population. In these studies, the authors adopted EC theory to interpret the outcomes, suggesting that cognition is grounded in the body and the body's relationship to the environment. Admittedly, EC theory can be applied to SoE in VR, but it is too general and inclusive to further explain its composition. According to Kilteni et al.'s (2012) framework of virtual embodiment, a sense of embodiment (or self-embodiment) in VR is the experience or feeling of ownership of a body, control over it, and the sense of being inside it. These experiences and feelings consist of three subcomponents: sense of ownership (SoO), sense of agency (SoA), and sense of self-location. Kilteni et al. deducted these subcomponents from an abundant review of previous studies to answer the question of how and to what extent a person can experience a virtual body in a virtual environment as their own. In this dissertation, I mainly focus on SoO and SoA, as they are the primary attributes affecting people's perception of and cognition related to a virtual body.

1.2.3. VR Analgesia as Non-Pharmacological Therapy

VR has been used for pain management for over two decades, and mounting evidence supports its effectiveness in pain modulation. Since the 1990s, Hoffman's research group has been conducting a series of studies and has convincingly demonstrated that immersive VR is an effective way to manage attention as a form of *pain distraction*, especially in the contest of acute pain (Hoffman et al., 2000; Hunter G. Hoffman et al., 2001a, b, c; Hoffman et al., 2011). In addition to assisting burn pain patients, VR distraction has also been proven to have an effect in other acute medical conditions, such as in interventions for cancer pain patients (Schneider et al., 2004), IV placement (Gold et al., 2006), wound care procedures (McSherry et al., 2018), and pediatric blood draw procedures (Gold & Mahrer, 2018).

Although the mechanisms of chronic pain differ from acute pain, researchers investigated the possibility of utilizing VR pain distraction to control the acute moment of chronic pain patients, and the results revealed temporary pain reductions after the study interventions (Amin et al., 2017; Choo, 2015; Hua et al., 2015; Ng et al., 2018; Simmonds, 2008; Wiederhold et al., 2014). Intriguingly, in addition to their examinations of attentional distraction in VR environments, Gromala et al. (2015a) and Oneal et al. (2008) addressed and represented pain in the virtual environment and explored pain *self-control (self-management)* to help the participating patients direct their attention to the pain itself (via MBSR or hypnosis strategies). In addition to measuring pain levels from self-reported questionnaires, Hoffman et al. (2003) moved further by designing an fMRI-friendly VR headset, and then scanned healthy participants' brains while inducing pain (Hoffman et al., 2004). The authors' fMRI data revealed that pain-related brain areas are less active after VR than before.

Gold et al. (2007) and Li et al. (2011) undertook a literature review to analyze the neurological implications of VR for pain attenuation, and they also explored potentially relevant mechanisms that cause pain. They agreed on the attentional distraction and emotional changes achieved by VR as well as the potential brain area changes that caused reductions in pain sensation based on the gate control theory of pain. Thus, VR can be used as a powerful pain control technique and tool so that patients can manage and alleviate acute or short-term pain. However, it is not yet known if the analgesic effects of VR persist beyond the sessions. Factors that influence the effectiveness of the analgesic effect include presence levels (Hoffman et al., 2004, Triberti et al., 2014) and other psychological aspects, such as feelings of fun or anxiety (Triberti et al., 2014).

In the virtual embodiment approach, the VR environment only shows a virtual avatar (or body) from the first-person perspective; it is not a 360-degree animated environment without virtual avatars. Researchers have investigated various visual presentations of virtual bodies and how pain is affected by the same avatar features relevant to the efficiency of the analgesic approach and, focusing on SoO, if a sense of embodiment correlates with pain. Such VR environments provide opportunities for people to map their body image onto a virtual character by creating a mental model of their bodies and eliciting an SoO (or SoA) based on that virtual body. Slater and Sanchez-Vives' research group believes that having an SoO over virtual avatars alleviates heat-induced pain, also known as the analgesic effect of virtual hand illusion, similar to the analgesic effect of rubber hand illusion (Martini et al., 2014; Martini et al., 2015; Sanchez-Vives et al., 2010).

However, virtual embodiment studies have been largely conducted by exposing healthy participants to pain stimulus. Findings have suggested that if a person's avatar looks similar to their real body (for example, its size and pigment), different types of pain are experienced in different ways (Matamala-Gomez et al., 2019). For instance, Matamala-Gomez et al. found that complex regional pain syndrome (CRPS) patients' pain ratings decreased while the virtual avatar's skin transparency increased, but peripheral nerve injury (PNI) patients experienced an opposite tendency in pain (Matamala-Gomez et al. 2019).Prior research found that many chronic pain patients have distorted body images when compared to healthy people (Gilpin et al., 2015). The conscious sense of one's body, or body image, is often taken for granted, but it is disrupted in many clinical states, such as phantom limb pain (PLP) and CRPS. Few virtual embodiment studies have been conducted with such chronic pain patients, and some evidence has revealed that unhealthy patients in certain VR embodiment conditions experience pain differently than the simulated pain induced in healthy participants (Martini et al. 2015; Romano et al., 2016; Matamala-Gomez, Diaz Gonzalez, et al., 2019). In other words, when seeing the same visual conditions, chronic pain patients appear to have different responses, possibly based on the kind of chronic pain they have.

The other challenges virtual embodiment research faces are that prior studies mostly manipulated avatar features and evaluated the correlation between SoO and VR's analgesic effect. However, how SoA may affect VR's analgesic effect is still under investigated. Therefore, one of my research trajectories is to further explore the association between virtual embodiment and induced pain with a focus on SoA; how the VR environment and avatar design features affect VR analgesia and are significant to informing future VR environment development and design.

Manipulating the avatar features of virtual bodies or body parts, such as their size, skin transparency, and movements, has been shown to offer analgesic effects to healthy people under pain stimulus as well as patients with chronic pain. Researchers have suggested that virtual embodiment is one of the potential causes of avatar-mediated analgesic effects, focusing on virtual hand and body illusion, or the SoO of the presented body or body parts (Gilpin et al., 2014; Käthner et al., 2019; Martini et al., 2014). However, prior findings indicated that manipulating each avatar feature may have varied effects on or correlations to pain modulation, which may also depend on pain types (Matamala-Gomez et al., 2018).

Therefore, I investigated two avatar features of virtual arms—visual realism (realistic arms versus abstract tubes) and motion states (synchronous versus static)—and explored how the induced ownership and agency further correlated with pain modulation. I recruited 18 healthy participants and 12 CRPS patients in two separate studies to reveal the influence of pain etiology on the same set of avatar features. In both studies, self-reported pain ratings and embodiment scores were evaluated.

1.2.4. Virtual Reality: The Ultimate Empathy Machine?

In a TED Talk, Milk (2015) proposed that VR is "ultimate empathy machine" (2:27), and this phrase was later adopted by researchers because the technology has the effect of evoking people's emotional engagement in their responses to virtual content (Bevan et al., 2019). Embodying an avatar from a first-person perspective leads to changes in cognition and perception; known as "perspective-taking" (Loon et al., 2018; Parsons, 2015). This occurs when people perceive a situation or understand a concept from another person's or group of people's point of view. For instance, embodying participants in a dark-skinned avatar from the first-person perspective led to a reduction of implicit racial bias (Peck et al., 2013), which was sustained over time (Banakou et al., 2016). However, other researchers have opposite opinions that against empathy, such as Bloom. He argued that rational compassion is more helpful for facilitating prosocial behaviors than empathy (Bloom, 2016).

As discussed in Chapter 1.2.2, VR has been proven to generate self-embodiment illusions, including SoO and SoA over virtual bodies with different genders, races, ages, and other visual characteristics (Bailey et al., 2016; Banakou et al., 2013, 2016; Lopez et al., 2019). Several studies have shown that when people are virtually embodied or represented online with a virtual body that differs from their own, they exhibit behaviors concomitant with the attributes of that body. Yee (2007) referred to this as the Proteus effect. Among other things, when people have a virtual body with a more attractive face than their real one, their social-spatial behavior alters—specifically, they stand closer to virtual representations of other people than they do if the virtual face is less attractive. Additionally, people will become more aggressive in negotiations if they are embodied in an avatar that is tall rather than short (Yee et al., 2007).

VR has also been developed as a training tool for medical education purposes because healthcare practitioners and providers require high empathy levels to effectively work with patients. Researchers simulated the interactive VR experiences of people with dementia and mental illness to improve their caregivers' understanding of this disease (Jütten et al., 2018; Lindsay et al., 2012; Wijma et al., 2018). Overall, researchers found that VR enhanced participants' empathy levels and understanding of these medical problems. However, no VR environments were created to simulate the experience of chronic pain or foster the understanding of how it presents chronic pain patients with life challenges and social stigma. This research gap motivated me to further explore how embodied VR can be designed for understanding pain.

1.2.5. Section Summary: VR Technology and Embodiment and Research Framework

Here, I summarize section 1.2, Research Background, and further discuss the interrelationships and connections between my two research trajectories—VR and analgesia and VR and empathy—to present the logical flow of my research problems and the experiments mentioned in the later chapters. First, I reviewed the definitions, characteristics, and problems of chronic pain and the models scholars have utilized to understand the composition of chronic pain. Next, I focused on VR and discussed how it works as a simulated and embodied technology that is powerful enough to induce the four types of perception illusions, including virtual embodiment. Following the explanation of virtual embodiment, I introduced the background and research problems that inform my research trajectories.

As shown in Figure 1.2, this dissertation aims at researching the three main issues experienced those with chronic pain: biological, psychological, and social (i.e., from the three aspects in the BPS conceptual model). The first research trajectory about VR and pain targets people in pain to provide methods for alleviating pain while the latter research trajectory about VR and empathy targets healthy people to build empathy and reduce the social stigma problem of pain patients. In my first research trajectory, the targeted audience was people in pain who saw a healthy virtual avatar with the purpose of developing their pain self-modulation. The visual and movement conditions of the avatar were investigated as factors that may impact VR's analgesic effects. The second goal was to assess the correlations between embodiment and pain outcomes. However, in the second trajectory, my participants were non-patients who saw the unhealthy virtual avatar of a chronic pain patient. My primary focus was to understand if being embodied in an avatar in the context of a narrative game affects people's empathy toward pain patients. Figure 1.2 illustrates the frameworks for this dissertation's research domains.

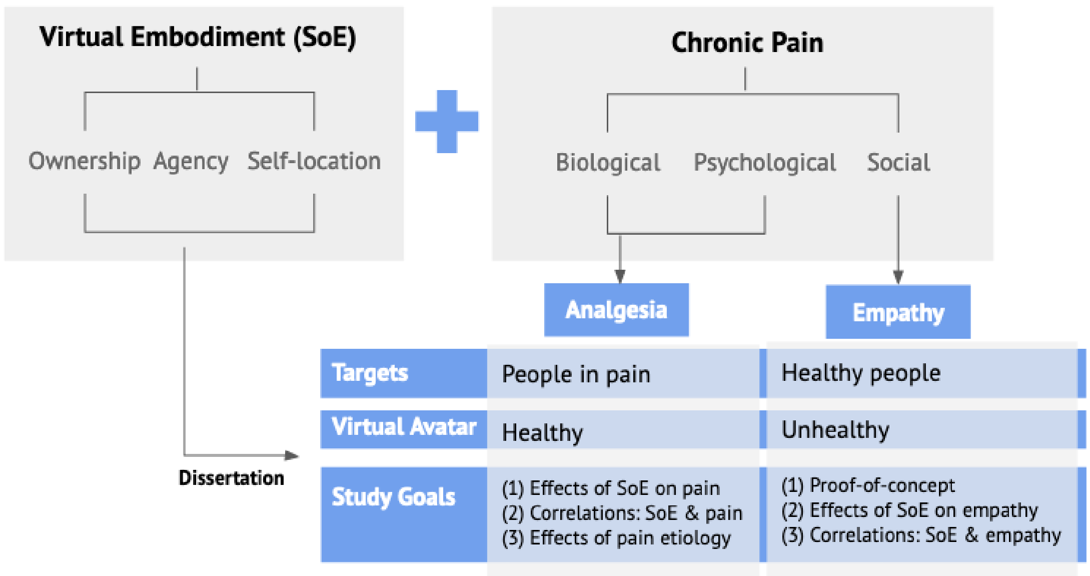

Figure 1.2 Framework for research domains.

1.3. Research Questions

Here, I summarize the research questions in my two trajectories to address the research gaps identified in Subsection 1.1, Research Problems, and to better understand and investigate the effects of virtual embodiment on pain reduction and empathy generation. My overarching research questions are: how can virtual embodiment affect people's perception of pain and address the BPS challenges that chronic pain patients face? Can a virtual embodiment approach effectively (a) support pain patients in modulating their pain and (b) stimulate empathy toward pain patients' conditions? What are the potential correlations between embodiment and pain levels and between embodiment and empathy levels? Below, each trajectory's specific research questions are presented.

1.3.1. Virtual Embodiment and Pain

My first research trajectory explores the mechanics of how avatar features modulate virtual embodiment and pain (see Figure 1.3 for concept map). My goals were twofold: first, to examine the effects of avatar features, such as the look and movement of virtual bodies, on pain perception; second, to research the associations between the elicited sense of embodiment and pain perception, with a focus on agency. Further, I wanted to understand if pain types affect the outcomes of embodiment and the effectiveness of VR analgesia by comparing healthy subjects under pain stimulus to chronic pain patients. Therefore, my research questions for virtual embodiment and pain trajectory are: (1) what are the effects of avatar features on embodiment and pain modulation? (2) What are the correlations between embodiment and pain? (3) How do healthy participants under pain stimulus and chronic pain patients respond to manipulations of the same avatar features? In answering these questions, my overarching goal was to provide inspiration for research on virtual embodiment's implications for pain modulation and inform the design of future VR environments to improve their effectiveness in pain modulation.

As a first step, I focused on how heat-induced pain might be affected by different VR visual conditions. The next step was to develop a controlled strategy for assessing the potential effects of virtual embodiment among chronic pain patients with different pain types. It necessarily required more emphasis on patients' responses than on inductions of precise pain-inducing stimuli because inducing more pain in a chronic pain patient can lead to adverse outcomes, such as pain catastrophizing, anxiety, or panic attacks (Gatchel et al., 2007). A more specific subset of questions is listed below.

(1) Virtual embodiment and the induced pain of healthy participants. How do the movements (synchronous and asynchronous movement conditions) of virtual arms affect healthy participants' perception of heat-pain stimulus? Is there any correlation between the sense of virtual embodiment (SoO and SoA) and pain?

(2) Virtual embodiment and CRPS. How do movements (synchronous and asynchronous movement conditions) and the appearance (abstract tubes and realistic arms) of virtual arms affect CRPS patients' pain? Is there any correlation between the sense of virtual embodiment (SoO and SoA) and CRPS patients' pain? The reason I chose CRPS patients is that Prior studies showed that viewing pictures of healthy hands or mirror therapy can reduce CRPS patients' pain, but these approaches are not as immersive and embodied as a VR experience. Moseley et al. (2005) found that CRPS patients have a faulty estimation about their body size, spatial mislocalization, or

decreased tactile acuity with direct correlation between body perception and pain. Thus, I'd like to know how viewing different appearances of a virtual body might affect their estimation of pain. Further, Matamala-Gomez et al. (2019) also assessed CRPS patients' pain reduction in different virtual embodiment conditions, the virtual arms' size, and transparency levels. I'd like to build upon their research and continue researching the effect of appearance (tube and arm shapes) and motion (synced and static) on CRPS patients' pain levels.

(3) Virtual embodiment and PLP. Can PLP patients reduce their pain when seeing the virtual avatar's phantom limb mirror the movement of the intact limb? Is there any correlation between the sense of virtual embodiment (SoO and SoA) and PLP? I recruited PLP patients because it's a special type of chronic pain, defined as painful sensations perceived in the missing portion of the amputated limb, and it's challenging to cure. Prior studies suggested that feeling the sense of ownership of a mirror or virtual hand can affect one's PLP perception. Researchers found that mirror movement in VR also successfully reduced PLP and findings suggest that feeling embodied in a body may be critical to PLP reduction. Therefore, I'd like to further explore how embodied VR affects PLP, and the potential relationships between embodiment and PLP changes. In Chapter 4.2, we included patients whose PLP were caused by limb amputation AND brachial plexus avulsion injury (BPA), because our BPA patients also felt PLP as diagnosed by healthcare professionals.

(4) Virtual embodiment, etiology, and pain. How does pain etiology affect virtual embodiment's analgesic effects? In other words, do the avatar features deployed in this research (movements and visuals) affect different populations in the same way? Do healthy participants feel different levels of embodiment than chronic pain patients with CRPS or PLP?

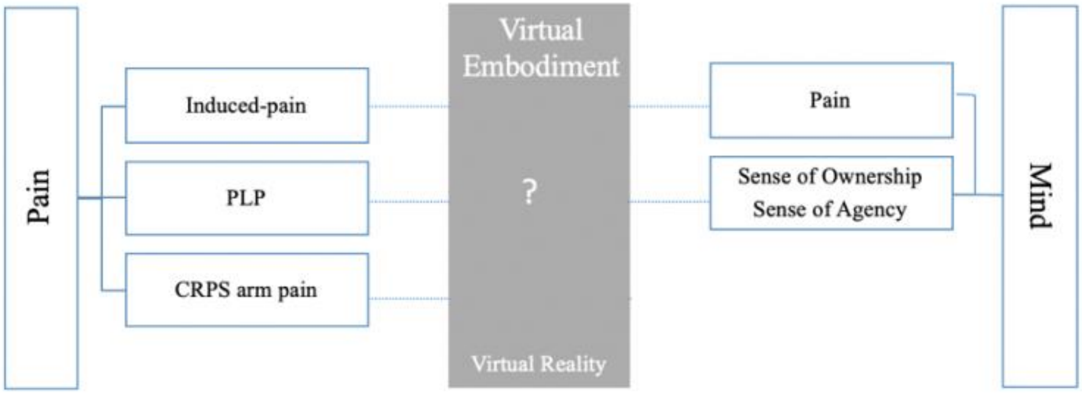

Figure 1.3 Map of research questions and conceptual framework of the VR and pain research trajectory.

1.3.2. Virtual Embodiment and Empathy

For the second research trajectory, my primary goal was to investigate the effectiveness of using an embodied avatar to stimulate non-patients' empathy toward chronic pain patients. Moreover, I have extracted potential design features and recommendations from this study for use in future VR applications that aim to stimulate empathy using an embodied avatar.

The specific research questions are:

(1) With what approaches can chronic pain be presented in a virtual avatar?

(2) Does being embodied in a chronic pain patient's avatar effectively stimulate healthy participants' empathy toward chronic pain patients? If so, is there any correlation between the sense of virtual embodiment (SoO and SoA) and healthy participants' empathy levels?

(3) What design features can stimulate healthy participants' empathy toward chronic pain patients?

1.4. Outline of the Dissertation

This PhD dissertation structure is shown in Figure 1.4 below.

Chapter 1. Introduction. I began with an overview of my research problems about virtual embodiment and pain. Then I introduced the background research on VR, embodiment, and pain to situate those research problems. I listed my research questions and outlined the dissertation. Finally, I concluded this chapter with the contributions of this dissertation.

Chapter 2. Virtual Reality and Pain Alleviation. In Chapter 2, I carried out a narrative review in VR research and studies on pain alleviation. I discuss the pain distraction approach and its analgesic effects. Then I introduce the related embodied pain modulation interventions, such as mirror therapy, RHI, and graded motor imagery interventions. These phenomena help reveal the underlying mechanisms of utilizing virtual embodiment for pain modulation. In reviewing pain distraction and virtual embodiment approaches, I summarize the studies' methodologies to differentiate these two methods and detail the landscape of existing research. Finally, I categorize what the literature views as the potentially impacting factors on VR analgesia, and I give an overview of the existing theories that explain it.

Chapter 3. Virtual Embodiment and Pain Alleviation: Studies with Healthy Participants Experiencing Pain Stimulus and CRPS Patients. In Chapter 3, I describe two separate experimental studies involving healthy people experiencing pain stimuli and chronic pain patients with CRPS. I further analyze the correlations between embodiment (ownership and agency) and pain to answer the research questions in my first research trajectory. I put these two studies together because they share similar study objectives, methods, and procedures. The only difference was the type of pain participants experienced. Comparing these two groups, I further discuss the potential effect of pain types on the study outcomes.

Chapter 4. Alleviating Phantom Limb Pain in VR: The Landscape and a New Attempt. In Chapter 4, the focus shifts to another type of chronic pain—PLP—which is a special type of pain that patients feel pain when they damage or lose a limb. Mirroring the movements of the impaired virtual limb in VR with the intact real limb has been shown to successfully reduce PLP. Nevertheless, few studies have explicitly measured the potential effects of embodiment on PLP modulation. Therefore, in this chapter, I explore the correlation between PLP patients' embodiment and pain changes. I present a literature review that analyzes the embodiment approaches of VR or AR studies, their methods, and their findings. The review results led to a more solid study design for the third experiment, which took the form of a longitudinal study involving five patients.

Chapter 5. Virtual Embodiment and Empathy. Similar to Chapter 2, in Chapter 5, I review embodied VR environments and their applications in the development of empathy. First, I discuss the general frameworks and dimensions needed to understand empathy, how embodied technology has been developed to foster it, and the reasons the technology works. Then I review the literature and present different scenarios and cases in which VR was used to foster empathy toward vulnerable populations. Last, I focus on utilizing embodied VR environments and other embodied digital platforms to foster empathy toward chronic pain patients, and this situates the background of my second research trajectory.

Chapter 6. Virtual Embodiment and Fostering Empathy toward Pain Patients. Chapter 6 consists of two studies on the iterative design-research process of an embodied VR game called AS IF. The purpose of AS IF is to foster non-patients' empathy toward patients with chronic pain. I started off from a proof-of-concept prototype in which participants were put in the shoes of a chronic pain patient from a third-person perspective. In the first version, participants' movements were captured to carry out motion-related tasks, such as connecting dots to complete the game's narrative story. With participant feedback from the pilot study, I iterated the game features and evaluated the new version in a second study. The narrative component was kept, but I altered participants' view from the third-person to the first-person perspective, and I changed the game tasks from puzzle solving to direct object manipulation. Finally, in this chapter, I propose design recommendations for creating empathetic and embodied VR applications for patients with chronic pain.

Chapter 7. Embodied Design in VR for Analgesia and Empathy. In Chapter 7, I summarize the significant findings of both research trajectories. I conclude by highlighting this dissertation's primary contributions to VR and embodiment research, especially for modulating pain and fostering empathy. Building on the literature, I also discuss my studies' results, the theories that explain their outcomes, and the studies' limitations. This dissertation's findings raise more questions for future research. Therefore, I propose follow-up research questions for both trajectories as well as potential experiments for future work.

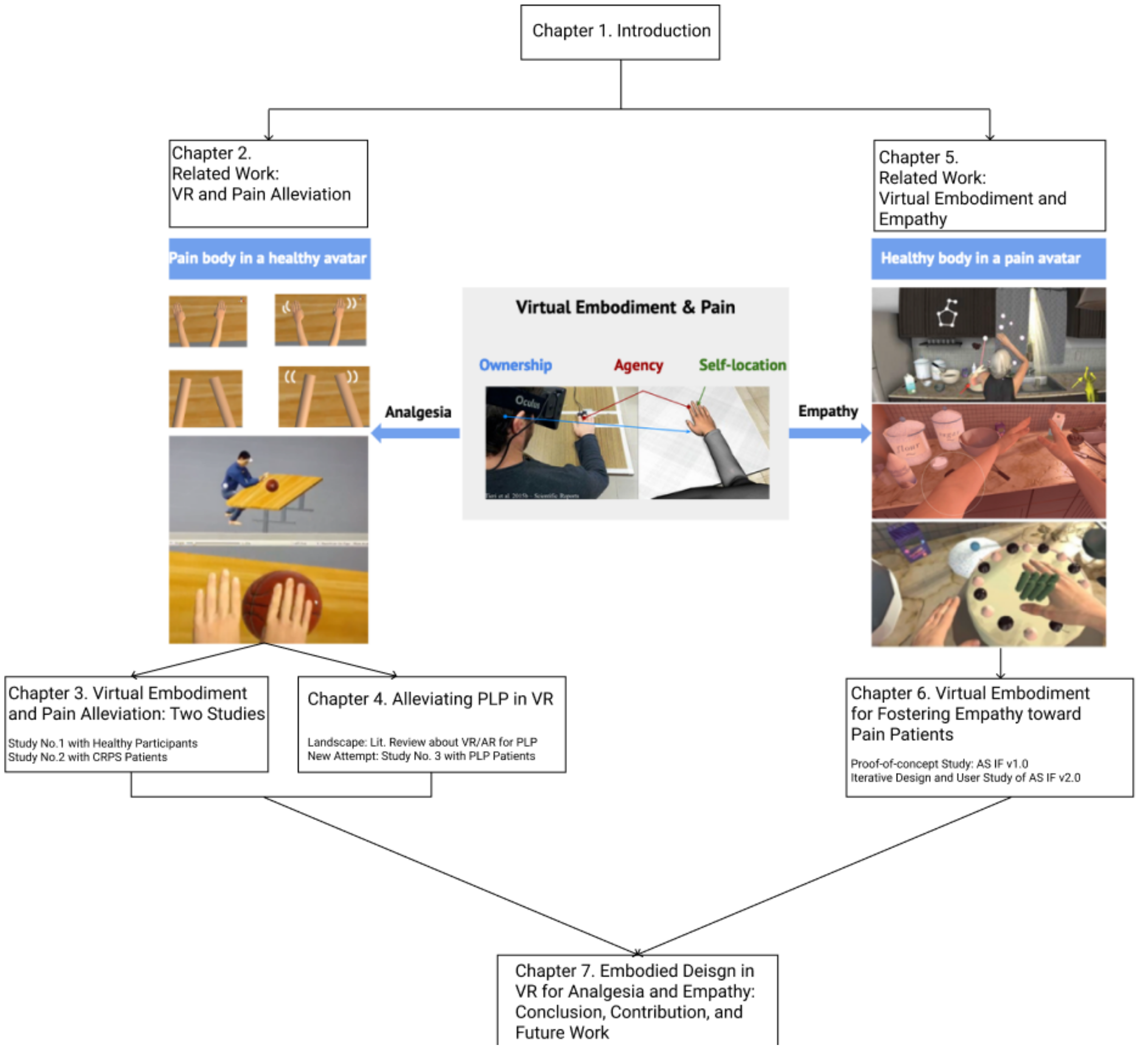

Figure 1.4 Dissertation outline diagram.

1.5. Dissertation Contributions

My dissertation examines the roles of VR in resolving the physical, psychological, and social challenges pain patients experience, and it offers an empirical understanding of how virtual embodiment affects patients' pain and others' empathy toward pain patients. This includes two main parts. First, this dissertation explores how an avatar's different avatar features (motions and appearance) can affect a person's sense of embodiment and pain reduction; it does so by consolidating three studies involving healthy subjects experiencing heat-induced pain, CRPS patients, and PLP patients. The insights from these three studies can help shape our scholarly understanding of how people in different types of pain respond to avatar features as well as how VR researchers and practitioners can better implement embodied VR environments to offer people analgesic benefits. Second, this dissertation acknowledges the social stigma that pain patients face, and it includes a design thinking process to create an embodied VR game people can use to better understand patients' invisible pain. Two rounds of iterative evaluations suggested practical ways of communicating pain with non-patients, leading to design recommendations and implications for future research.

Results from both trajectories also highlight the value and benefits of embodied VR for pain self-management and empathy. With its focus on a marginalized population, my dissertation contributes to the discourse of treating chronic pain. Often, chronic pain is challenging to cure and difficult to understand. This dissertation provides experimental findings as strong evidence to support technological solutions for people living with chronic pain.

To conclude, the findings from this dissertation contribute to the computer science and cognitive science areas, more specifically, the interdisciplinary fields of VR for pain management and empathy facilitation. VR developers and researchers will gain greater insights as well as actionable design recommendations from this research in designing proper embodiment features for pain and empathy. Cognitive scientists in pain and empathy could benefit from the data and its analysis of the three pain-related studies and the two empathy practices. The framework proposed in the last chapter also provides a clear flow of the potential underlying mechanisms of how VR works for pain and empathy for future studies to follow. My work contributes a new approach for HCI researchers, as it explores the roles of embodied VR in altering people's perceptions and behaviors. The conceptual framework also exemplify how researchers can look beyond the bounds of embodiment illusions, and look at the other three illusions (see Chapter 7.4.3). This work extends virtual embodiment from its three subcomponents to a broader design framework for pain management and empathy. Further, I examine underlying theories to explain the effect of virtual embodiment on these changes. This holistic research lens has allowed for a far more complete understanding of virtual embodiment and pain.

Chapter 2. VR and Pain Alleviation

In this Chapter, I adopted a narrative review approach to explore the research background of VR and pain alleviation. Immersive VR was introduced to the field of pain management at the beginning of the 21st century. Growing evidence has demonstrated its effectiveness in pain modulation, which is known as VR analgesia, but how and why it works are unclear. Further, few studies have discussed the factors impacting VR environmental design and how the two existing approaches to VR analgesia differ from each other. The approaches are detailed immediately below.

Attention distraction. This is the channeling of one’s attention into an immersive VR environment and is particularly relevant to acute pain patients (Bidarra et al., 2013; Gold et al., 2005; Wiederhold et al., 2014). It can also be thought of as focusing one’s attention inward to the pain. It can be combined with other cognitive therapies, such as mindfulness meditation and controlled breathing, that have been proven to help chronic pain patients self-manage their pain (Gromala et al., 2015).

Virtual embodiment occurs when a person sees a virtual body or has an SoO over one, and it can alleviate pain, especially that induced in healthy subjects (Martini et al., 2014). SoO is independent of pain, and prior research has been mostly exploring the potential effect of virtual body’s motion and appearances on pain, or the correlations between SoO and pain (Käthner et al., 2019; Martini et al., 2013, 2015; Zanini et al., 2017).

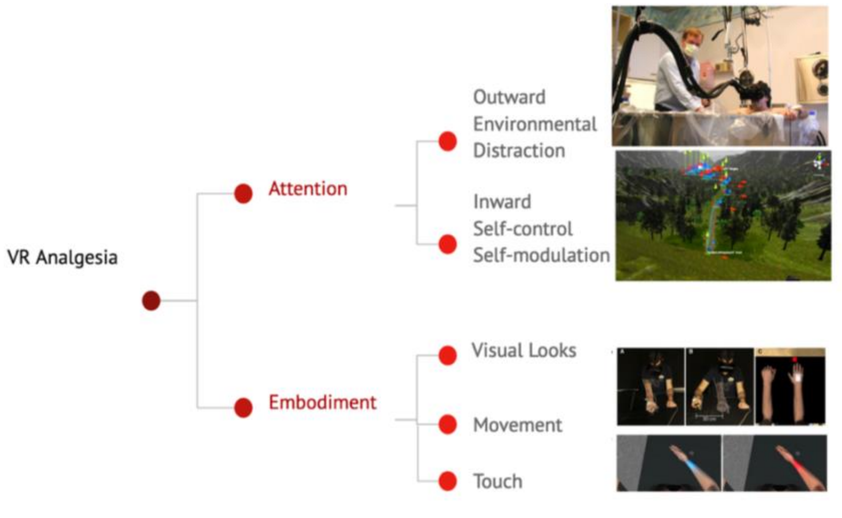

Figure 2.1 Diagram of two primary approaches to VR analgesia.

This chapter is organized as follows: I review the literature on both approaches, including study methodologies, research instruments, and materials. I also analyze factors that impact VR analgesia. Additionally, I explore the types of embodiment illusion used in pain-related behavioral-cognitive interventions, including mirror therapy, RHI, and virtual body illusion, as well as the various explanations of their analgesic effects that inform our understanding of virtual embodiment's effects on pain.

To set up this dissertation's theoretical framework, this chapter seeks to answer the following questions inspired by the literature: what are the approaches to VR analgesia? How has each approach been practiced in research settings? What is virtual embodiment, and what role does it play in pain modulation? What theories inform VR analgesia, and what factors affect it in practice?

2.1. Distraction in VR for Pain Alleviation

2.1.1. Prior Research

At the turn of the 21st century, Hoffman's research group began studying VR's relevance to pain distraction in a virtual environment called SnowWorld (Hoffman et al., 2001a, b, c, 2008, 2011). They first explored whether immersive VR environments reduce burn pain patients' acute pain, and their results showed significant improvement in patients' self-reported pain ratings. Because processing pain signals requires conscious attention and an individual has only a finite amount available at any given time (Villemure & Bushnell, 2002), Hoffman et al. (2000) hypothesized that immersive VR could compete with pain for limited cognitive resources and thus reduce pain levels. In other words, the authors thought that VR could draw the patient's focal spotlight into a virtual world, providing an intense immersion and shifting the patient's awareness away from their pain. Since then, Hoffman's group and other researchers (Das et al., 2005; Gold et al., 2006; Hoffman et al., 2007, 2011; Wiederhold et al., 2014; Chan et al., 2019) have pursued a series of clinical VR attention distraction studies. Hoffman et al. conducted a series of studies to understand if VR could provide better analgesia effect than other media distraction, and his group found that participants felt great perceptual and multisensorial intensity in VR environments that watching movies or playing games can' offer (Hoffman et al., 2001a, b, c; Hoffman et al., 2004). Also, Gold et al. compared the effect of pain reduction of the same game in immersive VR and in a 2D screen, and discovered that VR outperformed the screen because of its strong immersion (Gold &

Mahrer, 2018). However, most research didn’t follow up after the one-session lab intervention. Further, the VR environments have seldom included an avatar that patients can embody.

Similarly, directing attention inward in order to self-control pain can result in significant pain alleviation after the VR intervention than before, which is also called pain self-control or self-modulation). For instance, Gromala et al. (2015) evaluated how directing patients’ attention to real-time audio-visual feedback in VR affected pain and found that chronic pain patients’ pain levels decrease. The pain levels were visualized as fog, the thickness of which correlated with the intensity of pain. However, no study has yet compared the efficacy of directing attention inward into one’s body rather than outward into the environments.

Gold et al. (2007) and Li et al. (2011) analyzed the neuroscience of using VR for pain attenuation by conducting literature reviews to search for relevant pain mechanisms. The authors agreed on the attentional distraction and emotional changes achieved by VR and that the brain changes leading to reductions in pain sensations can be explained by the ascending and descending pain pathway systems. Gold et al. hypothesized that the emotional component of VR might further modulate pain by means of the connections between the amygdala, the ACC, and the periaqueductal gray (PAG).

Additionally, Hoffman et al. (2004) designed an fMRI-friendly VR headset and scanned healthy participants’ brains after using heat to induce pain. The fMRI data revealed that the pain-related brain areas (the anterior cingulate cortex, primary and secondary somatosensory cortexes, insula, and thalamus) were less active in the posttest condition than in the pretest condition.

In general, VR has shown great potential for patients seeking to manage or alleviate acute pain or chronic pain over the short term. However, it is not yet known if the pain distractive effect persists beyond the VR sessions or how long it lasts because very few studies (Ambron et al., 2018; Ortiz-Catalan et al., 2016) followed up with their participants once completed.

Beyond not knowing its long-term effects, the attention distraction approach has a few limitations. The VR games evaluated in research studies are either commercial products not specifically designed for patients or have very similar mechanics and user interactions to SnowWorld (e.g. throwing balls on a moving trail), thus producing similar outcomes (Wiederhold et al., 2014; Choo, 2015; Gromala et al., 2016; Jin et al., 2016). Further, current VR attention distraction studies have low evidence levels. Their data are considered high risk because of the studies' small sample sizes, novelty effects, and placebo effects. They are also characterized by short-term interventions that do not include follow ups as well as a lack of strong biological evidence. Measuring brain changes using fMRI data is expensive, time consuming, and complicated when participants need to wear an HMD. Still other studies have arrived at conflicting conclusions. To verify the effectiveness of VR analgesia, more evidence needs to be gathered to resolve three problems:

(1) most studies have been based on short-term interventions, and follow ups or long-term interventions are needed;

(2) the determining factors of VR analgesia are less investigated, as most studies utilized dated VR environments or commercial games, and more modern, bespoke interventions are required. Two reasons support explorations in this direction: (1) most of the results from prior studies were based on older version of VR environments. For instance, SnowWorld was initially designed for burn pain patients but later adopted in other situations, such as dental pain, heat-pain, and so on. In other words, most studies don't use VR that are specifically designed for a specific treatment modality. Further, (2) Technology advances so fast and the look and feel of VR environments constantly change; and

(3) most studies have lacked physiological evidence or proof of brain changes, such as fMRI or EEG data, which are needed to generate more robust evidence. Although no clear biomarkers of pain, there are compelling arguments that fMRI or EEG data may indicate neuroplasticity changes in the brain.

2.1.2. Research Methods

Here, I summarize the common research methods adopted in most VR pain distraction studies from study design, VR content, and instruments aspects.

2.1.2.1. Study Design

Before-and-after pilot studies with no control groups. Some studies used before-and-after comparisons to assess how VR environments or games impact participants' pain ratings, e.g., (Hoffman, Richards, et al., 2004; Gold et al., 2005; Shahrbanian et al., 2009; Hoffman et al., 2011). In these cases, only the VR experiment conditions were evaluated. For instance, some of Hoffman's studies evaluated VR interventions in a single experimental condition without control conditions (Li et al., 2011; Hoffman et al., 2004). The drawback was that this study's positive findings could have resulted from a novelty or placebo effect. This type of study is mostly seen in pilot or feasibility studies or experiments with PLP patients or those suffering from other types of chronic pain, as such patients are rare and hard to recruit.

Case studies or case series with a few participants. Case studies refer to in-depth or intensive studies of a single individual or specific group, whereas case series is a grouping of similar case studies. When participants are difficult to recruit in pain and VR research or researchers want to validate proof of concept and the technology's long-term feasibility and effectiveness, case studies or case series were generally conducted (Gershon et al., 2003; Hoffman et al., 2001a, c; Steele et al., 2003). The most commonly published case studies involved certain groups of chronic pain patients, particularly PLP patients (Ambron et al., 2018; Chau et al., 2017; Ortiz-Catalan et al., 2014). Researchers chose to conduct case studies instead of regular controlled experiments because PLP patients' mobility issues prevented their participation.

Randomized control trials. Hoffman et al. (2003) began by conducting a preliminary study with a small group of participants in which they tried all conditions (the within-subjects approach) or only one condition (the between-group approach). Recently, more and more studies have run randomized control trials (RCTs) and compared two or three VR conditions with a control condition to prove the analgesic effect of VR systems (Chan et al., 2019; Das et al., 2005; Gold & Mahrer, 2018; Jin et al., 2016).

2.1.2.2. Study Materials: VR Content

Research prototypes. Most researchers have used self-developed research prototypes, e.g., (Hoffman et al., 2011; Choo, 2015; Gromala et al., 2016), while a few have tested commercial VR games as listed in the next paragraph, e.g., (Amin et al., 2017; Montano, et al., 2011). Among all VR research prototypes, the earliest and most well-known is Hoffman's SnowWorld, which has been assessed multiple times (Hoffman et al., 2001b, c, 2004, 2011, Mühlberger et al., 2007). Their prototypes have also been evaluated for their effects on pain modulation, including SurrealWorld (Gutierrez-Martinez et al., 2010), SpiderWorld (Carlin et al., 1997), Dante's Valley (Mühlberger et al., 2007), Virtual Meditative Walk (Gromala et al., 2015a), Mobius Floe (Gromala et al., 2016), and various movie clips.

Commercial titles. Numerous VR companies have developed commercial games in different genres for pain management purposes, including Firsthand (Firsthand Technology, 2020), AppliedVR (AppliedVR, 2020), Virtual Therapeutics (Virtual Therapeutics, 2020), and KarunaLabs (Karuna, 2020). AppliedVR, for example, has developed interactive exploration games, breath-training applications, mindfulness applications, and relaxation applications, while FirstHand developed an interactive exploration game called COOL! and a breath-training application called GLOW. The companies conducted scientific studies themselves or with clinical partners to prove the effectiveness of their products, but few of their studies investigated how environmental design factors affect the games' analgesic effects.

2.1.2.3. Study Instruments

Self-reported pain ratings are generally used to measure study outcomes, and researchers usually adopt more than one rating to validate them. The Short-Form McGill Pain Questionnaire (SF-MPQ; Melzack, 1975), visual analog scale (VAS), and numerical rating scale (NRS) are commonly the primary pain measures. In some cases, secondary outcomes are measured. Secondary outcomes consider different aspects of chronic pain, such as frequency, quality, disability, self-efficacy (susceptibility to patient's self-management), intrusion in sleep, the patient's mood, presence of catastrophizing thoughts, the patient's health-related quality of life, and the patient's own impression of the treatment's efficacy of treatment. Such instruments include.

Pain Disability Index. This instrument is a seven-item questionnaire designed to investigate the extent to which chronic pain interferes with a person's ability to engage in various activities (Tait et al., 1990). An overall score is obtained by adding up the numerical ratings of the questionnaire's single items.

Short-Form Brief Pain Inventory. This instrument is a nine-item self-administered questionnaire used to evaluate the severity of a patient's pain and its impact on the patient's daily functioning (Cleeland & Ryan, 1994).

Hospital Anxiety and Depression Rating (HADS). This instrument is a fourteen-item scale with seven items related to anxiety and seven to depression. Doctors commonly use it to determine the levels of anxiety and depression a person is experiencing (Snaith, 2003).

EuroQol-5D-5L. This instrument is a standardized questionnaire used to investigate health-related quality of life in terms of health status and health evaluation (EQ-5D, 2020). Health status is measured in five dimensions (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression) on a five-point scale ("no problems," "slight problems," "moderate problems," "severe problems," and "extreme problems"). In the health evaluation part, the EQ VAS records the respondent's health on a vertical VAS, the endpoints of which are labeled "best imaginable health state" and "worst imaginable health state."

Pain Self-Efficacy Questionnaire. This instrument is a two-item questionnaire that measures pain self-efficacy, which is the belief held by people with chronic pain that they can carry out certain activities and enjoy life despite experiencing pain (Nicholas et al., 2015). The items are rated on a scale of 0 to 6.

Pain Catastrophizing Scale. This instrument is a six-item questionnaire that investigates catastrophizing thinking using a range of 0 to 4. Pain catastrophizing refers to a negative cognitive-affective response to pain and is associated with increased pain severity, disability, depression, and poor adjustment to chronic pain.

Patient Health Questionnaire. This is a screening instrument consisting of two items assessing the presence of a depressed mood and a loss of interest or pleasure in routine activities. The items are rated on a scale of 0 to 3.

Patients' Global Impression of Change. This instrument consists of a single question identifying a clinically significant change by rating the patient's belief about the efficacy of treatment on a seven-point scale that ranges from "no change (or condition has gotten worse)" to "a great deal better."

Additional measurements. Most researchers ask participants to supply background details, such as their age, gender, height, weight, type and use of medication, details about previous and ongoing interventions for chronic pain, and level and date of diagnosis as chronic pain patients. Additionally, semi-structured qualitative interviews might be conducted to explore participants' subjective experiences of using a VR system for pain self-modulation.

2.1.3. Section Summary

According to systematic literature reviews (Dunn et al., 2017; Mahrer & Gold, 2009; Malloy & Milling, 2010; Triberti et al., 2014), although VR research shows great initial promise in its ability to decrease pain and other negative aspects of painful medical and experimental procedures, the experimental design didn't control the bias in RCT study design and can be considered weak. In other words, they should be interpreted cautiously and in light of fundamental scientific limitations. In general, sample sizes continue to be small, losing the power to detect the possible real effect, i.e., type 2 error. Additionally, the methodology used to test the technology has been highly variable, even though VR has been tested with specific populations. Researchers who have adopted the VR attention distraction approach have used a variety of VR environments, pain measures, and study designs. Further, most have deployed a single intervention, and very few have followed up with participants. The long-term impact of VR in pain thus remains unclear. Future studies should use consistent and experimentally rigorous methodologies and recruit a larger number of participants to increase the power and generalizability of their results.

2.2. Embodied Cognition, Embodiment, and Pain

In this section, I first review how one's embodied cognition affects pain, the embodied phenomena related to pain, and the embodied cognitive therapies developed for pain modulation. As mentioned in Subsection 1.2.2, VR can elicit four primary forms of presence illusions: place illusion, self-embodiment illusion, physical interaction, and social communication (Jerald, 2016; Slater, 2009). In this section, I offer an in-depth explanation of each illusion, and I focus on the self-embodiment illusion because of its singular relevance to virtual body presentation.

2.2.1. Embodied Cognition, Embodiment, and Pain

2.2.1.1. Distorted Body Image and Pain

In everyday life, our sense of embodiment affects almost everything we do. Using a mapping procedure, the human brain annexes the invisible space out to the limbs' length from the body. Blakeslee and Blakeslee (2008) mention that this map connects one's cognition to the events possible in the space around the body. They also suggested that this map could include the shared space of another object, animal, or person. Therefore, the brain does not only map the body but also the space around it and even the social world.

Body image and body schema are two essential concepts when developing an understanding of embodiment and embodied cognition. In the context of body image and pain, differentiating the concepts of body image and body schema is important, as is explaining how they are associated with one's embodied experience and how they affect one's perception of pain. Gallagher (1986) argued that they are two distinct concepts that should be separately defined, and he proposed a phenomenological clarification of each. In short, body image refers to one's estimations of body dimensions. Body image is a perceptual, cognitive, or emotional awareness of the body, whereas body schema is neither perception nor the cognitive understanding/emotional apprehension of the body. Instead, body schema is a non-conscious postural performance of the body and operates the body in an unconscious, unowned, or anonymous manner. In the concept of body schema, the body functions holistically and is not in and of itself apart from the environment. Interestingly, according to Gallagher, body schema maintains equilibrium between one's body and the environment, but sometimes is also determined by body image.

Lotze and Moseley's (2007) evidence of neural representations of body image in the primary sensory and motor cortices suggested that patients in pain have distorted body images. The increased cortical excitability found in pain patients may help drive cortical reorganization. Although clinical evidence is scarce, imaging findings have revealed how one's body image may be distorted in pain and that the treatment of pain may reduce and normalize the distorted body image, which has significant clinical implications (Lotze & Moseley, 2007). Other experiments suggested that disrupted body images critically impact chronic pain patients (those with PLP, CRPS, back pain, and osteoarthritis) and alter sensory input for motor imagery and executed movement (Gilpin et al., 2015; Lotze & Moseley, 2007; Moseley, 2004, 2005, 2008). For instance, Moseley (2005) conducted a study with CRPS Type 1 patients and used healthy control participants to compare how they perceived their hand sizes. Participants were asked to select images that matched their affected limbs, and the CRPS 1 patients picked images of limbs 105% larger than their own limbs. Overall, 63% of CRPS 1 patients and 17% of control group participants selected an image of a limb larger than their actual limb, meaning they perceived the affected limb to be larger than it was. Other studies took other measurements and tests to evaluate and visualize patients' distorted body image, such as tactile function test using a two-point discrimination threshold measurement (Moseley, 2004, 2005, 2008; Osumi et al., 2014, 2015).

Here, I briefly explain PLP and CRPS and why most chronic pain studies have focused on it rather than other types of chronic pain. PLP is a type of chronic pain caused by limb amputation (Nikolajsen, 2012). Besides amputation, brachial plexus avulsion (BPA) injury—the detachment of the nerves from the nerve roots of the spinal cord in the arm—also leads to partial or complete arm paralysis and chronic pain (Wang et al., 2015). For instance, Teixeira et al. (2015)'s review showed that BPA patients experience PLP, similarly to some amputees, and they also found evidence from multiple studies that the central mechanisms play a more important role in BPA-related PLP. Most patients with BPA develop sensations in their damaged arm such as tingling, electric shock, and burning pain; this is similar to the PLP experienced by amputees (Abdel-Aziz & Ghaleb, 2014). Therefore, researchers believe that studying BPA has the potential to deepen the understanding of the roles that the peripheral and central nervous systems play in PLP (Russell & Tsao, 2018). The neural mechanism of PLP is still under debate. Some researchers proposed that cortical reorganization of neural representations of the missing limb and its neighboring body parts causes PLP (Flor et al., 1995, 2001; Karl et al., 2004). Others hold that the functional representation of the missing limb is preserved (Mercier et al., 2006; Raffin et al., 2012), and "peripheral" contributors—such as neuroma formation and ectopic firing in the residual nerves—are the major contributors of PLP (Kikkert et al., 2018; Makin et al., 2013, 2015). It has also been proposed that impaired sensorimotor circuitry leads to PLP because both central and peripheral factors play a role (Ramachandran & Altschuler, 2009; Sumitani et al., 2008).

With impaired sensorimotor circuitry, PLP patients also show degraded movement performance of the phantom limb. As a phantom limb is usually paralyzed or perceived as fixed in one or more particular positions (Ramachandran & Altschuler, 2009), it is difficult for patients to imagine moving their phantom limbs visually. Thus, the capacity of motor imagery (e.g., the time a patient takes to perform a task) might serve as a measurement of movement performance of the phantom limb, given that similar activations in the motor cortex during motor imagery and actual movements were observed in healthy individuals (Ehrsson et al., 2003). Indeed, previous studies demonstrated a prolonged response time and a lack of activation in the sensorimotor cortex during motor imagery tasks in amputees with PLP when compared to those without and that their response times, as well as activation, were closely related to the magnitude of the PLP (Diers et al., 2010; Lyu et al., 2016).

CRPS is describing excessive and prolonged pain and inflammation that follows injury to a limb. Defined by IASP, The hallmarks of CRPS as defined by IASP include the following: (a) specific injury or noxious stimuli, which may include surgery; (b) continued pain that is disproportionate to the noxious stimuli or injury, including allodynia and hyperalgesia; (c) changes in localized skin, including edema and changes in blood flow and coloration of the skin; and (d) no specific dermatomal or nerve pattern (IASP, 1996). It has acute (recent and short term) and chronic (lasting longer than six months) forms (Moseley, 2005). Although CRPS may improve over time, severe or prolonged cases are profoundly disabling. In short, CRPS is caused by damage to or malfunctions in the peripheral and central nervous systems, and it most often affects one limb or extremity (arm, leg, hand, or foot). It is a difficult disease to cure, and psychotherapy and graded motor imagery have been most commonly adopted in rehabilitations. In this dissertation, I only deal with the chronic conditions of CRPS.

Further, Moseley et al. (Moseley et al., 2008) also addressed the significant role of movement. In a motor imagery task, healthy participants had significantly faster reaction times than chronic pain patients, which was attributed to the pain patients' distorted body images (Moseley et al., 2008; Uritani et al., 2018). However, motor imagery, mirror box therapy (Ramachandran et al., 2009b; Ramachandran & Rogers-

Ramachandran, 1996), and combined graded motor imagery therapy (Bowering et al., 2013) have shown successful results in managing chronic pain, especially patients suffering from distorted body images, such as those with PLP or CRPS (Diers et al., 2010; Giummarra & Moseley, 2011). Below, I describe how mirror therapy and graded motor imagery therapy work and explain the role of embodiment and body image in these interventions.

2.2.1.2. Mirror Therapy

Initially developed by Ramachandran (2009a), the virtual mirror box is an intervention in which a mirror is vertically positioned on a table and a patient's intact hand is effectively superimposed on the felt position (visually superimposed position) of the phantom one. Researchers call this "mirror therapy" or "mirror exposure therapy" (e.g., Delinsky & Wilson, 2006; Chan et al., 2007; Henriksen et al., 2018). In Ramachandran and Rogers-Ramachandran's (1996) study, six out of 10 PLP patients reported perceiving the phantom hand when their normal one moved. The patients' kinesthetic sensation merged with the phantom hand, which put them in a pleasant mood. Not only did they experience a sense of ownership over the phantom arm, their PLP was mitigated (Dunn et al., 2017). Findings showed that most PLP patients experience a decrease in pain intensity when they perceive the willed visuomotor imagery of the affected limb (Sumitani et al., 2008). Later, Ramachandran et al. (2009b) discovered that using optical techniques to present a smaller hand in a mirror to PLP patients can also decrease their pain levels. The researchers believed that viewing the intact hand through a mirror can alter a person's body-related perceptions and emotions, which may also alter their body images.

To date, the mirror box technique (or mirror therapy) has inspired many current VR/AR systems, and designers have adopted the technique of mirroring the movement of PLP patients' intact limbs to reconstruct the movement of their phantom ones. This technique was also adopted in one of my studies involving PLP patients, which is described in Chapter 5.

Besides mirror therapy, other cognitive behavior therapies have also been developed to treat chronic pain, such as left/right judgment training and explicit motor imagery (Bowering et al., 2013; Moseley, 2006). Bowering et al. didn't consider Johnson et al.’s (2012) case series study because it wasn’t an RTC design. However, Johnson et al.’s (2012) received opposite results and found that mirror therapy didn’t work. Therefore, the effect of mirror therapy remains controversial and requires further explorations. Left/right judgment training refers to a person’s ability to identify left or right images of their painful body part(s) and is relevant because pain patients take longer to identify left or right body parts than healthy people (Moseley, 2004; Moseley et al., 2012). Explicit motor imagery describes the movements a person imagines. Motor imagery can be defined as a dynamic imagining during which an individual mentally simulates a physical action. It is the mental execution of a movement without any overt movement or peripheral muscle activation. Mulder (2007) found that motor imagery leads to the activation of the same brain areas as actual movement.

In 2004, Moseley et al. proposed a new form of cognitive behavior therapies, named Graded Motor Imagery (GMI), which included mirror therapy. GMI is increasingly applied in the treatment of chronic pain conditions. As shown in Figure 2.2, GMI includes three motor-related stages in chronic pain management. In a systematic review, Bowering et al. (2013) analyzed all the evidence proving the effects of GMI and its constituent components on chronic pain. The authors targeted studies that conducted RCTs, and eight met their inclusion criteria. By calculating effect size, they found that the overall methodological quality was low. Some conflicting results were found when motor imagery was used as a stand-alone technique, and no effect was seen in a left/right judgment training sub-intervention. However, other studies observed the positive effects of both mirror therapy and GMI. To conclude, mirror therapy and GMI might be useful, but the current evidence is limited by sample sizes and effect sizes.

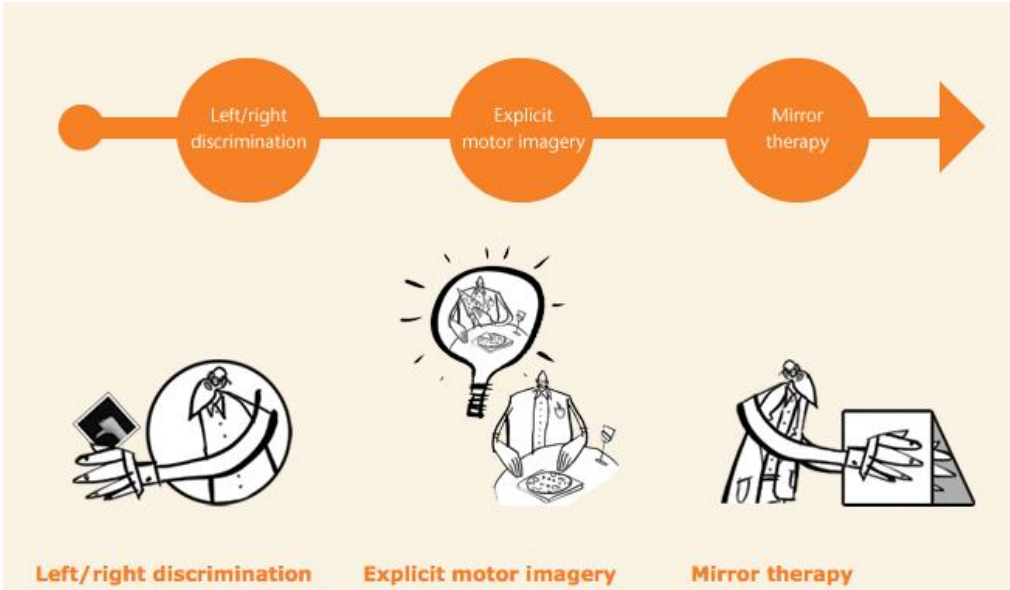

Figure 2.2 The graded motor imagery approach to treating chronic pain (Graded Motor Imagery, 2020).

2.2.1.3. Rubber Hand Illusion, Virtual Body Illusions, and Pain

Embodiment-illusion-triggered analgesic effect has been demonstrated with rubber hands and mirrors by neuroscientists and perceptual psychologists. Ramachandran et al. (1996) and Botvinick and Cohen (1998) wrote well-known studies that are relevant to VR. Studies that explored the Rubber Hand Illusion (RHI) found that people perceive a rubber hand as theirs when their actual hand is hidden (Botvinick & Cohen, 1998), and this can have an analgesic effect (Fang et al., 2019).

Therefore, I will now focus on studies that used RHI to influence people's pain (Mohan et al., 2012; Moseley, Parsons, et al., 2008). Cognitive scientists discovered RHI in the late 90s (Botvinick & Cohen, 1998), when the perception of owning a rubber hand was elicited by having study participants who are able to feel the sense of ownership (unlike blind people), experience multisensory integration of seeing the rubber hand touched while feeling the touches on the real hand, which led the participant to have a sense of embodying it. RHI can foster an SoO. Most studies found that the vision of a rubber hand offers an analgesic effect when a person incorporates it into their body image. However, studies on RHI and pain had conflicting findings: some found that RHI increases pain ratings (Fang et al., 2019), while another study found that it has no effect (Mohan et al., 2012). Martini (2006) proposed a theory to explain the conflicting findings, suggesting that the physical appearance of the rubber hand plays a critical role in driving the modulatory effect of body image on pain perception.

Although RHI is the illusion of owning a rubber hand, scientists have recently shifted their attention to how one perceives the body and hand in VR, and they discovered the Virtual Hand Illusion (VHI) or Full-Body Illusion (Martini, 2016). Similar to RHI, VHI is the feeling of owning virtual hands in VR. After researchers discovered that people could perceive virtual hands to be their own (IJsselsteijn et al., 2005; Petkova & Ehrsson, 2008; Slater et al., 2008, 2010), they began testing if SoO in VR can produce an analgesic effect (Martini et al., 2014; Gilpin et al., 2014; Martini et al., 2015; Matamala-Gomez et al., 2018, 2020). However, most studies had more positive findings than null effects (Martini et al., 2014; Martini et al., 2015); these results seemed to be strictly connected to the visual properties of the hands or other body parts.

2.2.2. Self-Embodiment Illusion and Virtual Embodiment

In this section, I first introduce the four presence illusions in VR, focusing on the embodiment presence and then discuss the definition and subcomponents of virtual embodiment in depth.

2.2.2.1. The Four Types of Presence Illusions in VR

The illusion of being in a stable place. This illusion is sometimes called place illusion (Slater, 2009) and sometimes spatial presence (Schubert, 2003). Slater (2009) described it as the feeling that one's physical environment is the most important aspect of their sense of presence. In another of his papers, Slater (2009) defined place illusion as "being there," and is a perceptual illusion that occurs automatically under the right conditions (sensorimotor contingencies). However, he also indicated there is plausibility illusion (Psi), which refers to the illusion that the depicted scenario is real.

The illusion of embodiment (self-embodiment). Self-embodiment has multiple working definitions. Kilteni et al. defined it as the ensemble sensations that arise in conjunction with being inside, having, and controlling a body (2012). Certainly, any feelings about their virtual body fall under this presence category, including SoO or the sense of having control over the body. For more information, see Section 3.1 of this chapter. Many cognitive science studies, especially those conducted by members of Slater's and Bailenson's research groups (Bailey et al., 2016; Banakou et al. 2016; Tajadura-Jiménez et al., 2017), tried to investigate how embodiment illusion alters the mind perceptually and/or behaviorally.

The illusion of physical interaction. This illusion occurs when a person feels a physical response that aligns with a visual representation. This response is not limited to tangible feelings; it also includes visual changes or audio feedback (Jerald, 2016).

The illusion of social communication (social presence, or co-presence). Social presence is the perception that one is communicating with other characters in VR either verbally or with body language (Gerhard et al., 2004; Jerald, 2016; Nowak & Biocca, 2003; Schroeder, 2005). The other characters could be computer controlled or user controlled. This component is another essential aspect of presence that most researchers investigate, including many of those in Slater's group (Slater et al., 2006; Oh et al., 2018).

2.2.2.2. The Illusion of Virtual Embodiment

In this dissertation, my focus is the effect of self-embodiment illusion on human perception, which is also called sense of embodiment or virtual embodiment in VR. SoE in VR is defined as **the experience or feeling of owning (SoO), controlling (SoA), and being inside a body (self-location)**. As discussed in Chapter 1, Section 1.2.2, I adopted Kilteni et al.'s (2012) definition and framework of virtual embodiment for this dissertation, and it specifies three subcomponents: SoO, SoA, and sense of self-location.

The sense of embodiment is defined as "the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body" (Kilteni et al., 2012, p. 2). According to Kilteni et al. (2012), embodiment consists of three subcomponents: SoO, SoA, and sense of self-location. SoO commonly refers to one's self-attribution of a body (e.g., Gallagher, 2000; Tsakiris, 2010), whereas SoA is concerned with the subjective experiences of motor control and the conscious experience of will (Blanke & Metzinger, 2009). Ownership, agency, and self-location are not inclusive to artificial bodies or body parts but also include avatars and mannequins (Petkova & Ehrsson, 2008; Slater et al., 2010; Slater, Perez-Marcos, et al., 2009). While my literature review revealed potential interrelationships among the three subcomponents (Braun et al., 2018), the current state of knowledge on embodiment does not enable further specification of their significance to the embodied experience (Kilteni et al., 2012).

SoO. This sense refers to one's self-attribution of a body (Gallagher, 2000; Gallagher & Marcel, 1999). Braun et al.'s (2018) literature review suggested that SoO describes the feeling of mineness that one experiences toward the body parts. People describe this feeling with statements such as "This is 'my' hand," "'I' am thinking this thought," or "'I' am the one who is having this feeling." Some studies have investigated which properties of the virtual body affect SoO, such as the transparency level of an avatar's skin (Martini et al., 2015), appearances of the virtual arm (Martini et al., 2013), and synchronous or asynchronous movement between real and virtual arms (Zanini et al., 2017). Further, getting visual feedback from the virtual world that is synchronous with tactile feedback from the real world like in the RHI phenomenon has also been associated with one's SoO in VR (de Jong et al., 2017).

SoA. This sense refers to the sense of having ''global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will'' (Braun et al., 2018). Unlike ownership, which describes an attributive relationship, agency is felt dynamically and presented in active movements (this is authorship rather than ownership; Braun et al., 2018). A person experiencing SoA in VR will say something like, "It seemed like I was in control of the virtual hand." SoA distinguishes one's self-generated actions from actions generated by other people (David et al., 2008; Moore, 2016). Sanchez-Vives et al. (2010) found that SoA in VR is easily achieved when a person's real-body motions are mapped to the virtual body in real time. Therefore, the development of SoA primarily depends on the synchronicity of visuomotor correlations, regardless of the artificial, mirrored, or virtual conditions. Numerous studies have found that asynchronicity between the visual feedback of the action and the actual movement negatively affect SoA (Blakemore et al., 2002; Franck et al., 2001; Sato & Yasuda, 2005).

Few studies explored the relationships or associations between SoA and pain in VR conditions compared to SoO. Moreover, it has rarely been studied separately from SoO (Braun et al., 2018). In one case (Braun et al., 2018), the synchronous feedback of movement (correlated visuomotor) not only increased SoA but also correlated with an increased SoO. Although I have examined SoO and SoA separately, quite a few researchers have investigated the interplay of SoA and SoO (Braun et al., 2018). However, in many quotidian situations, we experience SoO and SoA simultaneously. Since the operationalization of SoO and SoA are not necessarily exclusive, the measurement of each (and their self-location) can overlap (Ehrsson et al., 2007; Slater et al., 2008; Slater et al., 2010).

Sense of self-location. The sense of self-location refers to where a person feels they are located; generally, self-location and body space coincide with a person feeling self-located inside a physical body (Lenggenhager et al., 2009).

2.2.2.3. Study Instruments of SoO and SoA

In general, SoO has been well-examined using both quantitative approaches (task performance, questionnaires, and physiological biomarkers) and qualitative approaches (questionnaires or interviews). However, SoA has not been comparably well examined, especially in VR. Cognitive scientists have been studying the potential neurological models of how the brain computes SoA (Haggard & Chambon, 2012). Although some VR studies (Cole et al., 2009; Martini et al., 2014; Zanini et al., 2017) provided their participants with motor control over the virtual body (or body parts), only few measured SoA (Käthner et al., 2019; Matamala-Gomez et al., 2019).

Lacking a gold standard of measuring SoO and SoA, some researchers adopted the explicit method through participants' subjective ratings. In contrast, others relied more on implicit measurements, such as behavioral tests or biofeedback. Although aiming to measure the same sensations (SoO or SoA), implicit and explicit results could be different (Kong et al. 2017). Next, I discuss how each approach were utilized in varying studies.

Self-reported questionnaires and interviews (explicit measures). Most virtual embodiment studies rely on self-reported questionnaires to report SoO. For instance, all of Slater's group's studies (e.g., Slater et al., 2010; Aspell et al., 2009) adopted standard survey statements and questions to assess SoO. Statements included ''I felt as if the rubber hand was my hand'' and ''I felt as if the virtual body was my body'' (Aspell et al., 2009, p. 4), and questions included ''How much did you feel that the seated girl's body was your body?'' (Slater et al., 2010, p. 4). Likewise, the Sense of Agency Rating Scale questionnaire (Polito et al., 2013) has two factors: involuntariness, which represents a subjective reduction in control over one's own actions (e.g., "I felt that my experiences and actions were not caused by me", Polito et al., 2013, p. 208), and effortlessness, which represents a subjective increase in the ease and automaticity with which actions occur (e.g., “My experiences and actions occurred effortlessly,” Polito et al., 2013, p. 208). However, as when measuring SoO, researchers usually develop new questionnaires based on existing ones to fulfill their specific research goals. For instance, Slater’s group mostly asked participants to rate SoA using scales on a questionnaire, which appears to be the most widely used approach to evaluating SoA in VR conditions. Two statements that participants ranked were “It seemed like I was in control of the virtual hand” and “I felt as if I was controlling the movements of the virtual hand” (Sanchez-Vives et al., 2010, p. 3; Martini et al., 2014, p. 4).

Task performance (implicit measure). The specific tasks vary depending on the researchers’ goals for specific VR situations, and some tasks conducted in the real word to measure SoO are hard to carry out in VR. Although different proprioceptive estimation tasks, such as proprioceptive drift, have been used to measure SoO in non-VR situations (Botvinick & Cohen, 1998; Jsselsteijn et al., 2006) and a few VR studies (Sanchez-Vives et al., 2010; Slater et al., 2008), they have rarely been adopted in VR situations. However, a few studies (Banakou et al., 2013; Braun et al., 2018) utilize participants’ performance in body part estimation to measure SoO. In other cases (Ehrsson et al., 2007; Steptoe et al., 2013), researchers measured participants’ reactions when their virtual body was threatened.

However, apart from proprioceptive estimation tasks, motor tasks can be used to assess agency, such as the intention-binding task (Braun et al., 2018). Kong et al. (2017) included this task in VR and used it to measure participants’ SoA. The idea is that the more successfully the motor tasks are performed, the finer the control a person can achieve over the artificial body. Presumably, higher SoA correlates with higher task performance. The intention-binding effect refers to the subjective compression of time experienced between a voluntary action (e.g., a self-conducted button press) and its external sensory consequences (e.g., a sound played thereafter). A common finding is that this time interval is only underestimated when the action is voluntary, not when it is involuntarily (Braun et al., 2018).

Physiological measurement. Electrophysiological information, including that related to touch (Hohwy & Paton, 2010; Moseley, 2008), heart rate (Slater et al., 2010), as well as hemodynamic information (Kanayama et al., 2009; Press et al., 2008) and body temperature (Ehrsson et al., 2007) have been collected to measure SoO, though not in VR environments. Ehrsson et al. (2007) investigated physiological data and correlated the biomarkers with participants' SoO. However, physiological data seems to be necessary to indicate SoO but is not a primary means of measuring it. In my literature review, I did not find any studies that used physiological measurement to assess SoA levels in VR.

The central prerequisite of inducing SoO and SoA in VR is an avatar or, at least, part of one avatar, such as limbs or tubes. Correlated and synchronous visuomotor feedback in VR could contribute to stronger SoO and SoA. The explicit communication of one's feelings of owning (SoO) or controlling (SoA) an avatar can be qualitative. For instance, for SoO, "I felt as if the virtual right arm/hand was my own right arm/hand" (Martini et al., 2014, p. 4) could be a useful description; for SoA, it could be "During the experiment there were moments in which it seemed that my real arm was moving" (Zanini et al., 2017, p. 4). Even though participants of Zanini et al. and Martini et al. were shown unrealistic bodies or body parts, after an adaptation period, the aforementioned statements could also be used to evaluate or express feelings of SoO and SoA. Task performances' results can also be used to describe implicit feelings of SoO and SoA. Although not all studies have measured the implicit and explicit aspects of SoO/SoA together, a select few did show that explicit results can be significantly different than implicit results (Braun et al., 2018; Kong et al., 2017). For example, Kong et al.'s study showed that participants did not report a strong SoA but the implicit test showed that agency did exist. In my dissertation, I adopted the subjective SoO and SoA ratings. Carrying out the other implicit measurement may yield other findings.

2.2.3. Section Summary

"Embodiment" is a term here used to refer to a general sense of one's body as the center of identity and inseparable from sensory experience and perception. The sense of virtually embodying an avatar conveys a feeling of mineness from the first-person point of view. Kilteni et al. (2012) investigated components that inform the sense of embodiment, including ownership, agency, and the self-location of an avatar. In this section, I first described the body-related illusions and interventions relevant to pain modulation, such as body image and body schema RHI, VHI, mirror therapy, and graded motor imagery. Then, I cited literature that defines the framework of embodied cognition (Costa et al., 2013), embodiment (Longo et al., 2008), and virtual embodiment (Kilteni et al., 2012), and I explored potential measurements of its two primary subcomponents, SoO and SoA. Designing this structure helped me to better scope my research and investigate the subcomponents of embodiment in VR, such as SoO and SoA (Braun et al., 2018). The research on the definition and composition of virtual embodiment introduced here laid the foundation for both research trajectories.

2.3. Virtual Embodiment for Pain Alleviation

In this section, I discuss the study design, VR content, and instruments adopted by researchers in the virtual embodiment pain management approach.

2.3.1. Prior Research

In addition to exploring the attention distraction approach in VR, virtual embodiment studies suggest that merely seeing a virtual body can also have an analgesic effect on healthy people’s induced pain (e.g., heat-, cold-, pressure-, or needle-induced pain; Hänsel et al., 2011; Longo et al., 2009; Martini et al., 2014; Romano et al., 2016) and in patients’ perceived neuropathic pain (Matamala-Gomez et al., 2018). For instance, both Hänsel et al. (2011) and Gilpin et al. (2014) found that when pain was induced by experimental stimuli on the real body, seeing the virtual body in VR could increase pain thresholds compared to the control condition in which no virtual body was presented. This was similar to Longo et al.’s (2009) study in which participants experienced reduced pain when observing an arm in mirrors, and other researchers suggested that having SoO over an avatar (i.e., virtual body illusions) is the fundamental reason for the virtual embodiment analgesic effect (Gilpin et al., 2014; Hänsel et al., 2011).

Other studies have explored how different features or avatar features, such as avatar appearance and motion, influence SoO and the analgesic effect (Matamala-Gomez et al., 2018; Martini et al., 2015; Osumi et al., 2014). For example, Martini et al. (2015) and Matamala-Gomez et al. (2018) found that the transparency level of the virtual body’s skin affected healthy people and chronic arm-pain patients differently. Martini et al. (2015) discovered that the more transparent the virtual body, the less SoO participants felt, which the authors attributed to the higher heat-induced pain levels. In contrast, Matamala-Gomez et al. (2018) suggested that CRPS patients experience less pain when the transparency level is increased, though the opposite was found in patients experiencing PNI pain. Further, Osumi et al. (2014) investigated how an avatar's skin types, such as hairy, normal, or injured, affect heat-induced pain, and their findings demonstrated that the more a user has a negative impression of their avatar, the higher the pain level they experience.

In fact, previous studies have also found inconsistent relationship between SoO and pain in VR. Two studies (Martini et al., 2014; Zanini et al., 2017) on healthy people with simulated pain reported a negative correlation between SoO and pain, i.e., the more ownership people have for the avatar arm, the less pain they perceive. For instance, Zanini et al.(2017) found the conditions that elicited higher SoO (comparing arm and non-corporeal object) had a better analgesic effect when healthy participants' pain thresholds for thermal pain was evaluated, even though they didn't run a correlational analysis. In another study, Martini et al.(2014) also reported that their healthy participants' pain thresholds increased in higher SoO conditions when they manipulated the motion synchronicity (synchronous versus asynchronous) and appearances (object and arm) of the virtual arms. However, three other studies reported a positive correlation between SoO and perceived pain, which aligns with our results on CRSP patients. Martini and colleagues—the same group of researchers as Martini et al.(2014)—found that increasing the virtual arms' transparency resulted in less SoO and a higher pain threshold of healthy participants under thermal pain stimulation (Martini et al., 2015). Similarly, with healthy participants under thermal pain stimulation, Käthner et al.(2019) manipulated the virtual arms' controllability when a virtual water was simulated to pour over the virtual hand with water color varied. In their study, the controllability (synchronous versus asynchronous) modulated SoO; moreover, SoO positively correlated with pain ratings (2019).

Although a few studies elicited participants' SoO and SoA using the movement conditions of VR (Martini et al., 2014; Sanchez-Vives et al., 2010; Zanini et al., 2017), they associated levels of ownership with pain levels rather than agency. Many researchers (Matamala-Gomez et al., 2018; Gilpin et al., 2014; Hänsel et al., 2011; Martini et al. 2015; Osumi et al., 2014) did not provide high controllability of the virtual hands because their technical setup did not allow their participants to perform freehand movements. Hence, these studies did not measure or emphasize how levels of SoA might be associated with the analgesic effect. Sanchez-Vives's (2010) research, for instance, suggested that synchrony between visual and proprioceptive information—along with motor activity—is able to elicit SoO over a virtual arm. Martini et al. (2014) found that synchronous movement produces a significantly higher SoO compared to asynchronous movement, but the authors did not detect changes to pain levels. Moreover, they did not investigate SoA, and both the synchronous and asynchronous movement conditions were achieved via the researchers' manual movements. Zanini et al. (2017) compared an asynchronous movement condition with a still condition, but pain thresholds were not significantly affected by the movement factor either. However, they did not implement a synchronous movement condition or specifically investigate SoA.

More recently, Käthner et al. (2019) explored how the levels of controllability over virtual limbs affect the heat-pain threshold using three color-coded water conditions implying hot, cold, and normal temperatures. Unlike previous findings that focused on the association between SoO and pain reduction, the authors manipulated the levels of SoO and SoA. Their results implied that the control manipulation of the virtual hand does not influence pain ratings, but the conditions were limited to high control versus low control. Therefore, further investigations are needed to explore if and how movement-elicited SoA plays a role in changing one's heat-induced pain levels under different control conditions, such as no control versus high control. Further, although most virtual embodiment researchers manipulated the avatar's visual factors in experimental conditions with healthy subjects under thermal, needle, and pressure pain stimulus (Hänsel et al., 2011; Longo et al., 2009; Sanchez-Vives et al., 2010), very few validated the results with pain patients as the participants (Matamala-Gomez et al., 2019).

2.3.2. Research Methods

2.3.2.1. RCTs

Almost all virtual embodiment studies evaluated two to four visual conditions or motion conditions of the virtual body or body parts using a within-subjects or between-group approach (Martini et al., 2013, 2014, 2015; Matamala-Gomez et al., 2019; Romano et al., 2016; Hänsel et al., 2011; Longo et al., 2009; Sanchez-Vives et al., 2010). Because these studies tested induced pain (needle, pressure, heat, and cold pain) with healthy subjects, they didn't meet patients' recruiting difficulty (Martini et al., 2013, 2014; Martini et al., 2015; Matamala-Gomez et al., 2019; Romano et al., 2016).

Most of these studies had more than 20 healthy participants. But only a few studies were conducted with pain patients (Matamala-Gomez et al., 2019).

2.3.2.2. Study Materials: VR Content

Almost all the researchers in the literature developed specific VR prototypes because they wanted to compare certain avatar features, such as the transparency of skin, the size of the arms, and the color of the arms' texture (e.g., hairy or bleeding skin). Most of VR systems work with motion-tracking systems, such as wearable body trackers or markers, Leap Motion, and cameras, to provide synchronized virtual body movements. Compared with VR environments designed for attention distraction, such as SnowWorld, the VR prototypes in the literature were not gamified because cognitive science researchers focused more on the underlying mechanisms of a single VR factor's effect on pain, e.g., skin transparency, size, color, motion, and so on. Therefore, these prototypes were much simpler VR environments without any game-related components.

2.3.2.3. Instruments

Generally, researchers have collected pain threshold data, such as the thresholds at which changes in temperature are experienced as pain (Gilpin et al., 2014; Martini et al., 2013, 2014), duration a hand can be kept in cold water, or forces, or they have collected self-reported pain ratings in VAS or NRS, and sense of embodiment has been their primary outcome. No other pain rating questionnaires, such as the SF-MPQ, have been used because the pain has been induced on healthy participants and therefore not comparable to chronic pain. Sense of embodiment (SoO and SoA) has been measured using self-reported ratings in a questionnaire, and these questions have generally been derived from previous cognitive studies investigating people's sense of embodiment (Martini et al., 2014). Apart from evaluating the significant differences among experimental conditions, researchers have also run statistical analyses to test the effect sizes of differences in means between people's sense of embodiment and pain changes under different visual conditions. Further, secondary outcomes, such as immersion or presence, have occasionally been measured.

2.3.3. Section Summary

In this section, I first reviewed studies in which researchers manipulated avatar features in VR and evaluated the associated analgesic effects with healthy subjects (Hänsel et al., 2011; Longo et al., 2009; Sanchez-Vives et al., 2010) and pain patients (Matamala-Gomez et al., 2019a). All these virtual embodiment researchers manipulated different components of a virtual body to alter participants' perceptions of their SoO and SoA and assessed the potential correlations between embodiment and pain. Then, I summarized the study methods, study materials, and study instruments of the virtual embodiment research approach, as I did in Subsection 2.1.2 regarding the attention distraction approach.

Overall, findings from the virtual embodiment research were powerful and had a medium level sample size and RCT study method design. However, the virtual embodiment approach is in its infancy, as the studies were mostly conducted using healthy participants experiencing induced pain. Further, very few investigated neurological evidence, possibly because the difficulty in collecting biofeedback (EEG or fMRI) during VR studies when participants wear HMD. The overall accumulated evidence was even less than that of VR and attention distraction studies. As the overarching goal is to alter the distorted body image caused by chronic pain and help people modulate it, these studies, with their varied avatar features, should be replicated using patients as participants. The work that informed the development of this section inspired and informed this dissertation's study design and methods.

2.4. The Impacting Factors of VR Analgesia

Although numerous studies examined the outcomes of VR on induced pain, acute pain, and chronic pain management, very few (Elliot et al., 2007; Mühlberger et al. 2007) have explored the potential impacting factors or how and why these factors may influence the effectiveness of VR analgesia. After reviewing the literature, I categorized impacting factors into three aspects: VR content (components of environmental design), VR systems (equipment and hardware configurations), and participants (pain types and emotional responses).

2.4.1. The VR Content

Some VR environments used in attention distraction are mostly natural (e.g., SnowWorld, Dante Valley, COOL!, Virtual Meditative Walk, and Mobius Floe). Others are commercial VR games that include some interactions, such as InMind (Steam, 2015). Most VR environments share similar gameplay features: users explore the virtual world on an invisible rail and interact with the environment by throwing projectiles at various objects. However, virtual bodies have rarely been implemented. Researchers have focused on pain changes and the sense of presence in VR rather than the sense of embodiment or other different game mechanics, rather than what's designed in SnowWorld and the other few VR environments mentioned above.

Cold versus hot environments for pain management (red versus blue objects). Environmental factors that have been investigated include red or blue objects and their implied cold or hot sensations, which in VR simulate heat pain or cold pain. This environmental factor was evaluated because Hoffman's (2000) cold and blue SnowWorld environment effectively reduced heat pain. Although Hoffman et al. hypothesized that cold environment might help reduce burn pain and thus made the original design choice, no studies have proved it by then. The general belief was that red implies a hot sensation and blue a cold sensation (Elliot et al., 2007). Therefore, Mühlberger et al. (2007) hypothesized that pain triggered by heat or cold can be modulated by a warm or cold virtual environment. To validate this hypothesis, Mühlberger et al. (2007) recruited 48 healthy female participants for a within-group study and measured their heat and cold pain thresholds; motion sickness, participants' moods, and their self-reported immersion levels were also measured. Interestingly, the results suggested that both the warm and cold virtual environments reduced pain intensity and unpleasantness for both heat and cold pain stimuli compared to the control condition. Although VR reduced pain unpleasantness, the authors found no significant difference in efficacy between the environments.

In two recent studies (Käthner et al., 2019; Martini et al., 2013), researchers experimented with red and blue arms and a single environmental element separately and in a more fine-tuned way than Mühlberger et al. (2007), who analyzed the environment as a whole. Martini et al. (2013) measured the heat pain thresholds of healthy participants in four conditions (virtual arms with a red, blue, or green dot on it, or with the red dots outside the arms), and they found that a red arm in VR significantly decreases pain thresholds (i.e., increases pain) compared to normal and bluish skin. Therefore, they concluded that top-down modulation of pain through a visual input suggests a potential use of embodied avatars for pain therapy. In Käthner et al.'s (2019) research, they implemented red and blue colors on a virtual water tap and measured healthy participants' heat pain ratings. Most participants experienced a thermal sensation in response to the virtual water and associated the blue and red light with cool/cold or warm/hot temperatures. Further, the blue condition reduced pain, while the red condition increased pain and unpleasantness; both conditions had significant differences when compared to the control condition.

Creating hot or cold sensations using red and blue objects only seems to work when the objects are incorporated in a virtual environment in a meaningful way that stimulates participants' awareness, as they already know what these colors signify in terms of the sensations they are associated with. Both Mühlberger et al. (2007) and Martini et al.'s research connected hue with heat and with pain ratings successfully since they applied heat pain stimuli on their patients. For instance, in Martini et al.'s (2013) study, the researchers created a meaningful illusion for the participants in the red-dot-off-arm VR condition, so the participants might feel that the source of heat was away from their body.

Overall sense of presence (immersion)—level of distraction. Although researchers use "presence" and "immersion" interchangeably, these two terms refer to two aspects of a virtual environment. Presence" is defined as the subjective experience of being in a place and responding to increased physiological and emotional responses in VR (Cummings & Bailenson, 2015). "Immersion" is defined as the objective fact of being in an environment. It refers to the technological quality of media delivery or the extent to which a system presents a vivid virtual environment while shutting out physical reality (Cummings & Bailenson, 2015).

Triberti et al. (2014) believed that the level of presence is one of the fundamental factors for pain attention distraction in VR. However, only a few VR distraction studies measured presence explicitly and ran a correlational test using the pain outcomes. Gutierrez-Martinez et al. (2010) investigated the effects of VR-based analgesia on a group of 37 participants exposed to experimentally cold-induced pain. All participated in two consecutive sessions, one using VR (SurrealWorld) and the other only a blank screen. The VR session produced significant pain alleviation when compared to the control condition. The authors found a significant negative correlation between subjective pain ratings and presence ratings: the greater the sense of presence in VR, the more attention is drawn to the VR environment and the less pain is perceived. However, the control condition had no content (no sense of presence triggered at all); thus, how different levels of presence affect pain remains unclear.

Hoffman et al. (2014) explicitly compared high presence to low presence by adding in a white crosshair in front of the content. Each participant tried two conditions: high-presence and low-presence; the only difference was that the low presence had the white crosshair in the display. Presence questions were asked right after each condition. The authors noted that although participants' heads were immobilized and the machine noise was loud, participants still felt a strong sense of presence in VR in both conditions and the high-presence condition elicit a better analgesic effect than the low-presence condition. Similarly, in Hoffman et al. (2008) and Tse et al. (2002), researchers measured presence ratings or, in the case of Tse et al., the degree of immersion. They all identified presence ratings that were positively correlated with an increase of pain thresholds (Hoffman et al. 2008, 2014, Tse et al. 2002).

The appearance of the virtual avatar or body. The visual representation of a virtual body has mostly been explored in the virtual embodiment approach. Generally, researchers have used heat-induced pain on healthy participants and manipulated the appearance of the virtual body's upper limbs. The findings suggest that skin transparency (Martini et al, 2015; Matamala-Gomez et al., 2018), type (hairy, normal, or injured; Osumi et al., 2014), avatar size (Mancini et al., 2011; Matamala-Gomez et al., 2018; Romano et al., 2016) and the point of view (first person versus third person; Romano et al., 2016) might affect the SoO and pain perception. Martini et al. (2015) asked their healthy participants to observe a virtual arm with different levels of transparency in VR while they issued heat pain stimuli. Results showed that participants' SoO was significantly reduced when the avatar's transparency was increased. Although participants' heat pain perception did not significantly modulate, the researchers found a significant negative correlation between heat pain threshold and body ownership ratings. Osumi et al. (2014) had their participants observe various types of rubber hands (normal, hairy, injured, and twisted) and explored how each type affected heat pain perception. They found that the SoO is elicited by observation of the injured, hairy, and normal rubber hands. Furthermore, the injured hand was found to significantly lower pain thresholds when compared to the normal rubber hand. In another study, Mancini et al. (2011) examined virtual hand size in a mirror and its effect on heat pain perception. The enlargement of the hand enhanced analgesia, while the reduction decreased it.

Although manipulating different components of a virtual body's appearance has been tested in varied studies, experiments with pain patients are still rare, so these findings require more research before they can be validated. Further, this embodiment approach requires limb pain and has not shown any potentials for pain in other body parts or inside the body.

Game mechanics. Unfortunately, although researchers have measured the level of presence in VR and in participants' game experience, to my knowledge, very few studies published on or before February 2020 has investigated how VR game mechanics or components, such as rewards, uncertainty, or economic systems, influence the effectiveness of pain management. The few ones are introduced in the following paragraph.

Active versus passive interactivity. Some studies have investigated how passive or active interactivity in VR games impacts pain alleviation. Overall, interactive environments or game tasks tend to reduce pain more than non-interactive ones. For instance, Wender et al. (2009) measured 21 subjects' heat-induced pain ratings while using interactive and non-interactive VR. Interactive VR produced a 75% improvement of the perceived analgesic effect when compared to non-interactive VR. Other research compared the interactive VR system versus a 2D display that didn't have any interaction features (Gutierrez-Maldonado et al., 2011) instead of investigating the different types of interactions.

2.4.2. The VR Systems

VR equipment with different equipment provides different levels of presence, which affects the analgesic effect. For instance, Hoffman et al. (2004) proposed that the level of presence in VR affects how effectively the environment distracts people from their pain and that VR equipment plays a critical role in this. They recruited healthy subjects in a double-blind between-group study and divided them into what they called low-tech (2D desktop condition) and high-tech (immersive VR condition) groups. The researchers found that the participants experienced a significantly higher illusion of being inside the virtual world in the high-tech condition. Moreover, the high-tech group also experienced significantly more pain alleviation.

In another study, Tong et al. (Tong et al., 2016) compared the usability of DeepStream 3D stereoscopic display to Oculus Rift's VR HMD. The characteristics of these immersive desktop displays differ: one is worn, enabling patients to move their heads (Oculus Rift), while the other is peered into, allowing less head movement (DeepStream 3D, Firsthand.com, 2020). The findings suggested that patients feel a higher level of motion sickness in the Oculus HMD than the stereoscopic display. However, the authors did not collect pain ratings, so it is not clear if participants' pain alleviation differed between groups.

Furthermore, mobile VR (i.e., mobile devices that are used as a HMD in VR scenarios), because of its affordability and ease of use, has the potential of becoming an effective tool for pain management for patients. In another study, Amin et al. (2017) asked patients to play a VR game using both Cardboard VR (a VR construct that allows users to use inexpensive cardboard helmets that block out external visual stimuli and focus on their mobile devices) (Google VR, 2014) and Oculus Rift HMD. Although the Oculus Rift was found to be considerably more effective with pain patients than both the Cardboard and control conditions, Cardboard VR coupled with a smartphone also reduced patients' perceived pain intensity significantly. The results should encourage future research inquiries into mobile VR and the management of chronic pain. These findings suggested that equipment influences the effectiveness of VR analgesia, for instance, comparing 3D displays or HMDs with different screen resolution or field of view. Oculus released two new pieces of VR gear named Oculus Go and Oculus Quest in 2018 and 2019. These two HMDs are relatively low cost but still provide a high level of immersion. Thus, as the boundaries between a high-end HMD and low-cost mobile VR blur, patients will be easier to afford them and understand how to use them. Therefore, VR could have a bigger impact on reducing pain outcomes.

2.4.3. Participants

In this section, I summarized two primary factors of participants that could affect VR's analgesic outcomes: participants' pain types and their emotions.

2.4.3.1. Pain Types (Etiology)

Almost all virtual embodiment studies have evaluated the impact of varied avatar appearances on healthy participants' induced pain (Martini et al., 2013, 2015; Zanini et al., 2017), though Nishigami et al. (2019) and Matamala-Gomez et al. (2019a) were exceptions. The findings have revealed that pain types might be affected by avatar appearance. For instance, Matamala-Gomez et al. (2019a) explored the analgesic effect of different levels of avatars' transparency and size on pain patients. Their findings demonstrated that CRPS patients react differently than PNI patients. Additionally, CRPS and PNI patients react differently than healthy participants experiencing induced heat pain. Although all VR conditions decrease pain, for the CRPS patients, increased transparency of the virtual body decreased pain the most. Nevertheless, increasing avatar transparency increases PNI patients' pain perception, and Martini et al. (2015) found similar results regarding healthy participants. Additionally, CRPS patients' report distorted mental representations of their painful body part more often than PNI patients (Matamala-Gomez et al., 2019a; Moseley, 2005), meaning the distorted body images of CRPS patients might be the reason why they react differently.

Furthermore, this distorted body image hypothesis (Moseley et al. 2005) could also explain the conflicting results of the virtual body size's impact on pain perception among patients and healthy people. In the same paper (Matamala-Gomez et al., 2018), a larger or smaller virtual arm size was associated with higher pain ratings in CRPS patients than a normal size, though this was not the experience of PNI patients. However, in Mancini et al.'s (2011) study, larger hands enhanced analgesia and smaller ones decreased it when mirrors were used. Similarly, in Romano et al.'s (2016) research, a negative correlation between virtual body size and the skin conductance response (SCR) of healthy participants was found but not with subjective pain ratings in VR conditions. According to these studies, a possible explanation is that the less transparent virtual skin and the enlarged body part strengthen the SoO of healthy participants but that these representations might exaggerate the painful body parts of chronic patients. Therefore, the pain types, whether induced or chronic, might be impacting factors that affect the effectiveness of virtual embodiment's analgesic effect, which involves the appearance of a virtual body.

2.4.3.2. Emotional Responses: Fun versus Anxiety

Researchers believe that participants' emotional responses are fundamental to obtaining an effective VR analgesic effect, as emotional responses seem to be strongly connected to the sense of presence and perceived realism. According to previous studies (Hoffman et al., 2008; Sharar et al., 2016; Wender et al., 2009), both fun and anxious emotional responses are related to VR-based analgesia's efficacy, and the two responses were always independently analyzed. Gold et al. (2006) used validated measures to analyze affective pain (i.e., the degree of worry about the pain) and the Childhood Anxiety Sensitivity index to assess trait anxiety in their sample of children undergoing intravenous placement. While the association between anxiety and pain is a well-known phenomenon in clinical settings, as mentioned by Triberti et al. (2014), more emotionally relevant questions need to be assessed, such as how intense are emotions during treatment and how could a high or low emotional intensity (positive or negative valence) influence patient outcomes.

2.4.4. Section Summary

In this section, I categorized the factors impacting VR analgesia from three perspectives: VR systems (equipment and hardware configurations), VR content (environmental design), and participants' demographics (pain types and emotional responses). Overall, the hardware configurations of a VR system may affect one's sense of presence and VR's analgesic effects. Due to a lack of research, studies using the distraction approach did not reveal any essential differences among VR's environmental design factors. Only one took advantage of red and blue and tasks to modulate heat pain stimulus. Based on my review, I found that chronic pain patients respond differently to the virtual embodiment analgesia approach than healthy people undergoing pain stimulus. Therefore, I decided to include both healthy people and chronic pain patients in my dissertation to test the potential effect of pain etiology on the analgesic effect of the virtual embodiment approach.

Chapter 3. Virtual Embodiment and Pain Analgesia: Studies with Healthy Participants and CRPS Patients

In this chapter, I review two experiments I conducted to answer the following research questions: (1) How do avatar features (movements) affect the induced pain of healthy participants? (2) How do avatar features (movements and appearance) affect CRPS patients? (3) What are the correlations between virtual embodiment (SoO and SoA) and pain? I recruited 19 healthy participants and exposed them to heat pain stimulus in Study 1 and 12 CRPS patients in Study 2 to understand how pain types and etiologies change virtual embodiment's effect on pain reduction. In both studies, I evaluated the effect of embodied design factors, the elicited SoO and SoA, and their correlations with pain reduction. The findings can potentially provide insights and design recommendations regarding avatar features to VR researchers, clinicians, and chronic pain patients.

3.1. Research Background

As mentioned in Chapter 2.1 and 2.3, VR has been used to effectively reduce pain levels in both healthy participants exposed to pain stimulus and patients with acute and chronic pain. Since Hoffman et al. (2000) first applied a VR environment to the management of acute burn pain, many VR researchers have adopted the attention distraction approach to pain modulation, especially with acute pain patients (Das et al., 2005; Garrett et al., 2014; Gold & Mahrer, 2018). In addition to attention distraction, virtual embodiment is another approach researchers have used for pain modulation in VR interventions (Matamala-Gomez et al., 2019b). It addresses the impact of the virtual body or body parts and participants' sense of owning the body or its parts on pain reduction (Matamala-Gomez et al., 2019b).

As discussed in section 2.3, looking at a real or artificial body or body parts, real, virtual or rubber ones, can generate an analgesic effect on pain patients' perceived neuropathic pain or healthy participants under pain stimulus. Most studies suggested that VHI, full-body illusions, and body ownership illusions—the observation that participants perceive ownership of the virtual hands or body—may account for the analgesic effects (Martini, 2016). Researchers postulated that watching artificial hands stand in for real ones could suppress or inhibit pain-related neural activity in the somatosensory areas (Matamala-Gomez et al., 2019b). Longo et al.'s (2012) neuroimaging study proved this hypothesis and showed reduced activation of the primary somatosensory cortex and the operculo-insular cortex. Virtual arms' appearance and motions have also been explored, with researchers focusing on skin color (Martini et al., 2013), realism (Zanini et al., 2017), skin transparency (Martini et al., 2015), size (Romano et al., 2016), and movement (Martini et al., 2014; Zanini et al., 2017). Moreover, virtual arms' appearance (skin color: white vs. black) have also been explored under social context to understand its effect on implicit social biases (Banakou et al., 2020). Researchers found that when the scenario was affectively negative, the ownership illusion of White participants over a White body is lessened, and the implicit bias was higher for them in a Black body. This example indicates that the social contexts can also affect one's perception of ownership. Generally, results suggest that manipulating these visual factors in VR may significantly alter one's perception of ownership, which a few researchers have positively correlated with pain reduction (Martini et al., 2014; Zanini et al., 2017). In other words, the more ownership a person feels, the better the analgesic effect.

However, all but one of these ownership and agency manipulations were conducted with healthy participants under pain stimulus (Matamala-Gomez et al., 2019b). In a recent study, Matamala-Gomez, Diaz Gonzalez, et al. (2019a) manipulated skin transparency and the size of virtual hands and tested these conditions with CRPS patients and PNI patients. Their findings demonstrated that pain types affect the effectiveness of the strategies used to present virtual arms. For instance, the authors discovered a high probability of a positive association between ownership and pain ratings, but only for PNI patients, not CRPS patients. They therefore concluded that the best embodiment strategy is one that is tuned to pain etiology.

Unfortunately, they did not collect or analyze the potential correlations between agency and pain. Although some researchers have manipulated the movements of virtual arms and elicited changes in agency (Zanini et al., 2017), very few have explored the potential associations between agency and analgesic effects. Recently, however, Käthner et al. (2019) investigated motion-control-triggered agency and examined agency-associated changes in pain. They compared a high control condition in which the virtual arms were synchronized with the real arms' movements to a low control condition in which the virtual and real arms moved asynchronously. Their findings did not reveal any significant effect of agency on pain reduction, and they suggested that future studies explore stronger agency manipulation strategies, such as experimenting with the no control movement condition.

Focusing on agency, in the two studies described in Chapter 3, I manipulated virtual arm motions in both studies and provided two movement conditions because the literature suggests that the extent to which participants control the movements of virtual bodies or their arms significantly affects their SoA (Käthner et al., 2019). Synced movement conditions have allowed participants to have high degree of control over their virtual arms, whereas participants have otherwise had no control over their virtual arms and they have remained static. I assumed that the synced movement would elicit significantly higher agency than the static condition and be positively correlated with pain reduction. Moreover, building upon Matamala-Gomez et al. (2019a), I deployed a virtual realism factor in Study 2 with CRPS patients to test their SoO and associated pain reduction with realistic arm conditions and abstract tube conditions. Since Matamala-Gomez, Diaz Gonzalez, et al.'s experiment did not reveal any correlation between size- and transparency-induced ownership and pain, I would like to further explore whether virtual realism influences the analgesic effect in other patient populations. Building on Zanini et al.'s (2017) findings, I hypothesized that realistic arms would elicit a higher ownership level than tubes, which could be associated with a better analgesic effect. The main measures were self-reported pain ratings and embodiment ratings of ownership and agency. Below, I describe the methods, data analysis, and results of both studies.

3.2. Study 1: Virtual Embodiment and Pain Analgesia for Heat-induced Pain

3.2.1. Method

3.2.1.1. Participants

I recruited 19 healthy participants using a convenience sampling approach (14 females; mean ± *SD* age = 23.22 ± 3.35 years old). All were university undergraduate and graduate students who were recruited from social media and online forums, and all right-handed. All participants had normal or corrected-to-normal vision and no history of neurological or psychological disorders. The inclusion criteria were that participants had to be older than 19, and the exclusion criteria were the presence of clinical pain, health problems, or drug use issues. This study was approved by Peking University's ethics committee. All participants signed the consent form and were informed of the study's goals and procedures, how the heat pain would be induced, and that they could withdraw at any point without consequence. Each participant received monetary compensation.

3.2.1.2. Apparatus

The immersive VR system included an HMD made by HTC VIVE with 1080×1200-pixel resolution per eye and a field of view of 110 degrees (see Figure 4.1A). The motion capture sensor was the Leap Motion Controller (see Figure 4.1B), which enables observation of a roughly hemispherical area; this is especially appropriate for detecting finger, hand, and forearm movements from a distance of 1 meter.

Figure 3.1 A. HTC Vive HMD (copyright @ HTC Vive). B. Leap Motion controller (copyright @ Leap Motion). C. The Medoc Pathway CHEPS (@copyright MEDOC).

The Medoc Pathway CHEPS medical-grade machine (Figure 3.1C) provided the heat pain stimuli. I attached its 2.5×5.0 cm thermode to the front of each participant's right forearm with a strap. I ramped the temperature up from 32°C to 46.5°C in increments of 1.5°C/s. I held the peak temperature for three seconds and cooled it to a normal temperature in one second immediately after. I determined 46.5°C as the peak temperature because Suzan et al. (2015) identified it as a painful but safe temperature for most people.

3.2.1.3. Procedures

I adopted a within-subject design. The independent variable was the movement condition of the virtual arms (static vs. synced). The dependent variables were self-reported pain, SoO, and SoA ratings. Before the study, I gave participants three heat stimuli that I increased from 32°C to 46.5°C and held for three seconds. This process allowed participants to get familiar with heat-induced pain and understand how to rate their pain levels from 0 to 10. I chose to use self-reported ratings rather than threshold temperatures because from a pilot test with a different group of participants, I found that people got used to the heat-pain stimuli quickly. Moreover, their pain thresholds drifted to a large extent under the same study intervention, which made the results less trustworthy.

Afterward, I asked them to put on the HMD, and they experienced all three VR conditions in the counterbalanced order set out below.

(1) Control condition: Participants saw a virtual room without a virtual body or arms (see Figure 3.2A).

(2) Static arm condition: Participants saw static virtual arms from a first-person perspective. At the beginning, I asked them to position their real arms in a position and gesture co-located with the VR environment (see Figure 3.2B). During the study, I asked the participants to move their real arms the same way as in the Synced condition.

(3) Synced arm condition: Participants saw the virtual arms, which moved synchronously with the real arms (see Figure 3.2 C).

In both the control and static conditions, participants were not able to see the actual movement of their real fingers, hands, and forearms (hereby referred to as “arms”). In the synced movement group, they saw precisely how the movement of their arms was reflected in the virtual arms’ movements. In each condition and trial, I asked participants to perform the same gestures with their real arms and hands before and during the heat ramps. The gestures included different kinds of arms and fingers’ movements: (a) making a fist and opening the hand, (b) wave hands, and (c) posing number 1 to 10 using fingers. In each condition, I provided three heat stimuli with 30 seconds between each stimuli. I collected pain ratings immediately following each stimulus, and I collected embodiment ratings between each condition. I did not ask participants to rate ownership and agency after the control condition because no virtual bodies were displayed in that condition. Participants had a five-minute washout period (i.e., the washing out or away of pain stimuli experiences) between conditions.

Figure 3.2 A. Control condition. B. Static arm condition. C. Synced arm condition.

3.2.1.4. Instruments

Immediately following each pain stimulus, I asked participants to assess the pain they just experienced on a 11-point numerical rating scale (NRS). I told each of them that 0 meant no pain at all, 4 indicated the starting point of mild pain, and 10 referred to the worst pain they could imagine. At the end of the two experimental conditions, I asked participants to rate their ownership and agency from 0 to 10; 0 stood for “totally disagree” and 10 for “totally agree” (see Table 3.1). I adapted this approach from Martini et al. (2014) and Zanini et al. (2017).

Category	Questions: During the current experiment condition…
SoO	1. …I felt as if the virtual right arm and hand were my real right arm and hand. 2. …I felt that my real right arm and hand became virtual.
SoA	3. …I felt as if the virtual hand had a will of its own.

	4. …I felt the virtual fingers and hand move in the same way as my real fingers and hand.

Table 3.1 SoO and SoA Questionnaire.

3.2.1.5. Statistical Analysis

I averaged the single-trial pain ratings for each condition and subject. I then carried out a check of the outliers and identified no values (> 1.5-times the *SD* from the group's mean). None trials were excluded in all three conditions. To compare average pain ratings and embodiment ratings across conditions, I conducted a one-way ANOVA analysis with repeated measures and a post-hoc pairwise comparisons with Tukey tests for each dependent variable. If Mauchly's Test of Sphericity was violated and the estimates of sphericity were greater than .75, I used a Huynh-Feldt correction; but if the estimates of sphericity were less than .75, I adopted the Greenhouse-Geisser correction of F and p values from ANOVA indicated by F* and p*. If any independent variable or combinations had statistically significant effects ($p < .05$), Bonferroni-corrected post-hoc tests were used to determine which pairs had statistically different. If applicable, the effect size (η^2) is also reported for statistically significant effects. For comparison, η^2 = 0.01, 0.059, 0.138 correspond to small, medium, and large effect size. Further, non-parametric Spearman's correlation tests were used to examine any possible associations between SoO and pain, and SoA and pain, and SoO and SoA for each condition.

3.2.2. Results

3.2.2.1. Pain Ratings

A repeated measures one-way analysis of variance (ANOVA) revealed a main effect of the virtual arms factor on pain ratings ($F_{1,17} = 10.77$, $p = .001$, $\eta 2 = 0.57$). As shown in Figure 3.3A, both the static arm condition (mean = 5.61, SE = 0.42) and synced arm condition (mean = 5.5, SE = 0.41) related to a significantly lower pain rating than the control condition (mean = 6.44, SD = 0.46). The mean pain rating of the control condition was significantly higher than the static arm condition (mean difference = 0.83, $p < .001$) and the synced arm condition (mean difference = 0.94, $p = 0.002$). However, there were no significant pain rating differences between the static arm and synced arm conditions (mean difference = 0.11, $p > 0.05$).

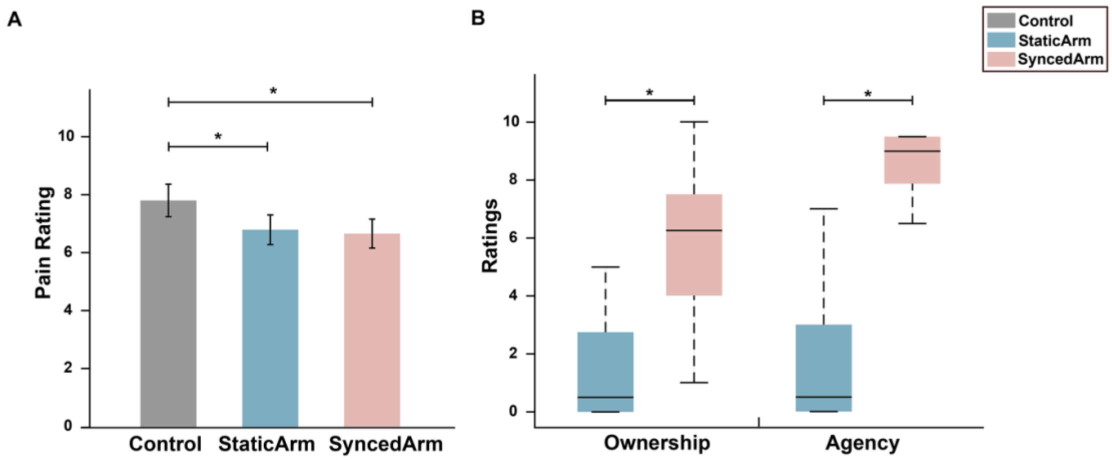

Figure 3.3 A. Mean values of pain ratings in each condition with SE bars. B. Mean values of ownership and agency ratings of static and synced conditions. C. Scatter plots of pain ratings and embodiment ratings.

3.2.2.2. Virtual Embodiment Scores and Correlation Analysis

A *t*-test showed that participants' ratings of ownership in the synced arm condition (mean = 8, *SD* = 2) were significantly higher than in the static arm condition (mean = 1.82, *SD* = 3.03), $t = 7.85$, $p < .001$. I found the same tendency in agency ratings of the synced arm condition (mean = 7.67, *SD* = 3.54), which were significantly higher than the static-arm condition (mean = 1.22, *SD* = 1.92), $t = 10.27$, $p < .001$. Thus, the results indicated that the virtual arms' motion states significantly affected participants' ownership and agency; synced movement elicited higher levels of ownership and agency than the static state. Figure 4.3B illustrates ownership and agency ratings in three conditions in a box plot. Overall, participants' ratings of ownership correlated with their ratings of agency ($r = 0.78$, $p <. 001$).

However, I did not find any correlations between ownership and pain ratings and agency and pain ratings in both static and synced conditions. Non-parametric Spearman's correlation test showed that participants' ratings of SoO and SoA were correlated with each other in the *Static* condition ($r_s = .35$, $p = .013$), and in the *Synced* condition ($r_s = .60$, $p < .001$). Across conditions, they were also correlated ($r_s = .45$, $p < .001$). However, I did not find any correlation between SoO and pain ratings ($r_s = .23$, $p = .55$) and SoA and pain ratings ($r_s = .19$, $p = .631$) after running Spearman's correlation tests across the two conditions. However, such correlation analyses pooled together data from the four virtual arm conditions, thus they might be plagued by autocorrelation bias. Therefore, I also examined the correlations between embodiment and pain under each experimental condition. Unfortunately, I didn't find any significant correlations either between SoO and pain, or between SoA and pain, under each VR condition.

3.3. Study 2: Virtual Embodiment and Pain Analgesia for Complex Regional Pain Syndrome

3.3.1. Method

3.3.1.1. Participants

I recruited 12 CRPS participants from pain doctors' clinics (four males; age: mean ± SD = 66.2 ± 9.3); all were right-handed. All participants were Type I, had normal or corrected-to-normal vision, and had no history of neurological or psychological disorders. The difference between CRPS Type I and Type II are that patients diagnosed with CRPS Type I have no nerve injury, but there is a confirmed nerve injury in Type II.

The patients had been diagnosed with CRPS for 9.3 ± 8.0 years (mean ± SD), ranging from 54 to 82 years old (median = 63). The inclusion criteria were that they had to be older than 19 and have been diagnosed with CRPS. The university's ethics committee approved the study. All participants signed the consent form and received monetary compensation.

3.3.1.2. Apparatus

I used the same equipment (VR headset and Leap Motion movement tracker) as in Study 1 except that the participants were CRPS patients in this study instead of healthy people under heat pain.

3.3.1.3. Procedures

This within-subject study had two independent variables: (a) visual realism (realistic arms versus abstract tubes) and (b) motion of the virtual arms (synchronous versus static movement). The dependent variables were self-reported pain, ownership, and agency ratings. To acquire baseline data, I asked participants to rate their pain levels before the VR interventions. Afterward, I asked participants to put on the HMD, and they experienced five VR conditions from a first-person perspective in the counterbalanced order set out below.

(1) Control condition (see Figure 3.4A): Participants saw the VR environment but not arms or tubes.

(2) Static tube condition (see Figure 3.4B): Participants saw tubes in VR that indicated abstract arms and stayed static. I asked them to co-locate and pose their real arms in the same way as the VR tubes.

(3) Static arm condition (see Figure 3.4C): Participants saw realistic, static arms in VR. I asked them to co-locate and pose their real arms in the same way as the VR arms.

(4) Synced tube condition (see Figure 3.4D): Participants saw tubes that indicated abstract arms in VR and moved synchronously with their real arms.

(5) Synced arm condition (see Figure 3.4E): Participants saw realistic arms in VR that moved synchronously with their real arms.

In each condition and trial, I asked participants to perform the same gestures as in Study 1 (Chapter 3.2.1.3) with their real hands. I collected pain, ownership, and agency ratings immediately after each condition. I did not ask participants to rate ownership and agency after the control condition because no virtual body was displayed in this condition. They had a five-minute washout period between every two conditions, during which they took off the VR HMD. Figure 3.5 showed a CRPS patient participating in the study.

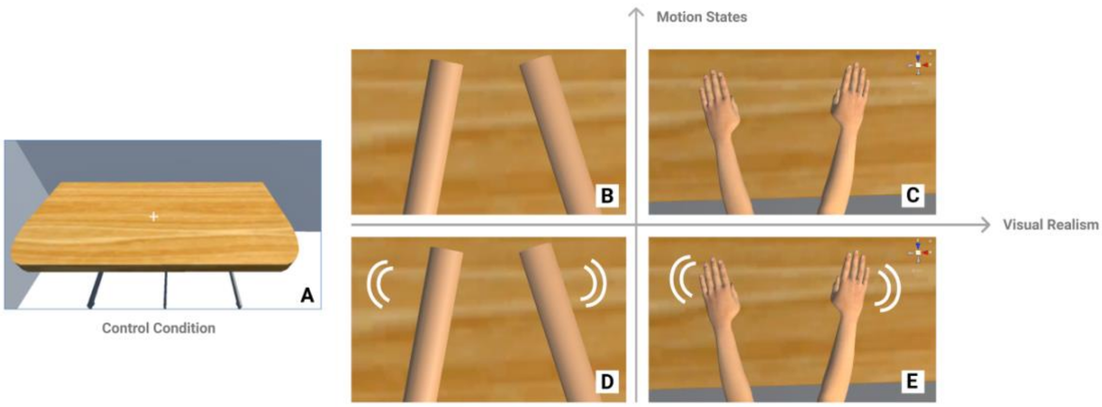

Figure 3.4 A. Control condition. B. Static tube condition. C. Static arm condition. D. Synced tube condition. E. Synced arm condition.

Figure 3.5 A CRPS patient was participating in the study.

3.3.1.4. Instruments

Study 2 adopted the same set of instruments as Study 1, including the 11-point NRS pain ratings and ownership and agency self-reported ratings (see Table 3.1).

3.3.1.5. Statistical Analysis

I conducted a 2*2 repeated-measures (two within-subject factors: visual realism and motion; two levels for each factor) ANOVA test to analyze the relations between two independent variables and each dependent variable (pain, ownership, and agency. If Mauchly's Test of Sphericity was violated and the estimates of sphericity were greater than .75, I used a Huynh-Feldt correction; but if the estimates of sphericity were less than .75, I adopted the Greenhouse-Geisser correction of F and p values from ANOVA indicated by F* and p*. If any independent variable or combinations had statistically significant effects ($p < .05$), Bonferroni-corrected post-hoc tests were used to determine which pairs had statistically different. If applicable, the effect size (η^2) is also erported for statistically significant effects. For comparison, $\eta^2 = 0.01, 0.059, 0.138$ correspond to small, medium, and large effect size. Further, non-parametric Spearman's correlation tests were used to examine any possible associations between SoO and pain, and SoA and pain, and SoO and SoA for each condition. I also conducted a linear regression analysis to predict pain using SoO and SoA ratings as predictors for pain in each condition, and the significance level of statistical tests was set at $\alpha = 0.05$.

3.3.2. Results

3.3.2.1. Pain Ratings

The two-way repeated-measures ANOVA test with Huynh-Feldt correction revealed that visual realism had a statistically significant effect on CRPS patients' pain ratings, $F^* = 29.33$, $p^* < .001$, $\eta^2(2) = 0.73$. The mean and *SD* values of pain ratings are shown in Table 4.2. I ran post-hoc paired-samples *t*-tests to find the pairs with significant differences (see Figure 3.6). The findings showed that the static tube condition had a significantly better analgesic effect compared to the static arm condition ($t = -3.767$, $p = 0.003$), and the synced tube condition also had as significantly better analgesic effect than the synced arm condition ($t = -3.527$, $p = 0.005$). However, the effect of motion (static versus synched) on pain ($F = 0.45$, $p >. 05$, $\eta^2(2) = 0.04$) and the interaction effect of visual realism and motion on pain ($F = 0.17$, $p > .05$, $\eta^2(2) = 0.02$) were not significant. In other words, I did not find any significant differences in pain ratings between the static tube and synced tube conditions or between the static arm and synced arm conditions. Therefore, results indicated that the virtual arms' appearance significantly affected the analgesic effect, regardless of the motion states.

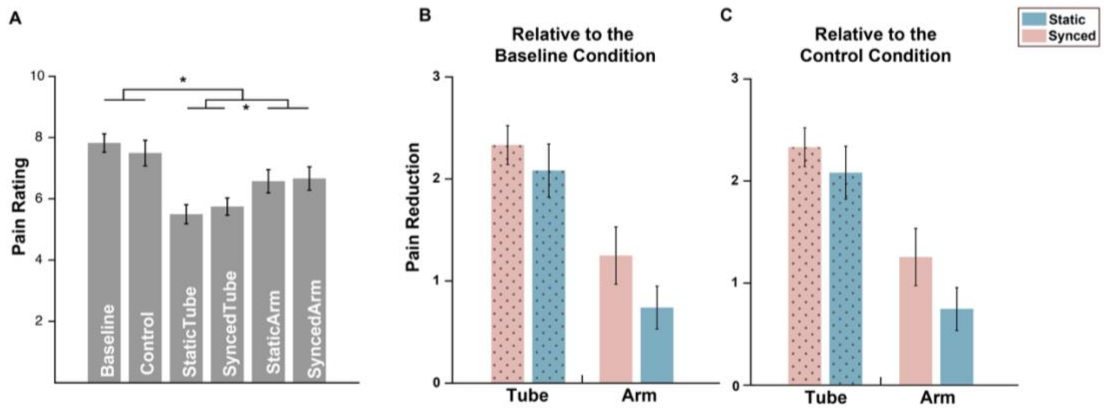

Figure 3.6 A. Mean self-reported pain ratings (baseline and five VR conditions with SE error bars). B: Means pain reduction to the control condition in four experimental conditions. C: Means pain reduction to baseline condition in four experimental conditions.

3.3.2.2. Virtual Embodiment Scores and Correlation Analysis

Next, I ran repeated-measures ANOVA tests to understand how visual realism and motion impact virtual embodiment ratings (SoO and SoA).

Sense of agency. I found that the motion factor had a statistically significant effect on participants' agency (F = 79.7, p <.001, $\eta^2(2)$ = 0.99). Post-hoc paired-samples t-tests showed that participants perceived significantly higher agency in the synced arm condition (mean = 8.727, SD = 0.753) than in the static arm condition (mean = 1.09, SD = 0.793), t =21.58, p < 0.01, and in the synced tube condition (mean = 8.818, SD = 0.965) than in the static tube condition (mean = 1.273, SD = 0.835), t = 21.18, p < 0.01 (see Figure 4.6A). Synchronized movement significantly improved participants' agency when compared to the static state, regardless of the virtual arms' realism levels. The findings did not show significant differences in participants' agency between the static tube and static arm conditions or the synced tube and synced arm conditions. This suggested that visual realism did not affect participants' agency, regardless of their motions. Further, the interaction effect of visual realism and motion was not significant either.

Sense of ownership. The findings suggested that the main effects of visual realism ($F_{1,11}$ = 69.88, p <.001, $\eta^2(2)$ = 0.86) and motion factors both had statistically significant effects on ownership ($F_{1,11}$ = 8.25 p =.015, η2(2) = 0.43). There is no interaction effect found of visual realism and motion factors on ownership ($F_{1,11}$ = 1.0, p

=.339, $\eta^2 = .083$). Post-hoc paired-samples *t*-tests revealed that the static arm condition (mean = 5.67, *SD* = 1.87) elicited a significantly higher ownership than the static tube condition (mean = 2.5, *SD* = 1.62), $t = 8.2$, $p < 0.001$; the synced arm condition (mean = 6, *SD* = 2.04) also saw significantly higher ownership than the synced tube condition (mean = 3.17, *SD* = 1.8), $t = 6.99$, $p < 0.001$ (see Figure 3.6B). This result indicated that visual realism levels affected ownership levels; when the motion states were the same, the realistic arm elicited higher levels of ownership than the abstract tubes. In comparing the two abstract tube conditions, I found that participants rated a significantly higher ownership level in the synced condition than the static condition ($t = 2.97$, $p = 0.013$). However, when comparing the two realistic arm conditions, synced movement and static movement did not significantly differ ($t = 1.3$, $p = 0.22$). This indicated that when the virtual arms were at a low level of visual realism (the tube condition), motion (static versus synced) affected participants' SoO. In contrast, participants did not perceive any differences in ownership during different motion states when they saw highly realistic virtual arms.

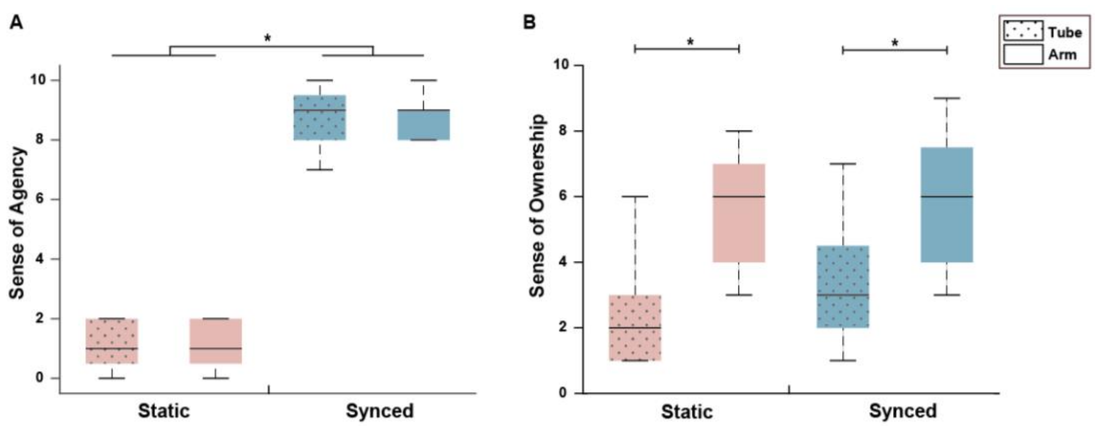

Figure 3.7 A. SoA scores' boxplot in four experimental conditions. B: SoO scores' boxplot in four experimental conditions.

3.3.2.3. Correlation Analysis

We first ran Spearman's correlation tests to assess the relationships between (a) pain and SoO, (b) pain and SoA, and (c) SoO and SoA under the four experimental conditions. When pooling together data from the four conditions, we found that pain ratings and SoO were positively correlated ($r_s = .367$, $p = .01$). We did not find any significant correlations between pain ratings and SoA ($r_s = .175$, $p = .234$), or between SoO and SoA ($r_s = .084$, $p = .569$). Results indicated that the higher the ownership elicited by the virtual body, the less pain reduction to baseline participants reported, which was similar to the pain rating predictions. However, such correlation analyses pooled together data from the four virtual arm conditions, thus they might be plagued by autocorrelation bias. Therefore, I also examined the correlations between embodiment and pain under each experimental condition. Unfortunately, I didn't find any significant correlations either between SoO and pain, or between SoA and pain, under each VR condition. In simple linear regression tests, when I analyzed ownership and agency's effect in predicting pain reduction to control, the findings did not reveal any significant predictors. Figure 3.8 shows a scatter matrix for the three dependent variables: pain, SoO, and SoA ratings, which further illustrates the potential null correlations between SoA and pain.

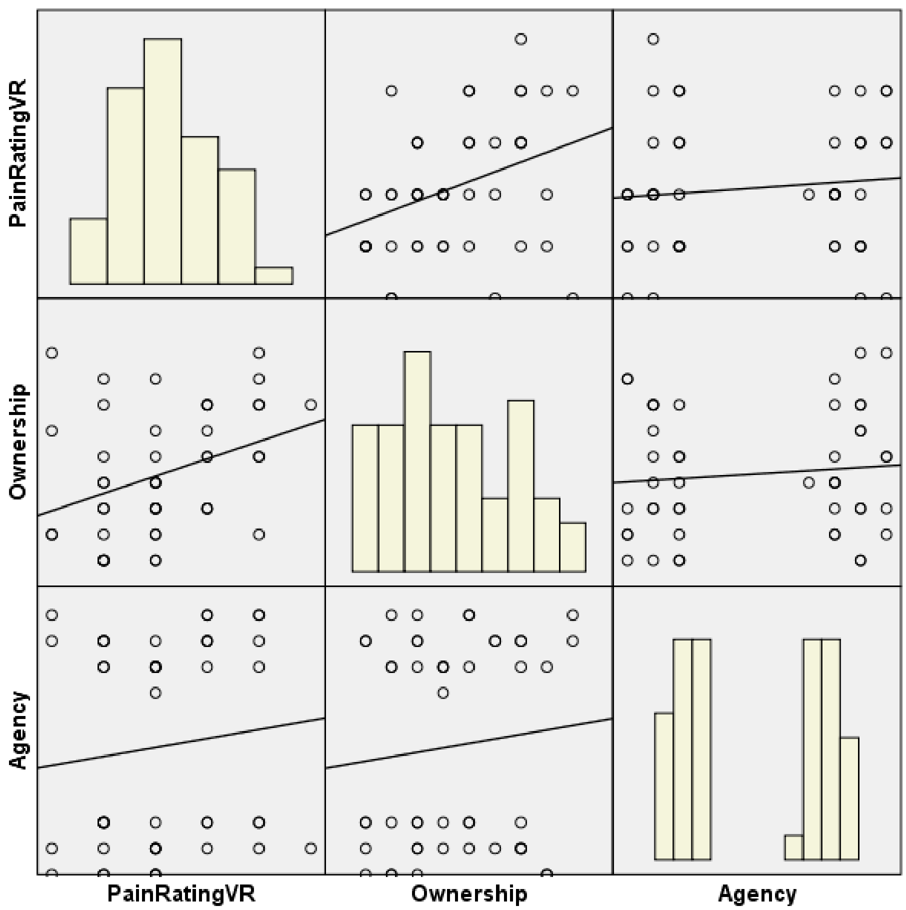

Figure 3.8 Scatter matrix for the three dependent variables: pain ratings, ownership, and agency with fit lines.

3.4. Discussions

3.4.1. Summaries of Both Studies

I aimed to understand the effect of two avatar features (motion and visual realism) on pain reduction. More specifically, I focused on the induced sense of virtual embodiment (ownership and agency) on pain reduction with healthy participants under heat pain in the first study and CRPS patients in the second. The results demonstrated that for both healthy participants and CRPS patients, seeing virtual arms in VR from a first-person perspective significantly reduced self-reported pain ratings compared to the control conditions in which the virtual arms did not appear. The mean differences between experimental conditions on the NRS pain ratings (0–10) of up to 1.2 to 2 points on the group level had previously been suggested to mark a clinically meaningful change in studies with pain patients (van der Roer et al., 2006). Therefore, Study 1 demonstrated meaningful changes in pain for both induced pain and chronic pain conditions (see Figure 4.3A and Figure 4.5).

Moreover, the results also showed that manipulating the motions and visual realism of the embodied virtual arms can strongly affect ownership and agency. Nonetheless, changes in virtual embodiment did not necessarily induce changes in pain ratings. Unlike what I hypothesized (that agency would affect pain), I did not find a significant effect of synced movement and the induced agency changes on pain reduction. I also did not observe significant correlations between motion-induced SoA and pain reduction in either study. Regarding the relationship between SoO and pain reduction, contrary to the hypothesis, the abstract tube conditions elicited significantly lower ownership but a significantly better analgesic effect than the realistic virtual arms conditions in Study 2. Although Pearson’s correlation tests did not find any correlations between ownership/agency and pain in both studies, multivariable linear regression results suggested that ownership is a negative predictor of pain reduction for CRPS patients. In other words, the visual realism factor negatively impacted CRPS pain reduction, as the abstract tube condition showed a better analgesic effect but less ownership than the realistic arm condition.

3.4.2. Visual Realism, Ownership, and Pain Reduction

In Study 2, the realistic arm condition elicited a significantly higher ownership level than the abstract tube conditions, suggesting that increased visual realism improved CRPS patients' SoO. However, patients experienced significantly higher pain ratings in the realistic arm conditions, and the multivariable linear regression analysis also revealed negative correlations between ownership and pain reduction. This result is contrary to that of Zanini et al. (2017), who conducted a similar study with healthy people in which realistic arms had a better analgesic effect than abstract tubes. Additionally, I observed a more contrary relationship (negative) between ownership and pain reduction in CRPS patients than prior studies conducted with healthy people (Martini et al., 2014; Zanini et al., 2017). For instance, Martini et al. (2014) found that the less transparent the virtual arms' skin, the higher the ownership healthy participants feel, meaning ownership positively correlates to pain reduction levels (Martini et al., 2014). The authors referred to VHI to explain the analgesic effect, and their findings showed that stronger VHI correlates with a better analgesic effect. Here, one of the possible causes of the negative correlation is attention distraction. In a VR environment, the virtual arms may distract patients from their bodily pain. Further, the co-located tube-shaped arms can be novel and visually more distracting than the realistic ones. Therefore, the abstract tube conditions reduce pain more significantly than the realistic arm condition. The second possible explanation is predictive coding. When participants see a tube-shaped presentation of their arms, the predictive coding mechanism may shift their brains' focus much farther away from their real body to map the appearance of the new arms in VR. I hypothesize that tubes might be too novel for CRPS patients to find proper references and cognitively map their real bodies to the virtual tubes. Therefore, participants focus less on their pain and it is further reduced when compared to the realistic arm condition. Unfortunately, virtual embodiment theory, or VHI, seems unable to explain the negative correlation between ownership and pain reduction. I'd suggest future work to further explore how varying appearances and motion states of virtual body affect different type of chronic pain patients' pain outcomes. See further discussions about design recommendations in Chapter 7.2.1 and future work in Chapter 7.5.2.

3.4.3. Motion States, Agency, and Pain Reduction

Apart from visual realism manipulation, the other primary focus of my studies was to explore how agency affects people's pain modulation. Results indicate that the agency manipulation was successful in both studies; healthy participants and CRPS patients all felt a significantly higher SoA in the synced and static movement conditions, regardless of pain types or appearance. Further, SoA was not proven to be a pain predictor in the linear regression analysis. Such findings were also in line with Käthner et al.'s (2019) research in which they did not identify differences between synchronous movement conditions (high control) and asynchronous conditions (low control). Although I compared high control and no control (synchronous and static) movement conditions, as suggested by Käthner et al., I was unable to reveal any effects of agency on pain in both studies. In these two studies, I only compared self-reported explicit ratings of agency. Similar to Käthner et al., my results did not show any effect of motion-induced agency on pain. Much like the authors, I believe that future research should implement intentional binding paradigms (Kong et al., 2017) to assess implicit measures of agency and investigate factors such as outcome choice and initiation of motor actions, which may lead to meaningful outcomes. Moreover, future research with more participants and testing data is required to draw a firm assumption on the correlation between agency and pain.

3.4.4. Study Limitations

Here, I address the limitations of both studies. Study 2 had a limited number of participants (12 people) because of the difficulty of recruiting CRPS patients. This may have limited my search for interrelationships among conditions. Further, both studies used subjective and self-reported measures of virtual embodiment perceptions. Hence, I only measured explicit virtual embodiment. The embodiment (SoO and SoA) scale wasn't validated and was a limitation of this research. Other objective approaches could be taken to measure the implicit aspects of ownership and agency in future studies to fully understand the associations between avatar features and pain reduction. For instance, measuring motor actions in intentional binding tasks can be useful in assessing implicit agency (Kong et al., 2017). Therefore, the significant changes of embodiment ratings lack evidence to reach clinical relevant findings or difference. So future research should explore the potential golden standards to measure SoO and SoA in VR. Further, even though pain has no biomarkers and participants' subjective reporting was the primary means of evaluating it, neurofeedback or biofeedback measurements of fMRI, SCR, galvanic skin responses (GSR), electroencephalogram (EEG), and/or heart rate variability (HRV) may also be collected to better understand the underlying mechanisms of pain modulation. Finally, I manipulated only two factors, each on two discrete levels, that affect participants' virtual embodiment. Future studies might benefit from manipulating continuous SoO/SoA conditions, and also benefit from a control group outside VR where participants look at their real arms.

3.5. Chapter Summary

This chapter examined the effect of virtual embodiment's two subcomponents—SoO and SoA—on pain reduction in two studies with CRPS patients and healthy participants exposed to heat-induced pain. The results showed that VR conditions with virtual arms significantly reduced pain for these two groups, regardless of the virtual arms' appearance or movements. However, no effects of agency on pain reduction were revealed in either study, and I observed a negative correlation between ownership and pain reduction in Study 2. The non-correlation between agency and pain and the negative correlation between ownership and pain raised further questions about exploring more specific virtual embodiment approaches or conditions to enhance VR analgesia. The findings also suggested that attention distraction or predictive coding could offer explanations other than VHI for the previously reported analgesic effects caused by seeing virtual bodies in VR environments.

Prior research compared VR with and without virtual bodies in non-interactive environments, but interactive environments in which people can interact with virtual objects, navigate space, or trigger changes may attract similar or more attention levels than simply seeing virtual bodies. Therefore, apart from embodiment, future research should consider measuring participants' attention levels, such as gaze detection, under interactive environmental settings and compare pain outcomes with and without the presence of virtual bodies.

These two studies contributed to VR analgesia research by examining the effect of two avatar features and their induced virtual embodiment on pain reduction. Findings from these studies not only revealed how visual realism and motion factors affect healthy people and CRPS patients' pain but also point to possible new directions and alternative explanations for the mechanisms of action in contexts of virtual embodiment. Further, these two studies imply that VR designs that strive for high levels of realism may be counterproductive in reducing the pain of chronic patients, such as those suffering from CRPS. To conclude, findings from this chapter will inform the design of virtual bodies or avatars for analgesic effects and also provide key understandings about the effects of virtual embodiment in pain to VR researchers and designers (see Chapter 7.2 for details about the design recommendations and Chapter 7.4 for the design framework).

Chapter 4. Alleviating Phantom Limb Pain in VR: The Landscape and a New Attempt

In Chapter 4, I conducted studies with both CRPS patients and health participants exposed to induced pain and analyzed the correlation between virtual embodiment and pain. To further explore the effect of virtual embodiment on pain reduction in other types of chronic pain patients, I studied PLP patients, and I present the results in this chapter.

PLP patients suffer from a unique type of chronic pain, and 90% of people experience it after limb amputation or severe injury, such as a BPA (Flor et al., 2006; Nikolajsen et al., 2006; Pezzin et al., 2000). These patients typically experience a poor QoL and a slow adaptation to their pain condition, and they report amplified feelings of depression and anxiety as well as maladaptive coping strategies (Giummarra & Moseley, 2011). PLP is challenging to treat, and multiple drug trials have failed to show efficacy (Ehde et al., 2000). Furthermore, what causes PLP is debatable (Giummarra & Moseley, 2011). Three principal mechanisms have been posited: peripheral factors, spinal factors, and central brain changes (Giummarra & Moseley, 2011). To explore these possible causes, researchers have taken many different approaches, such as mirror therapy (Ramachandran & Rogers-Ramachandran, 1996; Ramachandran et al., 1995).

In this chapter, I present the results of a systematic literature review, and I detail a case series. The goal of the literature review was to summarize and assess VR/AR game features and feasibility, study design, and analgesic effect and to shed light on future research. The case series experiment was carried out to answer the following research questions: (1) does controlling a virtual avatar in the mirrored movement of the phantom limb help PLP patients reduce their pain? (2) Is there any correlation between the sense of virtual embodiment (SoO and SoA) and PLP?

4.1. The Landscape: A Systematic Literature Review of VR, AR, and Phantom Limb Pain Alleviation

4.1.1. Research Background

As discussed in Chapter 2.1.2, researchers believe the immersive VR and AR generally provide a rich sense of bodily ownership in contexts of pain management, including PLP. For instance, Giummarra and Moseley (2011) emphasized the relationship between PLP and bodily awareness. They suggested that the VR approach is one of the most innovative techniques for manipulating bodily representations.

VR/AR applications have been implemented in two primary ways for PLP interventions. One approach is similar to mirror therapy; movements are mirrored in VR/AR, which is thought to induce vivid illusions of seeing the missing limb and enabling greater control of its imagined movements (Rodriguez et al., 2017; Heckman et al., 2013; Henriksen et al., 2016; Henriksen et al., 2017; Mouraux et al., 2017; Murray et al., 2007; Osumi et al., 2015; Osumi et al., 2018; Rothgangel et al., 2018; Sano et al., 2015; Wake et al., 2015). Although mirror therapy does not work for every PLP patient, it was reported to reduce PLP in eight studies reviewed here and among half their participants (Chan et al., 2007; Foell et al., 2014; Heckman et al., 2013; Kim & Kim, 2012; Mouraux et al., 2017; Murray et al., 2007; Osumi et al., 2015, 2017, 2018; Rothgangel et al., 2018; Sano et al., 2015). The other approach is motor execution, in which the movement of the patients' missing body parts are simulated in VR/AR according to the residual movements of the affected limbs. The movements are usually measured by motion trackers or biosensors that attach to their stumps, like EMG sensors or fiducial markers (Ortiz-Catalan et al., 2014, 2016; Perry et al., 2013, 2018; Zanfir et al., 2017; Zweighaft et al., 2012; Ambron et al., 2018; Ortiz-Catalan et al., 2016). Both mirror therapy and motor execution have shown great promise for PLP patients.

Researchers have tried to analyze or assess the effectiveness of VR/AR's analgesic effects on PLP. However, few have analyzed how VR/AR affected PLP patients' embodiment, phantom limb movement approach (mirror therapy and motor execution), and study design types. In 2014, Lenggenhager et al. (2014) reviewed multiple nonpharmacological therapies for treating PLP and discussed the role of embodiment in various treatments. The authors categorized the treatments based on how they reverse “maladaptive neuroplasticity” (p. 1). However, they did not report experimental details or the associated outcomes of VR/AR environments. Later, Dunn et al. (2017) explored current VR/AR research prototypes and studies on PLP. The authors summarized eight studies in total, all of which were case studies and case series. After their review, 10 more research studies were by January 2020. These investigations involved a greater number of patients and provided more insights into how sense of embodiment, varied study designs, and phantom limb movement in VR/AR environments affect pain. Therefore, drawing on the growing number of studies on VR/AR and PLP patients, my overarching goal was to examine how VR/AR affects patients’ PLP, understand the correlations between embodiment and PLP, and assess the study methods and outcomes of existing research.

4.1.2. Method

4.1.2.1. Search Strategy

To collect all available studies using VR/AR applications in PLP interventions, with another researcher, we conducted a literature search in various databases, including Cochrane, PubMed, IEEE, ACM, and Google Scholar. The primary search terms were “virtual reality,” “augmented reality,” and “phantom limb pain.” The secondary keywords included “sense of ownership,” “sense of agency,” “body ownership,” “body agency,” and “phantom limb movement.” Additionally, the two of us categorized and analyzed all the relevant studies identified in the reference lists. We compared our categorization and notes to make final decisions through discussions and reached into agreement about the classification and selection procedure.

4.1.2.2. Eligibility Criteria

The inclusion criteria were as follows: (1) type of study design (RCTs, non-randomized controlled trials, interrupted time series, before-and-after studies [controlled and not], cohort studies, case control studies, case series/case reports, systematic or scoping reviews, and meta-analyses); (2) type of intervention (VR/AR applications); (3) type of participants (healthy subjects or patients); (4) type of outcomes (any outcome); and (5) language (English). The exclusion criteria included: (1) type of study design (feasibility studies not on human subjects, technical or developmental descriptions, protocols, expert opinions, and personal observations); (2) type of intervention (non-computer-mediated VR or AR); (3) type of participants (nonhuman animal); and (4) originality (non-original data and methods included in other papers).

4.1.2.3. Study Selection

I reviewed and extracted the studies and papers. Twenty met the eligibility criteria and entered the final selection (see Figure 4.1 for selection processes). Among them, 13 used immersive VR, and seven used AR (non-immersive, displayed in tablets or monitors). See tables 4.2 and 4.3 for more details about each selected study.

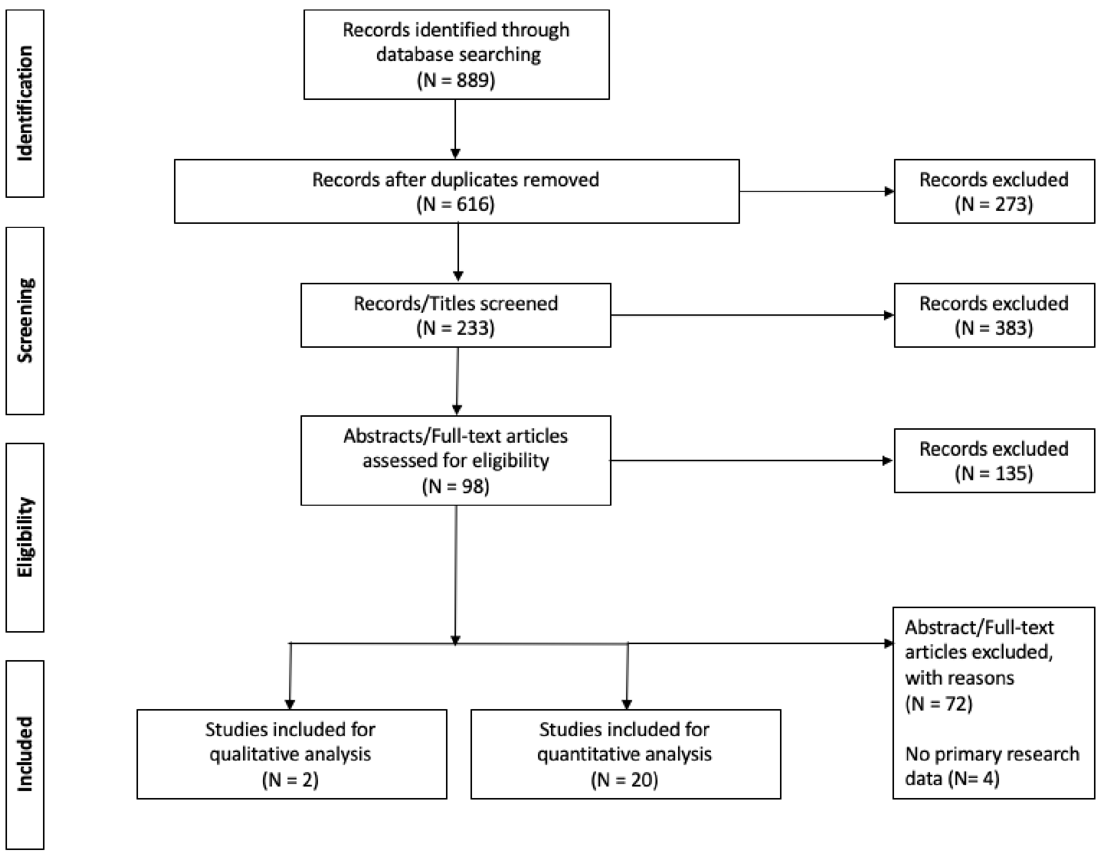

Figure 4.1 The selection process of reviewing studies included in this chapter.

4.1.2.4. Outcomes

The primary outcomes were pain intensity, embodiment, and phantom limb movement. Researchers generally assessed pain intensity with SF-MPQ and VAS or NRS. If they used other tools, I included them as well. The secondary outcomes are sense of embodiment in VR and phantom limb movement. As no standard scales or assessments were used for these two factors, I included any scale or qualitative interview results that researchers collected. The Modified Sackett's Levels of Evidence Table (PEDro scale) was used to assess the level of evidence for each of the 20 studies (see Table 4.1; PEDro Scale, 1999).

Levels	Evidence
1	RCTs with PEDro score ≥ 6
2	RCTs with PEDro score < 6, cohort and non-RCTs
3	Case control studies
4	Pre-post studies, post-test studies, or case series
5	Observational studies, clinical consensus, or case reports

Table 4.1 Modified Sackett's Levels of Evidence Table.

4.1.3. Results

Summaries of the included studies are presented in Table 4.2. I summarized the study design, including the number of participants, participant types, length of sessions, session frequencies, and follow-up periods. More specifically, almost half the studies had only two to nine participants, and three of those were case studies or case series. Four studies had 10 to 19 patients. The remaining three had 20 to 50. A total of 181 participants were included in all selected studies; 81 were upper limb patients, 45 were lower limb patients, and 16 were BPA patients. All 39 healthy subjects were recruited for feasibility tests in three studies. As for the frequencies of study sessions, approximately half conducted a single session. In six, researchers asked their participants to come in every one to two weeks. In two, participants were asked to come in every three to four weeks. In three, there were one to two days between sessions. Post-study follow ups were uncommon: in 17 of the 22 studies, researchers did not follow up with participants to determine if the effects of the VR/AR intervention persisted.

Studies	Study Design	Participants	Equipment	Intervention	Measurements	Primary Findings
Murray et al. (2007)	Case study	3 amputees (2 upper & 1 lower)	V6 HMD, 5DT-14 Data glove, Fastrak, motion sensors	MT, 4 VR tasks – placing objects, kicking a ball, tracking the motion of objects, aiming at a target	SF-MPQ, NRS and semi-structured interviews.	All 3 patients reported pain decreases to differing degrees (qualitative data). Quantitative data were not reported.
Cole et al. (2009)	Preliminary study	14 amputees (7 upper & 7 lower)	Ascension MoCap System	ME, 1 VR task – reaching and grabbing/pressing	SF-MPQ, VAS and semi-structured interview about agency and sensation	10 of 14 reported improved pain relief; the average pain reduction was 64%.
Zweighaft et al. (2012)	Usability testing	2 healthy subjects	Projector, mod-table, mirror, flock-of-birds tracking device, EMG sensor and table frames	ME, 1 VR task – moving, grasping objects	Qualitative usability measurement of the system: esp. ergonomics.	The system can detect certain gestures & provide visual feedback co-locating the virtual limb with the missing one.
Heckman et al. (2013)	Case study	1 upper limb amputee	AR tablet and infrared camera	MT, 1 AR task – observation of the phantom limb	Qualitative report of pain sensation.	Qualitative findings revealed decreased pain scores in one PLP patient.
Perry et al. (2013)	Preliminary study	7 amputees (upper)	EMG sensor, display	ME, 1 AR task – observation and posing gestures.	SF-MPQ, VAS; movement goals achieved.	VAS. Average Daily PLP: Improved from 6.8 to 5.2. SF-MPQ: Improved from 6.0 to 2.9 at baseline to 2.4 to

						3.4. 6/7 had improvement in signal to motion accuracy.
Ortiz-Catalan et al. (2014)	Case study	1 upper limb amputee	Camera, fiducial marker, myoelectric pattern recognition (EMG)	ME, 3 AR tasks – observation, car racing, posing gestures	SF-MPQ, VAS and qualitative feedback	The patient reported pain reduction and his phantom hand gesture changed from closed fist to a relaxing position.
Wake et al. (2015)	Preliminary study	1 upper limb amputee & 4 BPA patients	Cyber Glove, Kinect, Oculus Rift	MT, 1 VR task – reaching	SF-MPQ, NRS	4/5 patients reported pain improvement; Maximum Improvement: 86% in one patient with a tactile feedback condition.
Sano et al. (2015)	Controlled study	1 upper limb amputee & 5 BPA patients	Cyber Glove, Kinect, Oculus Rift	MT, 1 VR task – reaching	SF-MPQ	5/6 had a pain reduction, the rate ranged from 3.3% to 83.4%, with an average of 50.2%.
Henriksen et al. (2016)	Usability testing	12 healthy subjects & 1 upper limb amputee	Leap Motion, Oculus Rift	MT, 3 VR games– binding, pressing button & matching	The range of motion of each exercise, preferences.	The VR games increased participants' exercise level of the phantom hands.
Osumi et al. (2017)	Preliminary study	7 upper limb amputee & 1 BPA patient	Leap Motion, Kinect, Oculus Rift	MT, 1 VR task - reaching and grabbing	SF-MPQ, NRS, phantom movement representation (OI).	NRS: 39.1 to 28.4% pain relief (p = 0.015); SF-MPQ: 61.5 to 48.5% relief (p = 0.015).

Henriksen et al. (2017)	Case study (usability)	3 upper limb amputees	Noitom glove, Oculus Rift	MT, 3 VR tasks – binding, frequency & location discrimination	The illusion of body ownership, phantom limb movement, & controllability of phantom hand-body agency.	2/3 participants felt their intact and amputated hands were encouraged to move and they had an increased control of the amputated limb rep.
Ortiz-Catalan et al. (2016)	Preliminary study	14 upper limb amputees	Camera, fiducial marker, myoelectric pattern rec.+ machine learning	ME, 3 AR tasks – observing, matching gestures, car-racing direction control.	SF-MPQ, NRS, weighted pain ratings, pain frequency, sleep, activities for daily life.	Pain decreased by 47% for weighted pain distribution, 32% for NRS, 51% for the pain rating index; continued improvements remained 6 months after the study.
Rodriguez et al. (2017)	Usability testing	10 healthy subjects	Leap motion, Oculus Rift	MT, 1 VR task – reaching and grabbing objects or playing soccer.	Self-reported feasibility and usability of the VR game: functions, GUI, sound, ease of control, willingness to play.	The system can provide a natural and effective method for participants to interact.
Chau et al. (2017)	Case study	1 upper limb amputee	MYO band, HTC Vive	ME, 1 VR task – grabbing objects and another two games.	SF-MPQ, VAS, Wong-Baker FACES measurement.	McGill Pain Questionnaire, and Wong-Baker FACES pain scores decreased by 55%(p=0.0143), 60% (p=0.023), and 90% (p=0.0024).

Zanfir et al. (2017)	Controlled study	10 lower limb amputees	Lenovo Vibe K6 Mobile VR, VR Shinecon Bluetooth gamepad	ME, 3 VR task – hitting a ball, placing foot, lifting legs.	SF-MPQ, Pain Catastrophizing Scale, Amputee Body Image Scale, Depression and Anxiety Scale, Cognitive Emotion Regulation Scale.	MPQ in the VR group was lower than in the kinesiotherapy group (p<0.01). There was a significant improvement in QoL, pain catastrophizing & coping strategies.
Mouraux et al. (2017)	Preliminary study	1 upper limb amputee & 1 PBA patient	Kinect, Vision Kit (3D glasses)	MT, 1 AR task – posing gestures and playing a game.	VAS, MPQ, and DN4.	Overall, together with other types of patients, MPQ showed 34% decrease (p<0.01) in pain & DN4 had an18% improvement.
Ambron et al. (2018)	Case study	2 lower limb amputees	Arduino, inertial measurement units, Oculus Rift	ME, 4 VR games: maze, chess, checkers, browser.	NRS pain ratings and system usability scale.	Pain intensity rating results decreased by 100% and 93.7% for subjects 1 and 2.
Osumi et al. (2018)	Preliminary study	13 upper limb amputees & 6 BPA patients	Leap Motion, Kinect, Oculus Rift	MT, 3 VR tasks – drawing 8 figures, grabbing objects and reaching.	SF-MPQ, phantom movement representation (OI)	Patients' imagined movement & pain intensity was significantly restored. MPQ decreased 52.1%.
Rothgangel et al. (2018)	Randomized controlled trial	25 lower limb amputees	iPad/tablet	MT, 1 AR task – observation and basic motor exercise tasks.	NRS of PLP, pain disability index, sleep & mood NRS, EuroQoL,	Traditional MT reduced the duration of PLP significantly compared to VR or the control group in NRS. The

					overall healthy VAS, Global Perceived Effect, Pain self-efficacy questionnaire, etc.	AR approach had additional effects compared to MT in the follow up period.
Perry et al. (2018)	Preliminary study	8 upper limb amputees	Monitor, EMG data	ME, 1 AR task - not VR study, observation & posing gestures.	SF-MPQ, VAS, EMG	7/8 had significant PLP decreases in VAS & in MPQ compared to baseline score before the study.
Nissler et al. (2019)	Usability test (via a controlled trial)	15 healthy subjects and 1 amputee	HTC VIVE, and MYO EMG sensor	ME, 3 VR game tasks – limb movement and moving objects	Task performances in conventional and VR versions Box and Block test.	Box and Block type (conv. or VR) was significantly different within each of the three groups, but there were no significant differences between the expert users and the prosthesis user using his prosthesis in VR.
Kulkarni et al. (2020)	Pilot Study	11 upper limb amputees	Oculus Rift	MT, 1VR task–3 sessions, reaching a ball.	NRS, qualitative questions	There is insufficient evidence from these results to identify an effect of VR on PLP.

Table 4.2 An overview of VR/AR research for PLP treatment (MT Mirror Therapy, ME Motor Execution).

Further, I conducted a comprehensive analysis of the outcomes of the VR/AR applications. Below, I discuss the analgesic effect, motor therapy and motor execution comparison, and sense of embodiment.

4.1.3.1. Analgesic Effect

Seventeen studies collected and reported pain measurements with quantitative or qualitative methods, all of which found an analgesic effect (Tables 4.2). All the studies used more than one measurement instrument or evaluation. These included the SF-MPQ/MPQ (Ronald Melzack, 1975), VAS, NRS, the Douleur Neuropathique en 4 Questions (DN4) (Spallone et al., 2012), the Wong-Baker FACES Pain Rating Scale (Garra et al., 2010), the Pain Catastrophizing Scale (Cano, 2004), the Pain Disability Index (Tait et al., 1990), and a pain self-efficacy questionnaire (Nicholas, 2007). MPQ, VAS, and NRS were the three most commonly adopted instruments. However, very few studies also collected qualitative information about pain and experience from semi-structured interviews. In addition to their use of pain scales, some studies evaluated changes in patients' emotional and social states through the Amputee Body Image Scale, the Depression and Anxiety Scale, the Cognitive Emotion Regulation Scale, sleep and mood NRS, QoL, and overall health via the VAS. Twelve of these showed a significant PLP reduction after participation when compared to the control group. Although most of the 17 studies were case (series) studies or preliminary studies with low evidence levels (4 or 5), the outcomes from the VR/AR intervention appear quite promising. The average reductions in PLP (from 10 studies that had accessible MPQ, VAS, or NRS data) ranged from 50.2% to 64%; the lowest was 3.3%, and the highest was 100%. Although the VR/AR interventions showed promising analgesic effects, the measurements were still too simple and too short lived to represent the scope of the kinds and degrees of pain and the states that PLP patients experience. For instance, of all the studies reviewed here, only three followed up on the effect of their VR/AR intervention for up to six months and showed persistent analgesic effects.

4.1.3.2. Mirror Therapy and Motor Execution

Eleven studies adopted the mirror therapy approach; the rest implemented a motor execution approach to control the movement of the virtual phantom limbs. Studies with the mirror therapy approach reported an average pain reduction of 34%, 48.5%, 50.2%, 52.1%, and 86% (mean = 54.16%, *SD* = 19.18%), whereas studies that implemented the motor execution approach reported average pain reductions of 51%, 55%, 60%, 64%, and 96.8% (mean = 65.36%, *SD* = 18.25%). Although the two approaches have different underlying pain reduction mechanisms (Ortiz-Catalan et al., 2016), the evidence does not distinguish one's efficacy over the other.

4.1.3.3. Sense of Embodiment

Two of the studies evaluated the sense of embodiment (SoO and SoA) for a single session, but none measured SoO and SoA over time or followed up after the study. As Braun et al.'s (2018) stated, "SoO describes the feeling of mineness toward one's own body parts, feelings or thoughts" (p. 1), whereas "SoA refers to the experience of initiating and controlling an action" (p. 1). Cole et al. (2009) reported qualitative findings from patients' verbal reports regarding the SoA over the virtual body. For instance, one patient said he felt a touch sensation when he picked up an object in VR using his virtual phantom hand, while another reported a buzzing feeling in his virtual phantom fingers as he grasped an object. In Henriksen et al.'s (2017) study, participants also noted a sense of controllability over their virtual phantom limbs on a self-reported Likert scale. Two of three felt that their virtual amputated limbs could be controlled to complete the study tasks. Overall, however, SoO and SoA were not quantitatively measured, and how SoO and SoA perception relates to a reduction in PLP is still understudied.

4.1.3.4. System Usability and Feasibility

Four computer science studies focused on the usability and UX of the VR/AR system from an ergonomics perspective. Such issues include the ease of use with respect to control, functionality of the games, interactions with the environment, range of motion, intelligibility of the graphic user interface, and preferences regarding the 3D virtual environment. Healthy subjects were typically used to try out the VR/AR systems, which were conducted before officially testing them on PLP patients. In their study conducted with healthy subjects, Henriksen et al. (2016) found that their VR system was easy to control and participants liked their rehab games. They also suggested that their VR environment could increase the exercise levels of the phantom limbs. Another

Henriksen et al. (2017) study indicated that the same VR system seemed to provide an increased sense of controllability of the phantom hands.

4.1.4. Discussion

This review aimed to assess the analgesic effects of VR/AR, the movement approach of the phantom limbs in VR/AR, and the potential correlations between embodiment and PLP management. Converging data indicate that VR/AR can have a modest effect on reducing PLP patients' pain, although the intervention duration and frequency varied greatly. Overall, fewer than 10 patients' pain condition in these studies remained unchanged (Cole et al., 2009; Henriksen et al., 2017; Osumi et al., 2015; Perry et al., 2013; Perry et al., 2018; Wake et al., 2015), and one reported nausea in VR (e.g., simulator sickness; (Murray et al., 2007). I found that recent studies were not limited to case studies or case series, as their authors recruited more patients and examined the effects over a longer period.

However, although this review covered twice as many studies as the most recent one (Dunn et al., 2017), most of the study designs were heterogeneous and produced low-level evidence about VR/AR's analgesic effects; RCTs were also scarce. As shown in Table 4.2., patient types, study details (study lengths, measurements, session lengths, and frequencies), and the specific VR/AR tasks varied considerably across studies. Further, few studies measured changes in experience (immersion or presence) or sense of embodiment, which is thought to potentially underlie one's PLP reduction. Similarly, not enough data revealed how different study tasks and designs might affect pain changes.

4.1.4.1. Motor Execution or Mirror Therapy?

In some papers, the researchers argued that motor execution may overcome the limitations of mirror therapy. For example, Ortiz-Catalan et al. (2016) argued that mirror therapy could not provide a corresponding visual-motor feedback for PLP patients who can still move their stump or arm. In this case, the motor execution approach might have been a better choice, since both limbs—the residual and the intact—could have been used in the VR/AR session. It is worth noting that BPA patients and amputees without a stump might not generate enough measurable movement for motor execution. In this case, only the mirror therapy approach can be used. However, mirror therapy and motor execution have not been directly compared. Current evidence suggests that they are on a similar level of effectiveness when it comes to PLP reduction. Therefore, future studies with more participants and a controlled study design are required to elucidate the relative strength of each approach.

4.1.4.2. Measuring Sense of Embodiment and Phantom Limb Movement

The significance of embodiment on VR's analgesic effects has been investigated with healthy subjects and some CRPS patients (Matamala-Gomez et al., 2018). However, the relationships among SoO, SoA, phantom limb movement, and PLP sensations are not well understood, as quantitative evidence is still lacking. Although some studies proposed that phantom limb movement correlates with PLP relief, the supporting data is still scarce (Osumi et al., 2017 Ortiz-Catalan et al., 2014). A standard protocol and research paradigms are needed to better evaluate complex pain outcomes, SoO and SoA, phantom limb movement, and the correlations among these factors.

4.1.4.3. The Dosage of VR/AR Applications

To my knowledge, none of the published research explored the best dosage (the most effective session frequencies and session length) for pain reduction in VR/AR in general, let alone PLP specifically. Results from a single test lack substantial evidence to prove VR/AR's analgesic effects longitudinally. Based on this review, multiple 20–30-minute sessions appear to be a suitable dosage for PLP patients. Follow ups or participant check-ins could help researchers better understand the potential long-term effects of VR/AR environments.

I tried to minimize the possibility of my missing publications in the literature review by conducting an extensive search. However, a risk of publication bias toward a selection of positive results remained. Additionally, there is a small possibility of there being published studies that I did not identify. As discussed, there was heterogeneity between interventions, methodologies, and analyses. I also identified the potential flaws and limitations of prior studies. However, a sensitivity analysis of methodological limitations revealed the robustness of the results. These limitations should be considered when interpreting the results.

In pain research, patients' self-reports are valued (McCahon et al., 2005) because no biomarkers of pain have been discovered, and correlations between measurable data and the self-reported data and the actual physical arousal were tenuous. Four of the studies collected EMG data as motion inputs. None measured physical changes or outcomes apart from the patients' self-reported ratings. The potential reason could be that collecting biofeedback would have added to the complexity of the experiments, as a person cannot wear a VR/AR helmet while doing fMRI scans or collecting EEG signals. Nonetheless, with that in mind, cortisol levels, fMRI scans, EEGs, and other neurological measures might offer new insights into the underlying mechanisms of VR/AR analgesia in future studies.

To conclude, this literature review analyzed VR/AR studies developed and evaluated for treating PLP, with an emphasis on the efficacy of pain reduction and SoO and SoA, comparison of mirror therapy and motor execution approaches, and study design. Although the studies did not offer enough evidence to support the long-term effectiveness of VR/AR analgesic effects, empirical evidence so far suggests that VR/AR holds promises for reducing PLP. In summary, although the studies reviewed here had promising results, they were limited in terms of sample sizes, intervention frequencies, and controlled comparisons. Therefore, in future studies, I encourage researchers to carefully select protocols and VR/AR environments. Further, I suggest researchers collect not only overall pain levels but also pain characteristics and measures of sense of embodiment and phantom limb movement.

4.2. New Attempt: Focusing on Virtual Embodiment of the Phantom Limbs

4.2.1. Research Background

Researchers postulated that behavioral interventions for PLP might owe their analgesic effects to restoring the sensorimotor circuitry (Giraux & Sirigu, 2003). These interventions usually provide augmented sensorimotor experience of the affected limb, including tactile stimulation (Flor et al., 2001) and surrogate visual representation (Thieme et al., 2016). For example, in mirror therapies, the movements of the intact limb are reflected in a mirror, giving patients a vivid experience of their affected limb as if it is in motion (Thieme et al., 2016). While critical reviews of MT find its analgesic effects are limited (Chan et al., 2007; Finn et al., 2017), some researchers believe that this limitation is because the limb movements are restricted to the mirror surface (Sumitani et al., 2008). Combining virtual reality (VR) with MT has provided a better sense of embodiment of the phantom limb, including a sense of ownership (SoO) and a sense of agency (SoA) (Martini et al., 2014; Osumi et al., 2018) over their virtual body. In this article, the VR environment refers to immersive environments (Marks et al., 2014), where users are completely isolated from their physical surroundings and experience the three-dimensional virtual worlds through a stereographic head-mounted display (HMD). The resulting analgesic effects are comparatively stronger than those from traditional MT (Collins et al., 2018). However, most researchers focused only on the short-term analgesic effect from one VR session (Osumi et al., 2017; Osumi et al., 2018). In fact, longitudinal studies on PLP used representations of a virtual limb displayed on a computer monitor instead of in immersive VR per se (Ortiz-Catalan et al., 2016; Perry et al., 2013; Rothgangel et al., 2018). Thus, longitudinal studies involving VR are still lacking.

Here, I examined the long-term effects of VR-based MT interventions on alleviating PLP and the accompanying changes in the motor imagery capacity involving the phantom limb. I hypothesized that the VR-MT interventions could simultaneously alleviate the pain and improve the motor imagery capacity for the phantom limb across multiple sessions.

4.2.2. Method

4.2.2.1. Participants

I recruited five BPA and amputee outpatients, all of whom were diagnosed with PLP (all male, age mean = 50.2, age SD = 7.73 years) from China-Japan Friendship Hospital in Beijing. All suffered from medium to severe levels of daily pain, and three of five have been taking pain and/or anti-anxiety medicine. Detailed medical and demographic information is listed in Table 4.3. For the inclusion criteria, I adopted similar standards as in a previous study (Ortiz-Catalan et al., 2016): participants (1) need to be adults; (2) have been treated for PLP by at least one clinical approach; and (3) have not reported any pain changes for at least a year after the last session of prior treatments. Three patients exited the study before the planned 10 sessions because of their work and travel matters. They all signed the consent form and were informed that they could withdraw from the study without consequences. Each participant received monetary compensation. The Ethical Review Board of Peking University approved this study protocol (School of Psychological and Cognitive Sciences, #2018-06-02). Written informed consent was obtained from the participants for the publication of any potentially identifiable images or data included here.

	Gender & Age	Injury Cause	Injury	Injury Time (years)	PLP Time (years)	VAS score pre-treatment Out of 10	Previous Treatment	Current Medication	Time on Medication (years)
Patient 1 (P01)	Male 37	Car Accident	BPA (Right Arm)	1	1	6.86	PRDRG	Gabapentin	1
Patient 2 (P02)	Male 50	Car Accident	BPA (Right Arm)	18	18	5.93	DREZL	N/A (because medicine won' t help)	N/A
Patient 3 (P03)	Male 56	Car Accident	BPA (Left Arm)	19	19	7.44	PRDRG	Gabapentin, Estazolam Flupentixol & Melitracen Tablets	5
Patient 4 (P04)	Male 55	Car Accident	Amputation (Right Arm ,10 cm left left)	10	10	9.88	NRB	Gabapentin	10
Patient 5 (P05)	Male 53	Car Accident	BPA (Left Arm)	30	30	7.91	NRB	No pain medicine (because did not work) but melatonin for sleep problem	N/A

Table 4.3 Patients' Demographics and medical information (PRDRG = Pulsed Radiofrequency on Dorsal Root Ganglion; DREZL = dorsal root entry zone lesioning; NRB = Nerve Root Block).

4.2.2.2. Setting and Apparatus

The immersive room-scale VR system and HMD were from HTC VIVE with 1,080 × 1,200 pixels' resolution per eye and a field of view of 110 degrees. Unity software was used to develop the VR environment. Final IK Unity assets provide inverse kinematics' solutions for the avatar's body rigging and movement mapping (Final IK - Asset Store, 2019). Participants saw the environment from a first-person perspective of a gender-matched avatar and remained seated during the entire study. The VR controller, held by the intact hand, can register hand motion and button click.

4.2.2.3. Instruments

I assessed the changes in pain ratings both before and after the VR intervention. Two pain ratings were used (1) Short-Form McGill Pain Questionnaire (SF-MPQ), which is the pain rating index (ratings from 0 to 75) formed by the summed contribution of 15 characteristics of pain (Melzack, 1975); and (2) the visual analog scale (VAS) ratings from 0 to 10. Sense of embodiment (SoO and SoA) was rated once before the whole study and once after. Sense of ownership and SoA ratings were reported in an 11-point numerical rating scale (NRS) from 0 to 10, where 0 means "don't agree at all," and 10 means "strongly agree." The SoO and SoA questions (same as Table 3.1) were modified from related research (M. Martini et al., 2014). Further, the patients' depression and anxiety levels were measured using the Hospital Anxiety and Depression Scale (HADS) questionnaire (Snaith, 2003) once before the entire study and once after.

4.2.2.4. Procedures

Each session lasted approximately 1 hour with the following steps (Figure 4.2).

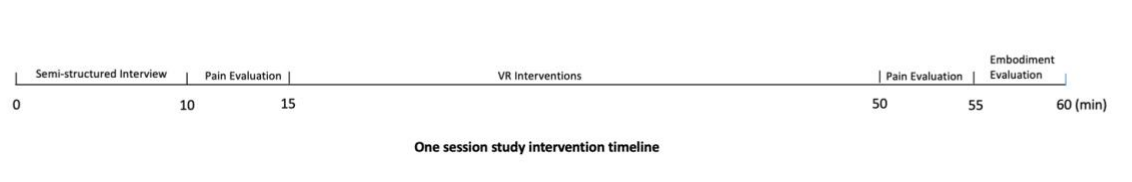

Figure 4.2 Study procedure for each single session.

(1) The patient filled out the questionnaires for self-reported anxiety and depression ratings before session 1, and SoO and SoA ratings after session 1.

(2) I conducted semi-structured interviews to collect the patients' subjective feedback before each session. The questions regarded (a) pain qualities and frequencies, (b) sleep quality, (c) medicine intake, (d) emotional changes, and (e) any other thoughts.

(3) The patient filled out the two pretest pain questionnaires before each session.

(4) The patient wore a VR HMD and held a controller in their intact hand, performing two motor tasks (a ball-pushing task and a ball-shoot task) for 30min (Figure 4.3). The ball-pushing task required the participant to push a ball off the table with extension of both virtual limbs whose motion was driven by the measured motion of the intact limb only. The ball-shoot task is to extend both limbs to shoot a basketball toward a basket. The order of these practices (ball-pushing vs. ball-shooting) run randomized and patients performed each for three times per session. Again, the motion of two limbs was driven by the intact limb only; the ball release was initiated by clicking the trigger button on the controller.

(5) The PLP patients carried out the motor imagery and motor execution tasks twice across the study period, once before all sessions and once after. I detailed the task instructions before a practice session when patients performed the two VR motor tasks by motor execution and by motor imagery, three times each. For the motor imagery test, patients were asked to visually imagine performing the two VR tasks with either limb (not both limbs); each test and each limb was repeated three times. They were instructed not to perform motor imagery unless they were told to. For the motor execution test, patients then executed each task with the intact hand for three times. For each trial, the patient clicked the trigger button of the controller once before the trial, and once after the trial to register the time needed for imagery and execution. "Imagery time" refers to the time patients spent for motor imagery test; similarly, "execution time" refers to the time spent for motor execution time.

(6) The patient filled out the posttest VAS ratings after each session.

(7) The patient filled out the questionnaires for self-reported anxiety and depression ratings, and SoO and SoA ratings immediately after the last session.

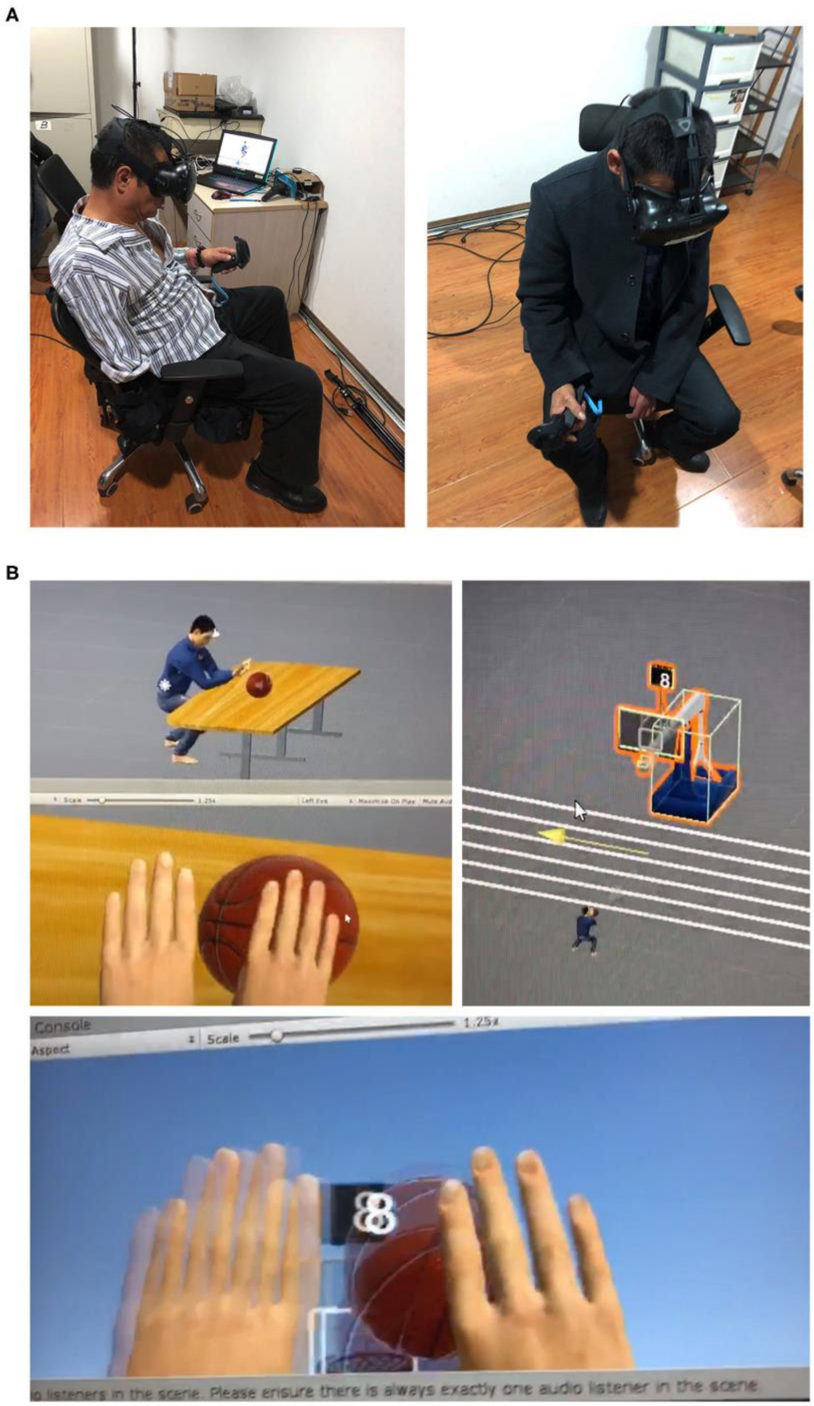

Figure 4.3 A. Patients performing the ball-pushing task with an HTC VIVE's controller held in the intact hands (left: P04; right: P03). B. The VR environment as depicted during the two tasks (the ball-pushing task and the ball-shooting task from third-person and first-person perspectives). Participants only saw the VR environment from the first-person perspective.

4.2.3. Results

4.2.3.1. Primary Outcomes—Pain Ratings

The pain ratings showed that all five patients had pain reduction, both before and after a session and across sessions (Table 4.4 and Figure 4.4). Patients P01 and P04 withdrew from the study after the third session, P5 after the fourth session; P2 and P3 completed all 10 sessions as planned. Because of the limited sample size, I opted to perform a non-parametric test to compare the pain ratings between the first session and the third session to examine whether the pain reduction was significant. The average of five patients' MPQ ratings was 16.4 (SD = 5.14) in the first session and 10.4 (SD = 5.03) in the third session, respectively. A Wilcoxon signed-rank test showed a significant improvement of pain rating in the third session compared to the first session with a large effect size despite the small sample size ($Z = -2.02$, $p = 0.043$, $r = 0.9$). Notably, all patients showed continuous pain reduction over consecutive sessions.

	No. of sessions participated	SF-MPQ rating reduction (%) (across sessions)			VAS (%) (across sessions)	VAS (%) (mean value before and after each session)
		Pain sensation categories	Emotional categories	Total		
P01	3	42.86	66.67	49.21	25.36	20.6
P02	10	83.33	100	87.76	39.29	4.09
P03	10	38.46	66.67	45.98	9.89	28.79
P04	3	52.94	33.33	47.71	5.87	8.82
P05	4	64.71	25.00	54.12	14.79	43.86
Mean (SD)	6 (3.67)	56.48 (18.08)	58.33 (30.05)	56.96 (17.49)	19.04 (13.47)	21.23 (15.95)

Table 4.4 Patients' pain reduction percentages between the first and last sessions of their participation of each individual and the group mean and standard deviation (SD) values.

Overall, patients reported an average improvement of 56.96% (SD = 17.49%) on the SF-MPQ ratings when comparing the last session. They took part in their first session. Specifically, 56% improvement (SD = 18.08%) was on the pain sensation categories (throbbing, shooting, stabbing, sharp, cramping, gnawing, hot-burning, aching, heavy, tender, and splitting) and 58.33% (SD = 30.5%) on the emotional categories (tiring exhausting, sickening, fearful, and cruel-punishing). Notably, all patients showed more than 50% improvement (ranging from about 50%, e.g., P01, to 90.91%, P02), although their initial pain ratings differed substantially (Figure 4.4B). Scrutinizing 15 pain qualities (Figure 4.5), I found that all patients initially experienced and subsequently improved on emotional categories in their SF-MPQ ratings. For the sensory intensity category, four of the five patients shared throbbing, sharp, and heavy experiences; the heavy sensation disappeared after the intervention.

Further, I also categorized the pain qualities into “kinesthesia-related pain characteristics” (splitting, exhausting, burning, aching, throbbing, stabbing, sharp, shooting) and “somatosensory-related pain characteristics” (gnawing, fearful, cramping), as a previous study found that VR mirror-movement therapy specifically improved the kinesthesia-related pain characteristics (20). However, I found that these two categories improved to a similar extent, with an average 50.47% (SD = 31.57%) and 56.67% (SD = 36.51%) improvement, respectively (Figures 4.4 D, E).

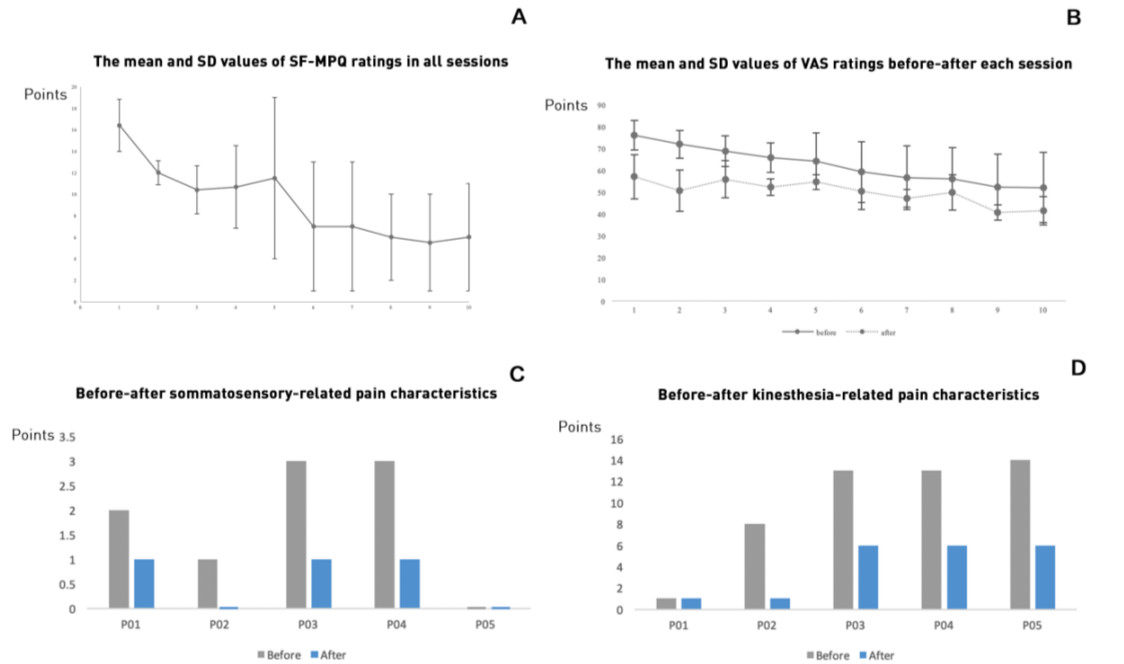

Figure 4.4 A. The average SF-MPQ ratings across all sessions. B. The average VAS ratings across sessions. C and D. Each participant’s ratings of somatosensory-related pain characteristics and kinesthesia-related characteristics (where P02 and P05 do not have bars meaning zero value). Here, error bars denote standard errors. All vertical-axis refers to the rating points of the scales used.

The VAS ratings showed a similar but less drastic analgesic effect than the SF-MPQ ratings (Figure 4.4B and Table 4.4) The averages of the five patients’ VAS ratings in the first three pretests were 7.6 (SD = 1.47), 7.19 (SD = 1.4), and 6.88 (SD = 1.56), whereas the posttests mean ratings were reduced to 5.71 (SD = 2.26), 5.07 (SD = 2.12), and 5.59 (SD = 1.91), respectively. The Wilcoxon signed-rank test showed that all three posttests had significantly reduced VAS ratings when compared to their corresponding pretests with a large effect size (for all three tests, $Z = -2.02$, $p = 0.043$, $r = 0.9$). Comparing VAS ratings across days, I found a marginally significant difference in pretest ratings between the first session and the third session ($Z = -1.75$, $p = 0.08$); however, the posttest ratings did not show a significant across-session difference ($Z = -0.41$, $p = 0.68$), possibly because the analgesic effect in each session masked the across-session differences. The average improvement of the VAS rating was 19.04% (SD = 13.47%). I found that each session induced an average improvement of 21.23% (SD=15.95%) when comparing the pre-test VAS ratings with the posttest ones. All five participants showed this one-session improvement. Given the small sample size in this study, I would like to state the statistics should be viewed with caution.

4.3.2.2. Phantom Limb Movement: Motor Imagery and Motor Execution Movement Time

The performance of motor imagery and execution was quantified by their movement time (Figures 4.5 A, B; individual data in Tables 4.5, 4.6). First, execution time and imagery time were similar for the intact limb, suggesting that participants followed my instruction. Both measures tended to decrease when measured again after the VR intervention, possibly due to a practice effect. As expected, I also observed that the impaired limb had substantially larger imagery time than the intact limb, with average of 12.83 ± 6.45 s and 17.23 ± 8.98 s for the ball-pushing and ball-shooting tasks, respectively. In contrast, the intact limb had average imagery time of 6.05 ± 3.30 s and 5.35 ± 1.79 s for these two tasks, respectively.

Critically, the imagery time of the impaired limb was reduced dramatically after VR intervention, averaging 5.19 ± 3.84 s and 5.80 ± 4.48 s for the two tasks, respectively. These reductions, averages of 60.59 and 66.53%, brought the imagery time to the level comparable to that of the intact limb, suggesting that the phantom limb movement was dramatically improved after the intervention.

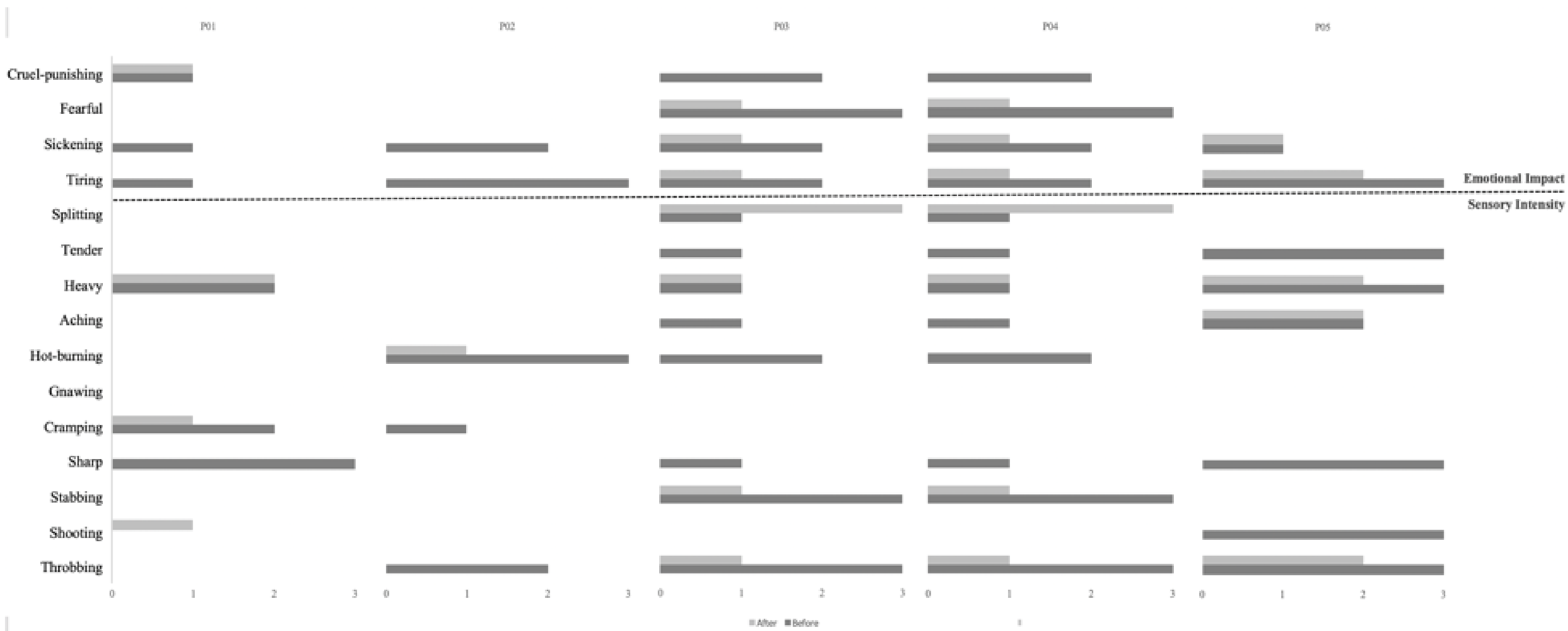

Figure 4.5 Each participants' SF-MPQ data, containing 15 pain qualities.

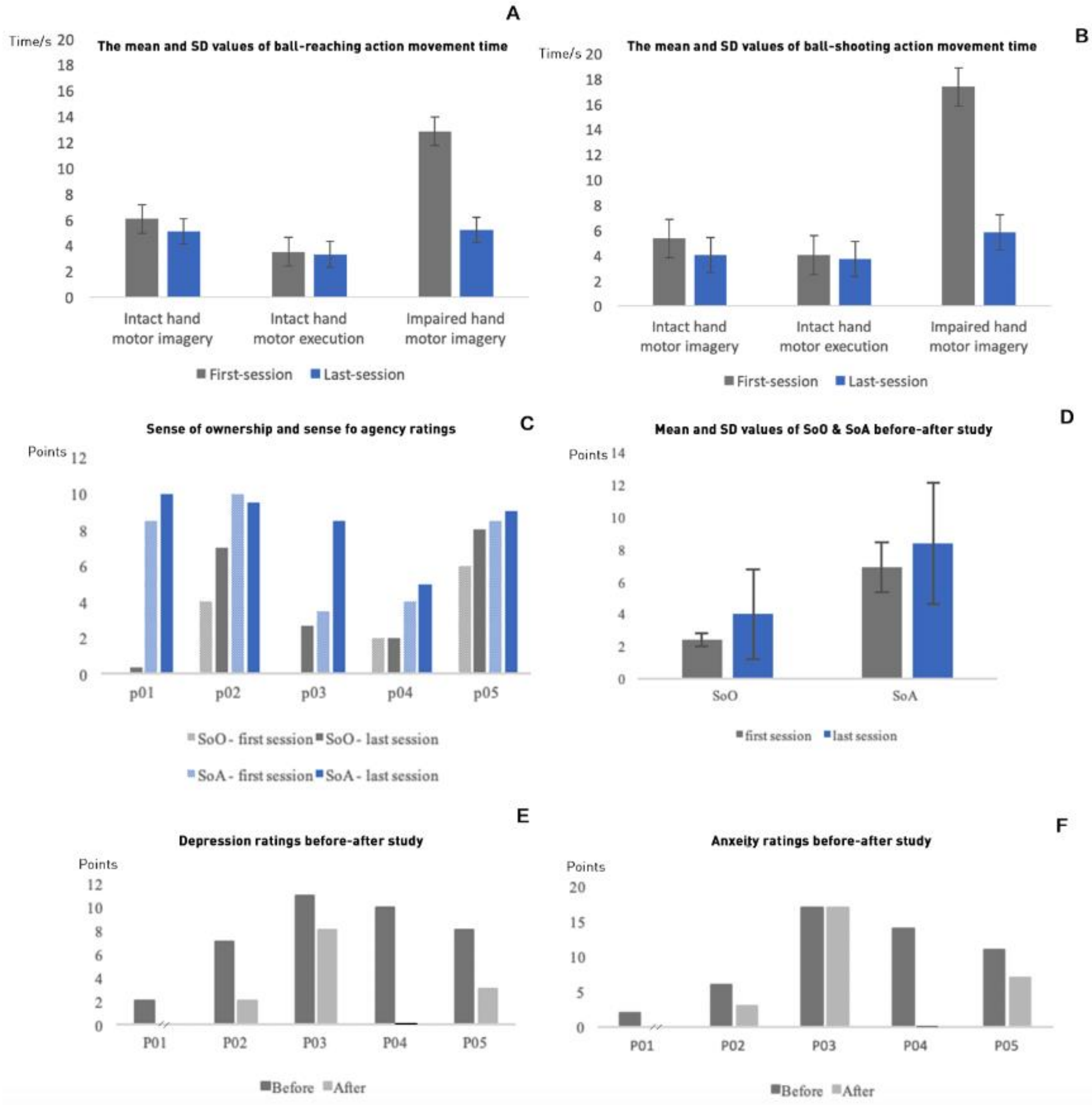

Figure 4.6 A, B. Mean and SD of motor imagery time and motor execution time for the ball-reaching task by both the intact limbs and the impaired limbs (y axis: in seconds). C. Each participant's sense of ownership and sense of agency ratings of their virtual body. D. The mean SoO and SoA ratings of the first and the last sessions. E, F. Patients' anxiety and depression ratings before and after the study (P01's after study depression and anxiety data were missing; P04's after-study rating means zero value).

	Mean and SD of the Reaching Action Reaction Time (s)	
	The First Session	The Last Session **(% of changes compared to the first session)**

	Motor Imagery the impaired hand	Motor Imagery the intact hand	Motor Execution the intact hand	Motor Imagery the impaired hand	Motor Imagery the intact hand	Motor Execution the intact hand
P02	3.929	1.21	1.51	2.457 (37.47)	2.041(-68.68)	1.55 (-2.65)
P03	17.376	7.273	1.92	3.402 (80.42)	2.619 (63.99)	1.99 (-3.65)
P04	17.864	7.11	4.488	10.867 (39.17)	6.58 (7.45)	3.929 (12.46)
P05	17.791	10.624	9.178	3.006 (83.1)	3.154 (12.46)	3.154 (65.64)
Mean	**14.24**	**6.554**	**4.274**	**4.933 (60.04)**	**3.599 (18.3)**	**2.656 (17.95)**
SD	**6.877**	**3.914**	**3.525**	**3.975 (25.12)**	**2.039 (64.49)**	**1.086 (32.63)**

Table 4.5 Patients' mean and SD values of their impaired and intact hands' motor imagery reaction time and the intact hand's motor execution reaction time in millisecond at the first and last sessions of their participation of each individual and the group mean (reaching action).

	Mean and SD of the Shooting Action Reaction Time (s)					
	The First Session			The Last Session **(% of changes compared to the first session)**		
	Motor Imagery the impaired hand	Motor Imagery the intact hand	Motor Execution the intact hand	Motor Imagery the impaired hand	Motor Imagery the intact hand	Motor Execution the intact hand
P02	4.988	4.081	0.9	2.573 (48.42)	1.842 (54.86)	0.94 (-4.44)
P03	29.781	7.136	1.88	3.383 (88.64)	2.444 (65.75)	1.67 (11.17)
P04	18.28	7.387	6.047	12.357 (32.4)	7.287 (1.35)	6.242 (3.22)
P05	23.574	3.573	3.55	4.901 (79.21)	4.454 (24.66)	4.565 (28.59)
Mean	**19.156**	**5.544**	**3.094**	**5.804 (62.17)**	**4.007 (24.33)**	**3.354 (6.27)**
SD	**10.55**	**1.996**	**2.252**	**4.474 (26.24)**	**2.455 (43.11)**	**2.481(16.48)**

Table 4.6 Patients' mean and SD values of their impaired and intact hands' motor imagery reaction time (in seconds) and the intact hand's motor execution reaction time in millisecond at the first and last sessions of their participation of each individual and the group mean (shooting action).

4.3.2.3. Sense of Embodiment Ratings

The rating of SoO and SoA for the avatar in the VR increased in this experiment (Figures 4.5 C, D). The ratings were measured twice through an 11-point NRS before and after all sessions, right after the participants took off the HMD. The questions for each category were added up and averaged to one score per category. The SoO and SoA ratings increased, from the first to the last session, by 66.67 and 21.74%, respectively. Average SoA increased from 6.9 (first session, SD = 1.32) to 8.4 (last session, SD = 0.89); Correspondingly, average SoO increased from 2.4 (SD = 1.66) to 4.0 (SD = 1.48). However, P04's rating of SoO and P02's rating of SoA did not increase.

4.3.2.4. Anxiety and Depression Ratings

The patients' anxiety and depression levels were measured using HADS, once before the first session, and once after the last session (Figures 4.5 E, F). I missed collecting the posttest ratings from P01 and P04 because they withdrew. All the remaining three patients experienced an improvement in anxiety and/or depression with varying degrees. P02 and P05 experienced an improvement in both the anxiety and the depression levels, whereas P03 showed improvement only on depression levels. Follow-up phone calls with participants after 6-month showed that they still experienced a slightly improved situation, but not as powerful as during or right after the study.

4.3.2.5. Qualitative Interview Analysis

All patients reported one or more positive changes after the intervention. Here, I report the qualitative results briefly. P01 said the VR intervention had provided him with an analgesic effect ranging from 2 hours or longer until he went to bed at night. However, his anxiety from over 10 years of suffering hardly changed. P02 did not report a substantial change in pain before and after each intervention, but he did report a substantial decrease in pain ratings across the entire study. Furthermore, he reported multiple pain sensations in SF-MPQ initially, and only one at the study's conclusion. P03, before the study, reported over 30 times of "unbearable bursts of pain every day," which he rated as 9 or 10 in VAS and lasted for 1 to 5 minutes. After the study, P03 reported that the intensity of his pain bursts was "much more endurable now" and that they lasted half the time. Notably, P03's quality of sleep steadily improved. Before participation, he woke up 8–10 times because of the pain bursts; at the conclusion of the study, he only woke up two to three times per night. P05's reported similar improvement in sleep: before the study, he reported, "I have problems falling asleep and I need to take pills. But now I don't need to." Surprisingly, even though I did not ask, three out of five patients mentioned that they dreamt that their impaired limb moved again, the same way it had before their injury. According to P05, “I had a dream yesterday, and I saw my right hand and arm moving! It felt so good and so vivid that I can still remember.” Thus, these semi-structured interviews showed that all five patients’ subjective experiences are consistent with the quantitative measures, including pain ratings and motor imagery time.

4.2.4. Discussions

This study with five PLP patients reveals that a long-term VR-MT intervention produced substantial analgesia, indexed by SF-MQP and VAS pain ratings, along with improved phantom limb movement, quantified by reduced motor imagery time. Short-Form MQP and VAS ratings showed different percentages of improvement, given that they measure different aspects of pain perception with different levels of responsiveness (Hawker et al., 2011; Scrimshaw & Maher, 2001). I also found an enhanced sense of embodiment with the VR avatar and improved ratings in anxiety and depression. I observed all of these changes in each patient, although with varying effect sizes.

These findings suggest that VR-MT interventions hold promise as effective analgesia for patients who suffer PLP, particularly considering that four out of five participants suffered severe PLP for more than 10 years, and were first treated with at least one of the traditional pain management methods. Therefore, it is unlikely that carryover effects from previous therapies can explain my findings. For the same reason, pain relief owing to natural regression to the mean effects is unlikely to explain the observed large effect. Furthermore, patients who were taking medication had already been on it for over 2 years without an increase in dosage during the study; this makes medications an unlikely explanation for the results.

In this study, five patients underwent the VR intervention for 4–6 weeks, ranging from 3 to 10 sessions (Table 4.4). Previous VR studies mostly had a limited number of participants in longitudinal tests. For instance, Murray et al. (Murray et al., 2007) conducted a case study with three patients over two to five sessions; Henriksen et al. (Henriksen et al., 2017) investigated the feasibility of their VR environment with three upper limb amputees over seven sessions, and Chau and colleagues’ case study involved only one PLP patient who participated in five sessions (Chau et al., 2017).

Other VR studies involved a single session with one or more patients (Ambron et al., 2018; Cole et al., 2009; Ortiz-Catalan et al., 2014; Osumi et al., 2018; Wake et al., 2015). One reason that prevents large sample sizes is that patients with PLP usually need the help of caregivers to travel, and most patients lived far from the research laboratory (not in the same province). I also found that patients I recruited were too physically inactive, mentally impaired, or socially disengaged to participate in the study.

While the potential of using VR for relieving PLP has been demonstrated, why and how it works remain unclear. Some researchers believe that having a sense of ownership over a virtual body in VR might alleviate pain for healthy subjects and pain patients (Martini et al., 2014; Matamala-Gomez et al., 2019a). Others proposed that VR distracts acute pain patients' attention from their pain by the multisensory, immersive VR environment (Bidarra et al., 2013; Gold et al., 2005; Wiederhold et al., 2014). Both explanations received respective support. In fact, a combination of modified embodiment and distraction—by pairing a VR intervention with mindfulness meditation in order to direct attention inward to awareness of and agency over a patient's body—was shown as an effective intervention for chronic pain management (Gromala et al., 2015a). The longitudinal data cannot be accounted for by distraction as the accumulated effect is obvious. I indeed observed more SoO and SoA, but their effect is relatively small.

With the growing evidence that the level of the phantom limb's movement may be correlated with a cortical or subcortical reorganization, others have also suggested that improved phantom limb movement may be associated with pain reduction (Giummarra & Moseley, 2011). However, in only one study was the phantom limb's movement actually measured quantitatively (Osumi et al., 2018). The data here also showed an improvement in movements of a phantom limb, quantified as a reduction in motor imagery time that was specific to the impaired limb. Given that the motor imagery was measured only twice, I believe that the practice effect alone could not explain the large and limb-specific effect. The observed 60.59 and 66.53% reduction in imagery time in the two motor tasks was remarkable because it dropped to levels comparable to that of the intact limb. The improvement suggests better control of the impaired limbs' movement. Osumi and colleagues used a bimanual coupling effect between the affected limb and the intact limb as an indirect measure of changes in phantom limb control. They found that bimanual coupling increased with VR interventions and, importantly, were correlated with the VR-induced analgesic effect. The findings of improved motor imagery in the affected limb are in line with Osumi et al. (Osumi et al., 2018) findings, suggesting that improved voluntary movement of the phantom limb might reflect the neuroplasticity changes in PLP patients that are associated with VR's analgesic effects. I did not run a correlation analysis between the improvement in motor imagery and the analgesic effect due to the small sample size.

The first limitation of this study is the small sample size which prevents us from establishing the correlation between pain reduction and accompanied changes in the phantom limb movement and embodiment. In future studies, I plan to conduct a longitudinal controlled trial with more samples and methodological improvements. For example, a motor imagery test can be performed measuring electromyography in residual muscles. Sense of agency and SoO can be potentially quantified by more objective approaches, such as intentional binding. I could also compare VR interventions without or without a virtual body. The VR experience can be complemented with haptic feedback to enhance embodiment (Sano et al., 2016). Importantly, the improvement in the phantom limb movement, as revealed by motor imagery time, can be further investigated by electroencephalogram or functional magnetic resonance imaging scans to probe possible neural reorganization brought about by VR interventions.

4.3. Chapter Summary

This chapter detailed a systematic literature review of studies on VR and AR applications used to address PLP and a longitudinal case series that evaluated how mirroring movement in VR affects PLP, embodiment, anxiety, depression, and phantom limb movement. The results of the review suggest that most studies on VR/AR interventions were conducted with a limited number of patients in a single trial. Few explored questions about how embodiment affects PLP, how multiple VR sessions might affect pain over time, or whether a patient's ability to move their phantom limb may affect their PLP. Therefore, I recruited PLP patients to answer these questions and to understand how embodiment correlates with different chronic pain types that differ from CRPS (as discussed in Chapter 3). Five PLP patients were recruited to practice two motor tasks in multiple VR sessions over six weeks. The results showed that repetitive exposure to an embodied VR intervention leads to reduced pain and improvements in anxiety, depression, and the sense of embodying a virtual body. Importantly, I also found that people’s ability to move their phantom limbs improves, which was quantified after giving participants shortened motor imagery time with the impaired limb.

Although the limited sample size prevented me from performing a correlational analysis, my findings suggest that providing PLP patients with a sensorimotor experience for their impaired limb in VR appears to offer long-term benefits and that these benefits may be related to changes in users’ control of their phantom limb’s movement. In other words, the SoO and SoA over the virtual phantom limb seem to enhance the control over the real phantom limb and reduce the patients’ pain. Moreover, this experiment also offers a potential novel approach to measuring a phantom limb’s movement by clocking the performance time of motor imagery tasks. However, further research with a larger sample size is required to draw a firm conclusion about the correlation between embodiment and PLP.

Chapter 5. Virtual Embodiment and Empathy

Research findings suggest that in addition to the opportunities it offers pain modulation, VR also promises to situate people in the perspectives of other social groups other than their own, for example, different gender, age, and race, and foster empathy towards one another. A stream of research has specifically highlighted VR's potential to elicit perspective taking, which is when a person perceives a situation and understands a concept from someone else's point of view. I would like to use virtual embodiment to help non-patients understand patients' social challenges. In this chapter, I first discuss the social stigmas that marginalized and vulnerable populations face, particularly that of chronic pain patients. I then discuss the definitions of empathy and the importance of generating it to address social stigma, and I review embodied technologies designed to foster it toward marginalized and vulnerable populations. Then I examine how VR has become the "ultimate empathy machine" (Milk, 2015, 2:27) and the commonly adopted study methods and VR interventions. I further explore the roles of virtual embodiment in fostering empathy and the potential of using the virtual embodiment approach to do so in a specific context: toward pain patients. The central questions of this chapter are: how does VR offer an empathetic experience and increase people's empathy? What is the role of virtual embodiment in creating VR environments that foster empathy? How can VR be used to enhance non-patients' understanding of pain patients?

5.1. Social Stigma and Empathy

5.1.1. Acknowledging Stigma & Its Presence in Patient Care

In its original meaning, "social stigma" referred to a marking or tattoo that was cut or burned into the skin of criminals, slaves, or traitors to visibly identify them in public places (Goffman, 1986). Today, the term refers to an attribute that extensively discredits a person, reducing them from whole and typical to tainted and discounted (Dubin et al., 2017). According to Goffman (1986) and Slattery (2003), there are three types of social stigma.

(a) Overt or external deformities, such as scars, physical manifestations of anorexia nervosa, leprosy, or of a physical or social disability, such as obesity.

(b) Deviations from norms and mores, including dropping out of school, working a low-wage job, being a single parent, going bankrupt, struggling with addiction, being a homosexual, being unemployed, attempting suicide, practicing radical political behavior, being dependent on welfare, committing adultery, having a mental disorder, getting pregnant as a teenager, having a criminal background.

(c) Tribal stigmas related to ethnicity, nationality, or religion.

Pain and chronic pain patients can experience a combination of two social stigmas: overt deformities because of their injured body parts and deviations from norms and mores caused by pain, such as the use of opioids, having a mental disorder, or dropping out of school or work. However, chronic pain conditions are generally invisible, unlike scars, deformities, or objective evidence seen on imaging. Chronic pain patients don't display overt symptoms of injury, so people stigmatize chronic pain patients with the labels of complainers, malingerers, opioidphobia or drug-seekers (CMAJ News, 2018; CBC News, 2019). Because of the stigma, patients with chronic pain usually experience emotional challenges—approximately half are depressed, and a third have had suicidal thoughts (Buchman & Ho, 2013; Choinière et al., 2010). Stigmatization might reduce patients' self-esteem and social supports, leading to isolation. More severely, it can also lead to discrimination, which itself can result in the loss of status, rejection, exclusion, and the patient's avoidance of social interaction; it can also lead others to be hostile with the patient and withhold help (Link & Phelan, 2001).

Chronic pain patients' social stigma does not only stem from the public's misunderstanding or lack of knowledge about their BPS conditions but also from patients' caregivers and health-care professionals, including doctors, physicians, and nurses (Dubin et al., 2017). Researchers have assumed that health-care providers acquire stigmatizing behaviors during their medical education. When they begin learning, their teachers expose them to an implicit or hidden curriculum that suggests that some patient characteristics (e.g., obesity, substance abuse, mental illness, and poverty) are the result of personal choices rather than other more crucial contributing and causative factors (Phillips & Clarke, 2012). Interventions are required to combat this kind of conditioning. Empathy is a key construct in social relationships, and research has linked it to prosocial behavior. Hence, encouraging greater empathy and the nonjudgmental acceptance of people who live with chronic pain and need help will alleviate pain patients' stigma in clinical and other social settings. While some researchers believe that one's empathy is a social skill that could be improved, others argue that rational compassion is more helpful for facilitating prosocial behaviors than empathy (Bloom, 2016). Therefore, this chapter defines empathy, its composition, and the embodied experiences created for encouraging it.

5.1.2. Understand Empathy

Generally, empathy has been viewed as the process whereby one person tries to understand the subjectivity of another person accurately and without prejudice (Wispé, 1986). Cuff et al. (2016, p. 20) defined it as a multifaceted social skill or fundamental dimension of human development that improves interpersonal relations and is critical to social processes (it helps build social connections with others and supports prosocial behavior).

Although researchers in fields as varied as psychology, computer science, and health science hold varied definitions of empathy, they have taken two primary approaches to studying it: the **cognitive empathy approach and the affective empathy approach**. In the former, empathy is a process of understanding another person's perspective (Decety & Jackson, 2016), and the term is used interchangeably with "perspective taking." In contrast, affective empathy studies the observers' emotional responses to other people's affective states (Reniers et al., 2011).

Researchers have adapted a varying approach to understand and define empathy. For instance, in Davis' research, he proposed an organizational model of empathy-related construct, which considers both interpersonal and intrapersonal outcomes from cognitive and affective levels (Davis, 2006). Others have dissociated perspective taking from empathy, arguing that empathy stresses feelings and motives, while perspective taking is the ability to see things from another point of view. In this dissertation, I have adopted a multicomponent approach to define empathy from three aspects of awareness of another's states: **perspective taking (cognitive), affective empathy (emotional), and physical empathy**.

Although physical empathy has been less frequently mentioned, psychologists also propose that other people's physical sensations should be considered part of empathy and be known as "compathy" (Morse et al., 1998, p. 3). This type of empathy addresses physical responses triggered by emotions. For example, caregivers usually have physical responses to patients' distress and may even share physical symptoms. Compathy often occurs when a person observes another person suffering from a disease or injury and experiences similar distress in their own body (Morse & Mitcham, 1997).

Much as there are many definitions of empathy, there are many models for understanding it as well. Davis's (2006) model describes perspective taking (cognitive empathy) and affective empathy as the primary components, and the scientific community views it as the gold standard. It consists of four factors:

(1) perspective taking, referring to a person's ability to adopt another's viewpoint;

(2) fantasy, referring to a person's ability to relate to the feelings of a fictitious character;

(3) empathic concern, referring to a person's feeling of being involved in others' emotions; and

(4) personal distress, referring to a person's feeling of sorrow over others' pain.

Researchers believe that the perceptual and behavioral processes of empathy foster group living and are a foundation for beneficial social interactions (Preston & de Waal, 2002). Empathy can also lead to or improve prosocial behaviors (e.g., helping behaviors) and better social adjustment (Blanke et al., 2016). For instance, patients receive better treatment outcomes when treated by therapists with greater empathy (Moyers et al., 2016, p. 20). In another example, medical students who have a greater level of empathy demonstrate higher clinical competence (Ogle et al., 2013). On the other hand, a lack of empathy implies the inability to view the world from other people's perspectives or be affected by others' feelings, and the resulting risk is that someone lacking empathy might exhibit prejudices or violent behaviors (Nienhuis et al., 2018).

Here, I would like to mention a few other terms—"compassion," "altruism," and "empathic distress"—to differentiate them from empathy. Compassion is an emotional and motivational state of care for the well-being of others (McCall et al., 2014). While empathy refers more generally to one's ability to take the perspective of and feel the emotions of another person, compassion is when those feelings and thoughts include the desire to help. Altruism is characterized by behaving prosocially at a cost to oneself (de Waal, 2008). Empathic distress is when one is upset by the distress of another (Batson et al., 1987), which is one of the factors that consists of empathy.

5.1.3. Promoting Empathy with Technology

Research has shown that empathy and helping behavior can be promoted with prosocial digital media and computer-mediated communications, such as social media, video games, and VR applications. According to Rosen (2012), empathy developed in this manner is called "virtual empathy" (p. 1). This section explores the various technology-based tools for developing it.

5.1.3.1. Social Media

Since 2010, the popularity of social media networks, such as Facebook, Twitter, and YouTube, has rapidly accelerated. These networks are platforms on which people share their lives with friends and strangers alike. While the platforms are often criticized as breeding grounds for antisocial behavior, they also play a role in fostering empathy. Researchers have found that people not only tend to create a more positive impression of themselves on social media but are also more responsive to prosocial campaigns and activities (Caplan, 2003). Moreover, social media provides a platform for changing unidentifiable statistical victims into real people. Social media campaigns have proven to be effective ways of eliciting empathetic attitudes and generating individual and organizational support for causes. For instance, crowdfunding is used extensively by patients and their families to raise funds for expensive medical treatments (Kenworthy, 2019). In another case, Kazley et al. (2016) examined approaches to soliciting kidney donations on social media on social media sites. Although using social media to generate empathy seems to be the most promising approach to reaching the general public, it is limited in its immersion and engagement levels when compared to video games or VR applications.

5.1.3.2. Videogames

Studies have shown that video games are a useful vehicle for fostering understanding of and empathy toward vulnerable populations (Greitemeyer et al., 2010). Researchers have examined the effectiveness of video games in fostering empathy and social awareness of different issues, such as unemployment, cultural and political conflicts, and community challenges. For instance, Belman et al. (2010) presented three games to cultivate empathy: Peacemaker, Hush, and Layoff. In Peacemaker, the player inhabits the role of either the Israeli prime minister or Palestinian president during a particularly volatile period of the Palestinian-Israeli conflict. The player's goal is to create conditions that make a two-state solution viable. The player has to negotiate peace by making political, economic, and security-based decisions while the game presents unexpected events generated by its AI. Similarly, in Layoff*,* players adopt the perspective of a corporate manager who terminated the jobs of non-player characters during a financial crisis. The game designers aimed to create an empathy bond between the players and the manager so the players can experience challenging decision-making moments.

All three games described above encourage empathy through perspective taking (also called "role playing" in game research) and narrative storylines, which are the common approaches taken in other empathetic games. For example, Looy et al. (2010)described Poverty Is Not a Game (PING), a 3D adventure game in which the player adopts the identity of one of two adolescents and searches for ways to survive. The creators of PING hoped to raise awareness of the mechanisms that underlie poverty and social exclusion. Bachen et al. (2012) examined Real Lives, an educational game that allows learners to live simulated lives in other countries. In this game, students experience what life is like in another country, including the education system, employment, marriage, having children, and confronting diseases and natural disasters. This game uses real-world data to determine the probability of events that occur in the characters' birth countries (Bachen et al., 2012).

Overall, video games can provide more immersive perspectives on marginalized groups. However, most are pilot prototypes and lack scientific validations for their empathetic effects. Recently, researchers (e.g., Bachen et al., 2012; Bailey et al., 2016; Barbot & Kaufman, 2020; Bertrand et al., 2018) have shifted attention to VR technology and have used it as a medium for communicating empathy because it generates high levels of immersion and perspective taking.

5.1.3.3. 360° Videos, Cinematic VR, and Embodied VR.

Some studies didn't identify significant differences in empathy levels increased in a non-immersive 360° video condition and the cinematic VR condition. For instance, Sundar et al. (2017) compared three storytelling media by having participants engage in VR and non-immersive 360° video conditions; they were more empathic toward the characters than when they read *The New York Times* stories on which the games were based. Further, in an autism study, Weinel et al. (2018) found that when it came to generating empathy, VR cardboards offered limited benefits when compared to 360° YouTube video formats. However, Schutte and Stilinović (2017) found that the VR format resulted in greater engagement and a higher level of empathy (empathic perspective taking and empathic concern) when the protagonist was a refugee than the control group in 2D video format. Therefore, further empirical evidence is needed to validate the distinctive potential of cinematic VR over other media in prompting empathic responses.

Overall, cinematic VR can promote empathy, but may not significantly outperform the 2D video format. Apart from this cinematic approach, VR researchers take the embodiment approach to fostering empathy. Since using embodied VR for empathy is one of this dissertation's primary research trajectories, I have reviewed VR-related work and research in a separate section below.

5.1.4. Section Summary

This section aimed to clearly define empathy and state the importance of generating empathetic understandings of vulnerable groups. I first discussed one of the most severe social problems patients experience—social stigma—and why empathy is important in resolving this challenge. I then explained and defined empathy's physical, cognitive, and emotional characteristics to set a theoretical foundation for understanding empathy in this dissertation. To conclude, I briefly introduced the media and technology approaches researchers have taken to foster empathy, and I did this with a specific focus on social media and video games.

5.2. Facilitating Empathy in Embodied VR Environments

5.2.1. Prior Work: VR and Empathy

In addition to their findings related to pain modulation, virtual embodiment studies have demonstrated both cognitive and emotional effects on people's empathetic attitudes (Ahn et al., 2013; Ahn et al., 2016; Hamilton-Giachritsis et al., 2018). Embodied VR applications foster understanding by having users inhabit virtual avatars with appearances that differ from their real-world bodies, and this constitutes perspective taking. To date, most of the empathy-related VR applications include an avatar representative of a population toward which empathy is desired, and they allow people to view or control the avatar from a first-person perspective. Empathetic perceptual and behavioral changes have been elicited when a person virtually embodies a marginalized person's point of view and visceral experiences in their daily challenges and encounters.

Most recent research has focused on VR's potential to elicit perspective taking. This phenomenon can be physically manifested in VR by literally and virtually having people experience another perspective (Falconer et al., 2014; Hamilton-Giachritsis et al., 2018; Herrera et al., 2018; Maister et al., 2015; Schutte & Stilinović, 2017; Shin, 2018; Slater & Sanchez-Vives, 2016; van Loon et al., 2018). For instance, Slater's group and other researchers validated the finding that virtual embodiment can implicitly or explicitly affect people's cognitive perceptions, emotions, and behaviors (Banakou et al., 2013; Maister et al., 2015; Osimo et al., 2015; Slater et al., 2008; Steptoe et al., 2013). Most of their research received improved outcomes of biases. However, in a recent study, Slater's group identified a situation that embodying White people in a Black virtual avatar made their racial bias worse than the White avatar condition (Banakou et al., 2020). One thing to note is that the focus of Slater group's research didn't address empathy per se but measured implicit biases, which I consider to be the cognitive part of empathy. Their findings provide surprising and provocative evidence that people can map their avatars' body image or identities onto their own body images on two levels: (1) multimodal physical sensation (visual, audio, tactile, or combinations thereof) and (2) sensorimotor correspondences between the physical body and the virtual body (motor). Therefore, the appearances (visual presentations) of the avatars and their motor synchrony with the real bodies' movements foster perspective taking.

Many VR applications seek to provoke empathy in specific targets, raise awareness of specific social problems, or change mindsets concerning social issues, such as domestic violence (Seinfeld et al., 2018). Applications have also sought to foster understandings of eating disorders by using avatars with distorted body shapes (Riva et al., 2016), and they have encouraged helping behavior with superhero avatars (Rosenberg et al., 2013). Further, multiple studies have reported evidence of a reduction of implicit race bias in immersants who inhabited an avatar with darker skin or different physiognomic features in multiple studies (Banakou et al., 2013, 2016; Nakamura, 2020). Oh et al. (2016, p. 201) found that having people embody an elderly avatar was more effective in reducing ageism. In other studies, embodying adults in virtual children led to perception changes of object sizes and implicit self-identification, which does not occur when the body is adult sized (Banakou et al., 2013; Tajadura-Jiménez et al., 2017). However, as mentioned earlier, Weinel et al. (2018) found that VR cardboards offer limited benefits over 360° YouTube video formats when it comes to eliciting empathy.

So far, researchers have successfully altered people’s cognitive and affective perceptions by embodying them in avatars of different races, ages, sexes, and mental disorders, and they have even embodied people in animal avatars. However, the underlying mechanisms of how VR fosters empathy remain under investigated. Next, I summarize the potential impacting factors presented in the literature.

5.2.2. Impacting Factors of Embodied VR

Although empathy consists of physical, cognitive, and affective aspects, researchers believe that it is an *ability* that can be cultivated (Read, 2019) and directed at will (Persson & Savulescu, 2018), particularly its cognitive and affective aspects. Van Loon et al. (2019) used muscle training as a metaphor to explain the process of empathy exercises; the authors said that “empathy is like a muscle which one can work to increase its strength” (p. 2), though empathic perspective taking depends on individual capabilities (Ahn et al., 2013). Therefore, the next question is: what are the underlying mechanisms or factors that impact the empathy levels fostered by embodied VR?

Drawing on the literature, Barbot and Kaufman (2020) identified five dimensions that affect changes in empathy: immersion, sense of presence, user engagement, SoO, and SoA, all of which were concluded to be UX-related impacting factors or predictors. In particular, the authors noted that SoO and SoA (virtual embodiment) best predict empathy changes.

Of the dimensions, sense of presence includes four primary types of illusions, as covered in Chapter 2, Subsection 2.2.2, and these four illusions are interrelated. However, Barbot and Kaufman's findings are conceptually confusing, as they do not consider the illusions' interrelationships. Rather, the authors defined "presence" as a sense of involvement and the realism of the experience, which, more precisely, is the sense of being in a stable place.

Although researchers have measured presence as a whole, the roles of each illusion in facilitating empathy should be clarified. Further, the interrelationships between embodiment and a sense of presence should be discussed, as should embodiment's significance relative to all presence illusions. In Barbot and Kaufman's (2020) paper, the engagement factor was defined as "the sense of involvement, connection with, and enjoyment of the content", which seems to overlap with the definitions of the four types of illusion and their associated experiences. Further, Barbot and Kaufman also argued that "engagement builds upon the sense of presence" (p. 2), and they believed that presence and engagement can become even stronger in VRs which elicit embodiment. Presence and engagement include a collection of other factors, which are not meta-factors that can be directly analyzed or associated with changes to empathy. Rather, they overlap one another.

As noted in Chapter 2, researchers have used the terms "immersion" and "presence" interchangeably to refer to the experience of being in a place. However, the terms point to different aspects of this experience. Again, "presence" is defined as the subjective experience of being in a place and responding to increased physiological and emotional responses in VR (Cummings & Bailenson, 2015). "Immersion" is defined as the objective fact of being in an environment. It refers to the technological quality of media delivery or the extent to which a system presents a vivid virtual environment while shutting out physical reality (Cummings & Bailenson, 2015).

Based on Barbot and Kaufman's framework, I propose modified versions of the potential impacting factors of using embodied VR to enhance empathy by dissecting the components of presence: immersion, sense of being in a physical place, sense of embodiment (virtual embodiment), sense of physical interaction, and sense of social presence. Next, I discuss how researchers have associated each of these factors with embodied VR's effectiveness in fostering empathy.

5.2.2.1. Immersion

VR Content can be delivered through various hardware platforms and systems: some are immersive formats such as HMD, cardboard VR, and CAVE; others are non-immersive formats, such as 2D monitors. Several studies have compared immersive (HMD) versus non-immersive modalities (2D monitor) to elicit empathy. Some found that immersive modalities were more conducive to empathy than non-immersive modalities (Ahn et al., 2016; Schutte & Stilinović, 2017). For instance, Ahn et al. (2016) found that immersive VR allows participants to take the perspective of animals and experience a greater connection between themselves and nature than they would with a 2D video format. Schutte and Stilinović's (2017) findings indicated that VR formats result in greater engagement than 2D formats when people watch documentaries (the study focused on participants watching a documentary about a young girl living in a refugee camp). Contrarily, as mentioned in Subsection 3.1.3, Weinel et al. (2018) did not note significantly higher levels of empathy when their participants used cardboard HMD instead of 2D videos. These findings did not uncover a consistent direction of how a stronger immersion level impacts empathetic attitudes, and future studies should focus on how the immersion factor affects empathy.

5.2.2.2. Sense of Presence

Schutte and Stilinović (2017) argued that a format's immersive quality is not related to empathy so much as a sense of presence that represents "a platform for the experience of empathy" (p. 709). According to Nicovich et al. (2005), empathy and sense of presence may share common features, including the projection of the self into an environment and adopting the experience of another with thoughts and feelings related to that experience. In other words, a sense of presence may facilitate feelings of connection with others and an understanding of others' perspectives. For instance, the authors' findings showed that the degree of presence is associated with a person's general inclination toward empathy. Ahn et al. (2013) found that the sensory experience of color blindness in VR elicited participants' empathetic feelings and concerns for people who are color blind. Even though presence and empathy share common features (i.e., perspective taking), they are separate concepts: more specifically, presence provides a platform for the experience of empathy (Carey et al., 2017).

Other factors can be further explored to understand how embodied VR affects empathy. For instance, the novelty effect of VR should be researched thoroughly and validated in longitudinal experiments. The impact of VR on empathy may decrease with the level of familiarization with the technology and affect first-time users and participants who have more experience in different ways. Further, most VR incorporates narrative elements or storylines. Therefore, narrative mechanics and the way narratives are presented may also impact empathy levels.

5.2.3. Research Methods

In this section, I summarize the research methods used in existing embodied VR and empathy studies, focusing on their study design, VR content, and empathy assessments.

5.2.3.1. Study Design

Some researchers have conducted within-group or between-group in-lab experiments (Banakou et al., 2016; Behm-Morawitz et al., 2016; Neyret et al., 2020; Peck et al., 2013; Rosenberg et al., 2013). In their experiments, participants were embodied in avatars that the researchers intended to represent groups toward which they wanted participants to feel empathy, and they were then embodied in a normal avatar or one with an opposing identity in the control condition. For example, to compare racial bias changes, participants were put in a black-skinned avatar for the experiment condition and a white-skinned avatar for the control condition (Banakou et al., 2016; Behm-Morawitz et al., 2016). Before-after comparisons have also been conducted without control groups (Wijma et al., 2018). The independent factors can either be the appearances of the embodied avatars or the interactions they have with other avatars in the same environment. There has also been a noteworthy absence of longitudinal studies, a lack of diversity in the sample populations, and little knowledge about the medium differences (e.g., desktop VR versus cardboard VR) and long-term effects of the interventions.

5.2.3.2. Study Materials (VR Content)

As they have done for VR in pain management studies, most researchers have developed VR prototypes for various empathy scenarios. The VR content has been highly customized to different research questions, and very few VR commercial titles have been created. The embodied avatars, virtual spaces, social interactions, and interactivity with virtual environments have all been designed in the context of researchers' goals. Interestingly, these unique VR applications share three common features: (1) they deploy a virtual body from first-person perspective in a virtual place; (2) they tend to use body motion systems to track people's full- or partial-body movements in the real world and synchronously present those movements; and (3) they tend to have a narrative story or, at least, a narrative background for the virtual scene, and this is achieved via environmental design and interactive tasks. These features are the basis of virtual embodiment and the other three attributes of presence illusions.

5.2.3.3. Empathy Assessments

Researchers have selected a wide range of instruments and behavioral tests to measure empathy outcomes. Multiple empathy questionnaires have been developed by cognitive scientists and psychologists, including the Compassion Scale (Pommier et al., 2020), the Basic Empathy Scale (Jolliffe & Farrington, 2006), the Toronto Empathy Questionnaires (Spreng et al., 2009), the Questionnaire for Cognitive and Affective Empathy (Reniers et al., 2011), the Baron-Cohen and Wheelwright's Empathy Quotient (Baron-Cohen & Wheelwright, 2004), the Kiersma-Chen Empathy Scale (Kiersma et al., 2013), and the Interpersonal Reactivity Index (Gerry, 2017). These questionnaires were developed for different aspects of empathy; they pose different questions, and some are for different populations.

Some researchers have opted to use customized performance tasks to measure implicit attitude changes, including gender or racial bias through the Implicit Association Test (Lopez et al., 2019; Peck et al., 2013) and action conformity through the Milgram Obedience Test (Neyret et al., 2020). A few researchers have either adapted the above mentioned questionnaires to accommodate their specific experimental conditions or combined a few to receive a more comprehensive understanding of empathy changes. For instance, Barbot and Kaufman (2020) included three items from the Interpersonal

Reactivity Scale, three from the Questionnaire for Cognitive and Affective Empathy, and three from the Questionnaire to Assess Alexithymia for Adolescents.

In the human-computer interaction (HCI) field, Carey et al. (2017) proposed a holistic approach to measuring all aspects of empathy in VR environments with researchers' observations and subjective data capture. In their method, the Wheel of Emotion (Plutchik, 1980) was selected to measure affective changes. The VR-adapted Other in the Self Scale (Aron et al., 1992) was also suggested to measure the cognitive aspect of empathy (perspective taking). Although Carey et al. drew on this measurement based on internal design iterations and reviews without study validations, the holistic measurement provided inspiring insights for HCI researchers. To conclude, the most appropriate empathy assessment matches one's research questions (aspects of empathy) and directly addresses the study outcomes or participants' behavioral changes.

5.2.4. Section Summary

In this section, I first presented the research and primary use case scenarios for fostering empathy in VR. Then I analyzed the factors that potentially impact the development of empathy in VR, and these were adapted from Barbot and Kafuman's (2020) recent framework. I also offered an in-depth review of the four attributes of presence illusions and their potential roles in affecting empathy. Finally, I discussed the literature's general research methodologies, including study design, content, and empathy instruments; the work that went into constructing this section helped me better plan and justify my research method.

5.3. Facilitating Empathy toward Patients

To my knowledge, few researchers have used embodied VR to foster empathy toward pain patients. Here, I introduce the cases in which researchers elicited empathy for people with pain in video games and VR environments. The findings showed that digital media, such as video games and VR, could be an effective and powerful way of conveying experiences of pain. My goal in constructing this section was to identify potential approaches to digitally representing pain so I could refer to them when creating embodied experiences to foster empathy toward people with pain, particularly people with chronic pain.

Different media have been explored to address the physical, psychological, and social challenges this population faces. The primary approach has thus far been perspective simulation of the targeted user group’s symptoms and experiences. The ways of communications include:

(1) audio simulations (Skoy et al., 2016);

(2) visual simulations:

  a. 2D videos, interactive systems, and video games (Cosgray et al., 1990; Drigas & Papoutsi, 2016; Jansen, 2020; Reed, 2017; most of these researchers’ simulations were game-based);

  b. VR (Dyer et al., 2018, p. 201; Wijma et al., 2018); and

(3) psychosocial role playing:

  a. point-of-view multimodal simulation or role play (Levett-Jones et al., 2017).

In each study, the focus of patients’ medical conditions was unique and ranged from dementia and other forms of mental illness to cancer and age-related disease to patients undergoing more general treatments. Most of the research prototypes were developed as training tools in the context of medical education because health-care practitioners and providers (e.g., doctors, nurses, pharmacists, physical therapists, caregivers, and health-care trainees) require high levels of empathy to effectively work with patients. Studies have shown that these simulation approaches seem to help practitioners and providers develop a better understanding of what patients go through, which helps in building trust with them. Next, I review these approaches and list a few cases under each category.

5.3.1. Audio Simulations

Audio simulations are meant to advance understandings of and empathy for those who regularly hear voices. Orr (2017) used audio simulations to create the symptom of hearing voices that patients with mental illness experience. To increase empathy for patients with mental illness, Skoy et al. (2016) asked pharmacy students to listen to an audio recording that simulated auditory hallucinations. Both authors found that empathy scores significantly increased after the simulations. However, since the audio was designed to be distracting, scary, and mean, Davidow (2018) argued that this approach might not function as intended and could increase people's fear and hopelessness.

5.3.2. Point-of-View Role Play with Wearable Technology

In this approach, researchers ask participants to adopt the role of a patient or a caregiver and perform a scenario in an experiment. Wearable items or suits are usually used to support the physical simulations. For instance, in Levett-Jones et al.'s (2017) study, students undertook the simulation in pairs. They were randomly allocated to the role of either a person with acquired brain injury or a rehabilitation nurse. The simulated patients wore a hemiparesis suit that replicated the experience of dysphasia, hemianopia, and hemiparesis. Participants reported significantly higher mean empathy scores post-simulation compared to pre-simulation. Similarly, Christina et al. (2012) also used role play to enhance nursing students' soft skills, including their empathy levels. In addition to academic studies, a few commercial products are available to increase the public's understandings of certain medical conditions. In a news report, three men put on so-called empathy bellies, which are wearable pregnancy simulators made by Birthways Inc., to experience a pregnant woman's belly (Empathy Belly, 2016). The same company also produced empathy lungs, a chronic obstructive pulmonary disease simulator for understanding patients' breathing difficulties (Birthways, Inc, 2016).

5.3.3. Visual Simulations: Videogames

Even when players are concerned about winning a game, research has demonstrated that games and video games have a high potential for fostering empathy toward a certain population (Greitemeyer et al., 2010; Konrath et al., 2011; Kral et al., 2018; "Lemmings (Video Game)," 2019; Olivier et al., 2019). Many games have been designed to increase understandings of and eliminate discrimination against patients with various medical conditions. Specific techniques have been adopted to enhance empathy, such as narratives and storytelling, virtual agents, and biofeedback. Narrative storytelling enables players to experience the consequences of medical conditions on a vulnerable population's work, family, and social relationships. For instance, Elude represents the mental struggles of depression patients with visual barriers that players need to conquer in a 2D platformer game (Rusch, 2012). A Day in the Life of an Inpatient relays a hospitalized patient's ward experience and tells stories reflective of a typical day in such an environment (Cosgray et al., 1990). Using interactive texts, Depression Quest presents players with the daily choices of a person suffering from depression (Zoe Quinn, 2013). Finally, That Dragon, Cancer tells the story of a four-year-old who fights cancer; a before-after comparison study showed its effectiveness in improving empathy (Chen et al., 2018).

In addition to storytelling, intelligent virtual agents have also been introduced to medical trainees to improve their interpersonal communication skills with patients (Deladisma et al., 2007; Halan et al., 2015). Unlike video games, virtual agents directly simulate interactions between health-care practitioners and real patients. One study explored the effect of the virtual agent's impacts on participants' empathy levels in a text conversation application (Halan et al., 2015). Another study compared participants' responses to a virtual patient to that of a standardized (human) patient (Deladisma et al., 2007). Although participants gave more genuine feedback to standardized patients, the findings of both studies revealed improved empathic responses and verbal and nonverbal communication skills.

Biofeedback mechanisms play a critical role in constituting feedback loops in interactive systems in which biosensor data are used to provide real-time feedback to users via data visualizations, games, narratives, or VR. Physiological states are integrated into a game, and physiological responses can be used to enhance participants' sense of embodiment (Kors et al., 2016), modulate emotional arousal (Muñoz et al., 2016), or mapped to empathic abilities (Schoeller et al., 2019). Biofeedback appears to increase the sense of embodiment (Lobel et al., 2016).

5.3.4. Visual Simulations: VR

Recently, researchers began using VR as a medium to simulate scenarios that foster empathy. Findings from prior studies indicate that immersive VR simulations have the potential to enhance people's engagement with the targeted groups and promote a higher level of empathy in medical education and in increasing public awareness (Dyer et al., 2018; Loon et al., 2018; Wijma et al., 2018). For example, it can be used for difficult-to-simulate scenarios from a first-person perspective and to standardize a scenario, and it can also be used in medical exams. In a few studies, researchers used

VR to interactively simulate the experiences of people with dementia to improve their caregivers' understanding of the disease (Jütten et al., 2018; Lindsay et al., 2012; Wijma et al., 2018). Another group of researchers created a VR prototype to train employees who work for aging services (Dyer et al., 2018). In Dyer et al.'s research, they developed a VR game, called The Alfred Lab, which teaches participants about macular degeneration and hearing loss from the perspective of a 74-year-old African American man. Likewise, Labyrinth Psychotica is a virtual environment created to simulate the visual and audio experiences of schizophrenia (Nikolov, 2018).

5.3.5. Section Summary

Overall, researchers found that VR enhanced participants' understanding of patients' health problems and increased participants' empathy for vulnerable populations. However, there are limitations to its usefulness: it is expensive, and follow-up evidence supporting its long-term effectiveness is lacking. In reviewing the literature, I did not find a VR simulation with a scenario aimed at pain patients. Therefore, I designed my second research trajectory to explore ways of having people experience pain in an embodied VR to develop their understandings of people with pain. The studies I conducted on this topic are introduced in Chapter 6.

Chapter 6. Virtual Embodiment for Fostering Empathy toward Pain Patients

According to conservative estimates, chronic pain affects one in five people in industrialized countries (Dahlhamer, 2018). However, public awareness of it was remarkably low until the recent opioid crisis (Eriksen et al., 2006). As a result, stigma is a problem the people who live with chronic pain frequently face (Ruddere & Craig, 2016), and it often leads to self-isolation. More than loneliness, social isolation is correlated with a decreasing quality of life and earlier morbidity (Coyle et al., 2011; Turk & Monarch, 2018). As treating long-term pain means managing it, caregivers and health-care professionals must find ways of understanding the lived experience of chronic pain sufferers—in other words, they must understand what it is like to actually live with the debilitating effects of long-term pain and how it impacts a patient's BPS realities, ability to function, and QoL (Turk & Monarch, 2018).

Many researchers have evaluated how technologies, such as social media, video games, and VR, can foster the affective and perspective-taking aspects of empathy in both clinical and nonclinical settings. The immersive and convincing nature of VR has profound effects on people's perceptions and may confer meaningful benefits to cognition and behavior. Despite the growing interest in using VR applications to generate empathy, few studies have focused on empathy for people living with chronic pain. To my knowledge, the correlation between virtual embodiment and empathy and the impacting factors of embodiment on empathy have not been studied. I created a VR game called AS IF to address these research gaps and foster empathy toward the growing number of people who live with long-term chronic pain. Based on my prior work, I iterated the design twice and overhauled my approach in two user studies. This chapter introduces the game design, the two mixed method studies, and the study results.

6.1. Study 1: Design and Evaluation of AS IF Version 1.0

6.1.1. Design Objectives and Game Development

AS IF was developed in Unity game engine with Microsoft Kinect as the body motion sensor. As users try to perform everyday tasks, they witness specific physical limitations while they simultaneously hear the musings of a chronic pain patient. In these ways, the game simulates the experience of having a body that is in pain, albeit in very limited ways. Decisions to focus the game on movements and an avatar build on the Embodied Simulation Theory, which suggests that people reuse their mental states or processes represented in a physical format in functionally attributing them to others (Gallese & Sinigaglia, 2011).

The game starts with an introductory tutorial that shows the player how to interact with the system, and how the motor tasks work. When players move their limbs, the body sensor changes the position and orientation of the avatar in microseconds; this creates an illusion that the player “inhabits” or is mirrored by the avatar. As players perform tasks (solving puzzles by connecting virtual dots in a line as shown in Figure 6.1B), they experience some of the avatar’s mobility limitations “as if” they are facing these physical limitations in real life, like chronic pain patients might. Players hear the voice of the avatar, a chronic pain patient who provides directions about how to perform the game’s tasks. The avatar also talks about what it’s like to live with pain, and how it affects things as simple as everyday tasks. “Pain” is made visible by red areas that appear on the avatar’s joints (as the red and yellow arrows indicated in Figure 6.1B). This indication of pain appears when the avatar’s range of motion becomes limited, and therefore hinders the player’s ability to accomplish tasks through the avatar.

Figure 6.1 A. Left: the setup and game mechanism of AS IF. B. Right: a participant interacts with AS IF through a virtual body (an “avatar”). The red arrow points to the avatar’s body part affected by chronic pain (the elbow), while the yellow arrow indicates the player’s mirrored gesture in the real world.

After completing the tutorial level, the player is introduced to a narrative of a grandmother in a kitchen (Figure 6.2B). The avatar communicates with the use of voice-clips, that she is baking a birthday cake for her granddaughter. Using the avatar, players then perform tasks (connecting dots in one line to form certain shapes) of making a cake step-by-step while they hear audio self-talk of what it is like to perform such everyday tasks from the perspective of a real patient. When the player completes each task, audio feedback and ambient sounds are triggered. Currently, the game offers only one scenario – playing as the grandma to bake the cake for her granddaughter's birthday party.

Figure 6.2 A. The overview of the VR game's environment. B. The first-person player view in AS IF.

6.1.2. Study Method

6.1.2.1. Study Intent

The aim of this study was to find out whether AS IF can motivate empathy and improve non-patients' willingness to help patients given the timeframe of the study intervention.

6.1.2.2. Participants

Participants were recruited through a convenience sampling method, with ads placed in university campus media and emails sent to faculty and student groups. The exclusion criterion was any reported history of a chronic pain diagnosis. Fifteen people participated in the study, aged from 20 to 34 years old (M = 24.8, SD = 3.8); 27% were female (N = 4).

6.1.2.3. Study Procedures

Upon arrival at the lab, participants were briefly introduced to the study procedure and were instructed to read and sign the consent form. Before the gameplay, participants were asked to fill out the pre-intervention questionnaire, which included a revised Compassion Scale and the Willingness to Help Scale. Next, they were given instructions about the game's rules and thereafter played AS IF for 10-15 minutes. After playing the game, players were asked to fill out the post-intervention questionnaire (the same as the pre-intervention). Finally, researchers conducted a 10-minute semi-structured interview with players, which were audio-recorded. Afterwards, the data were transcribed and coded.

6.1.2.4. Instruments

To measure quantitative changes in empathy and attitude before and after playing the game, the study used two instruments: an empathy questionnaire and a scale measuring a willingness to help People with Chronic Pain (PWCP). The self-report empathy questionnaire was modified from the Compassion for Others Scale, developed and validated by Pommier et al. (Pommier et al., 2020) In the revised version, the term "other people" was replaced by "people with chronic pain" in all of the questionnaire's items. The word "when" was modified to "if" since participants may not have had the chance to interact with PWCP, and since they responded to a hypothetical scenario in the game. The original scale consists of six subscales: kindness, indifference, common humanity, separation, mindfulness, and disengagement. Each subscale has four items. I adopted the kindness, indifference, separation and disengagement subscales as those most closely related to chronic pain. The revised scale had 14 (vs. 24) items in total, as shown in the Appendix A. For each statement, players indicated how often they behaved in the manner stated on a 5-point Likert scale. The total score of the Empathy Scale was calculated and then the summations of each subscale were added together. For the willingness to help PWCP, a scenario was presented: “You’re preparing for an important interview tomorrow. However, a friend who has chronic pain asks you to help by giving him a ride to the airport, a two-hour drive.” Participants indicated their willingness to help on a 11-point Likert scale.

6.1.3. Results and Discussions

For the quantitative data, the pre- and post-intervention comparisons of the Empathy Scale and Willingness to Help Scale were analyzed using one-tailed paired-samples t-test. For the qualitative data, the in-person interviews were first transcribed into digital form. The inductive open coding approach was used to analyze the interview data. Each sentence was labeled by codes and related codes were categorized together after the entire transcript was coded. Significant emerging patterns were highlighted, summarized and grouped into themes. As shown in Figure 6.2 A, for the scores of Willingness to Help before and after the game intervention, a significant increase in the post-intervention score was observed (M = 8.00, SD = 1.49) compared to the pre-intervention score (M = 6.89, SD = 2.73), $t_{14} = 2.132$, $p = 0.026$. The effect size for this analysis was found to be a median effect (d = .50) according to Cohen’s (1988) convention. For the Empathy Scale, the total scores in the pre-intervention (M = 60.27, SD = 7.53) and the post-intervention score (M = 62.93, SD = 6.97) did not reach statistical significance; $t_{14} = 1.480$, $p = 0.081$. For the Compassion Scale’s subscales of kindness, indifference, separation and disengagement, the separation subscale showed a statistically significant decrease in the pre-intervention (M = 9.90, SD = 3.09) and the post-intervention scores (M = 8.57, SD = 2.27); $t_{14} = 2.098$, $p = 0.027$. The kindness ($p = 0.44$), indifference ($p = 0.14$), and disengagement ($p = 0.23$) subscales were found to be statistically non-significant between pre-intervention and post-intervention scores.

The quantitative results indicate that while completing tasks in AS IF, players achieved a significant increase in the Willingness to Help score with a median effect size. However, the game failed in increasing empathy toward PWCP. This lack of eliciting empathy may result from flaws in the game design and other factors, such as a short duration of gameplay and not enough repeated exposure to the game. The findings from the interview below may be used as potential design implications for future empathy games. Three main themes emerged: building the embodied connections, visually representing pain and storytelling increases emotional attachment and empathic attitude.

Building the Embodied Connections: Relating a Real Body to a CP Patient's Virtual Body (Avatar) Helps Generate Immersion and Fosters Empathy. Creating a sensible and reasonable level of embodied connection (i.e., virtual embodiment), is an important way for players to feel immersed in the game world and especially to feel that they are "in the shoes of" a chronic pain patient. The game's tasks require full-body movements, which are mirrored by the avatar. Because the avatar moves in concert with the player, some players reported they felt they were immersed in or were embodying a chronic pain patient. Some players reported that they liked how the physical limitations led to frustration, and that they felt tired and hopeless at the end of the game. For instance, P01 said,

> "I gained some understanding of these people psychologically. I realize they live in a depressed way, their body encounter(s) frustration. I, therefore, have some sympathy for them."

Other players, however, interpreted the disabled movements as software bugs because their movements were intentionally disrupted by the program and participants couldn't control the avatar's motion seamlessly.

Visually Representing Pain: Providing More Feedback. The visual depictions of pain in AS IF appeared less successful than movement constraints. Most participants, for instance, did not notice the red areas on the avatar. As P03 reported, "I sometimes saw the visual effect changed in the game, but I didn't realize it is related to chronic pain." Some participants suggested adding more visual and sound effects to make the pain areas more obvious. P08 said "I would prefer to have more pain-related sound effects like "ouch!" and visuals in the game to remind me that I were a patient." A few participants said that the visual feedback the red areas – was not enough, so they suggested that in addition to visual responses, tangible feedback like pressure or heat would be more helpful ways to more fully experience some pain-related sensations.

Narrative Storytelling Creates Emotional Attachment and an Empathetic Attitude. Narrative storytelling and role-playing in AS IF helped to create a connection between the player and avatar, and helped players identify with a greater sense of what chronic pain patients may experience. Situating the players appropriately in a pain-related identity was an important way to elicit an empathetic response from the players. Most reported they felt a sense of relatedness through the narrator's (a patient) musings, and said that it provided them with a mission to help this patient complete her job. In these two ways, players reported that they felt "as if" they were the patients, e.g. P11: "The story, you hear the story so you get emotionally attached. She still has to work and cook the cake," and P04, "I felt like the old grandmother. I am touched with emotion… When the non-harmonious sound plays when you do wrong… it is very emotional." Other aspects of the game were not successful. Some participants, for example, mentioned that the connect-the-dots puzzle "pulled them out" from the actual game experience. As P04 mentioned: "Dots are too noticeable, (and they) distract me from (the) character. I was too busy trying to solve the puzzle." Moreover, some participants reported that while the actual actions of a task (like blending eggs and flour in the bowl) worked, tasks should be more commonly experienced. According to P04: "Design something that everyone does for sure in real life, like wash dishes."

Although results of the study did not indicate a significant effect on the total score of the revised Empathy Scale, it did show a significant decrease in the separation subscale. The sense of separation is when individuals see another person as separate from themselves and tend to stay isolated in the instance of an other's suffering (Elizabeth Ann Pommier, 2011). The game's embodied simulation, whether intentional or not, may lead to frustration, similar to chronic pain patients' suffering. This shared frustration may explain the decrease in separation from PWCP after the gameplay. Such quantitative findings were in line with the qualitative interview data. The study limitations include a non-randomized, uncontrolled quasi-experimental design which precludes a causal inference of the game intervention to the outcomes. Other limitations of the study were its small sample size, uneven gender distribution and possibly the youthfulness of participants. Furthermore, I only have one scenario in this game, which could be a limitation, as the players may not feel the context is relatable.

6.1.4. Conclusions

The visual-motor synchronicity of a player's full-body movements mirrored by the avatar appears to elicit identification with the avatar. Results from the mixed-method study revealed that the game was effective in improving the willingness to help chronic pain patients, but did not show a significant increase in compassion toward PWCP. Therefore, I iterated the design of AS IF according to participants' feedback, and conducted the second study as described below in section 6.2.

6.2. Study 2: Design and Evaluation of AS IF Version 2.0

6.2.1. Design Objectives and Iterations

As mentioned in section 6.1, initially, a non-VR desktop version of AS IF was developed and tested using Microsoft Kinect. Later, I conducted a study to evaluate the effectiveness of this interactive game system (Tong et al., 2017). I found that my participants wanted to interact with virtual objects and manipulate them directly, rather than solving the more abstract connect-the-dots puzzles. Further, some suggested viewing the avatar from a first-person perspective rather than a third-person perspective to foster a stronger sense of embodiment. Therefore, I redesigned AS IF and switched the motion capture system from Microsoft Kinect's platform to an immersive VR platform, the HTC VIVE. In contrast to the initial version, the movement tasks of AS IF are now realistic—direct manipulation of objects by using one's hands (via controllers). Instead of connecting the dots to get something done, the VR player makes a cake by direct action, such as breaking an egg. In this new version, participants play from a first-person perspective rather than the prior version's third-person perspective.

6.2.1.1. Narrative and Stories

The narrative of AS IF primarily remained the same as prior participants favored the story and settings. Similar to the initial version, the VR game starts with an introductory tutorial that shows players how to use handheld controllers to interact with AS IF and its virtual objects. As the players as grandmother attend to each task of cake making, they simultaneously hear the grandmother's self-talk: the hopes, frustrations, and fears that stem from the ways chronic pain affects her.

6.2.1.2. Representations of Physical Pain

When the VR player moves each handheld controller, the grandmother avatar (the virtual body inhabited by the player) moves synchronously. A widely adopted Unity package named Final IK was used to achieve this synchronous movement function

(Final IK - Asset Store, 2019). This synchronous movement from a first-person perspective creates an illusion that the player inhabits the avatar—the player thus feels as if they are embodied as a grandmother. When the player interacts with the virtual objects, they also experience the avatar's physical limitations that result from pain. The idea is to enable the player to get a sense of chronic pain patients' emotional and psychological sufferings. Here, physical pain is made visible in two ways: by limited movement (range and the ability to hold onto an object; Figure 6.3) and by a same visual cue as mentioned in 6.1.1 (reddened joints in the arm). Another visual effect is that when pain spikes in the game, red flashes appear to mimic the onset of a headache (Figure 6.4). Consequently, these indications of pain are a form of feedback, and players quickly learn that they hinder their ability to accomplish tasks through the avatar.

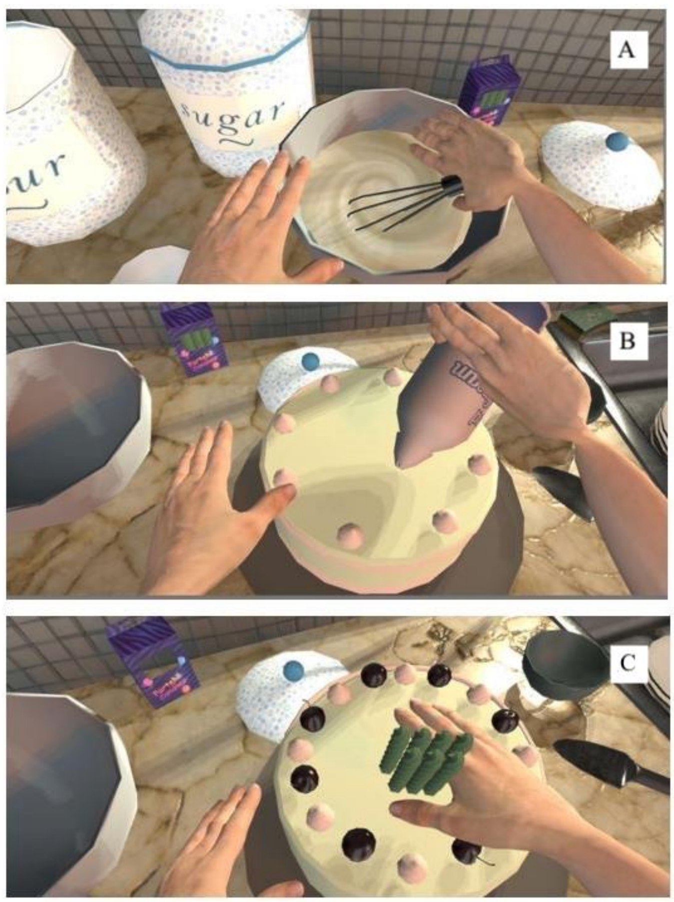

Figure 6.3 Three selected game tasks in AS IF. A. Mixing the flour with milk. B. Adding cream. C. Adding birthday candles.

Figure 6.4 Some of the movements of the virtual avatar’s limbs in AS IF become limited when pain increases (as circled in the figure). In addition, red flashes signal the onset of a headache. During the flashes, a transparent red layer appears over the visible areas of the virtual environment.

6.2.2. Method

6.2.2.1. Study Intent

The goal of this research study was to determine if a serious VR game, such as AS IF, may influence participants’ empathy for patients with chronic pain and to explore what factors may be important to elicit empathy. Furthermore, based on participants’ feedback on this version of the design, I summarize the fundamental design principles and game components to help guide future works.

6.2.2.2. Participants

Altogether, 18 participants (4 females), aged 19-39 years (mean 24.8, SD 3.8 years), were recruited through a convenience sampling method for this study. I placed advertisements in the university campus media and sent emails to the faculty and student groups. The inclusion criterion was anyone older than 19 years, and the exclusion criteria were anyone (a) who had a pain condition or (b) was a pain patient or (c) did not understand English. No participants had a reported history of a chronic pain diagnosis; this was an essential requirement because personal experience of chronic pain could bias expectations of AS IF.

6.2.2.3. Apparatus

Participants experienced and could interact with objects in the virtual environment via a wired, stereoscopic HTC VIVE head-mounted display (HMD) and its handheld controllers. I developed the game using the Unity game engine, which was responsible for rendering and running the game during the study. These real-time rendered scenes of AS IF were sent to the HMD through SteamVR (HTC VIVE) suites; the software was responsible for data between Unity and the devices via an API called OpenVR.

6.2.2.4. Procedures

A mixed-method design approach was adopted in this pre-test, post-test study. Participants' empathy levels toward chronic pain patients before and after playing AS IF, and quantitative questionnaires and qualitative interviews were used in parallel to derive the findings (Creswell & Clark, 2011). The study lasted for 35 to 40 min in total. On arrival, participants were briefly introduced to the purpose of the study and the entire procedure and were then asked to read and sign the informed consent form. Next, participants were asked to fill out the pre-intervention questionnaire (Appendix A), which included the Empathy Scale (revised from the Compassion Scale (Elizabeth Ann Pommier, 2011)), the Willingness to Help Scale, the VR-adapted Other in the Self Scale, and the Emotional Wheel evaluation. During the intervention, participants were first shown how to play AS IF, and then, they played it for approximately 10-15 min.

When they finished the game, participants were asked to fill out the posttest questionnaires to assess their level of empathy toward patients with chronic pain. The posttest questionnaires were a repeat of the Empathy Scale, the Willingness to Help Scale, and the Emotional Wheel evaluation. The Other in the Self Scale was added to assess the relationship between self and the first-person perspective in the VR experience (Appendix A). In addition, participants were given a Sense of Embodiment questionnaire to evaluate their perceived level of immersion in the VR game. Finally, through a 15-min semi-structured interview, participants discussed their experience, provided feedback, and offered researchers their ideas about the game. The interview topics were primarily about the game's interactions, depictions of pain, and physical impact on participants' empathetic attitudes in AS IF. Meanwhile, the session was audio recorded to ensure that the captured data were accurate.

6.2.2.5. Instruments

I used multiple instruments to measure various aspects of empathy. For instance, the Empathy Scale, adapted from Pommier Compassion Scale (Elizabeth Ann Pommier, 2011; Pommier et al., 2020), measures multiple-dimensioned implicit cognitive changes, whereas the Willingness to Help Scale detects explicit cognitive changes. Wheels of Emotion reflects emotional changes, and the VR-adapted Other in the Self Scale assesses the perspective taking aspect of empathy. As chronic pain is a complex process that involves physical, emotional, and social aspects, I adopted instruments that account for cognitive and affective empathy perspectives regarding pain (Appendix A).

To determine which instruments were validated and the most appropriate, I compared existing instruments, such as the Basic Empathy Scale (Jolliffe & Farrington, 2006), Toronto Empathy Questionnaires (Spreng et al., 2009), and Baron-Cohen and Wheelwright's Empathy Quotient for people with autism (Baron-Cohen & Wheelwright, 2004). After thoroughly examining questions from each scale and evaluating how the scales may fit and be adapted for my purposes and population (patients with chronic pain), I selected the Compassion Scale (Pommier, 2011; Pommier et al., 2020) for its appropriate number and types of questions.

In the previous study of the initial version of AS IF, the Empathy Scale, the five-point Numerical Rating Scale (NRS), and the Willingness to Help Scale (11-point NRS) were used to understand if and how that game may have affected participants' cognitive empathy levels. A total of 2 pretest questionnaires were also used in the previous version: (1) the Empathy Scale was used to assess implicit empathy (unconscious emotion) and (2) the Willingness to Help Scale was used to assess explicit empathy (conscious emotion).

For the current VR version of AS IF, the Wheel of Emotion (Carey et al., 2017; ROBERT Plutchik, 1980) and the VR-adapted Other in the Self Scale (Weidler & Clark, 2011) were adopted to measure any emotional changes associated with empathy and the degree of perspective taking according to the suggestions of Carey et al (Carey et al., 2017). The Wheels of Emotion provides a comprehensive list of emotions and standardizes the data collected (according to Plutchik's Psycho-Evolutionary Theory of Emotion), whereas the Other in the Self Scale helps players articulate how they related to the grandmother's avatar. Moreover, to further investigate embodiment in the VR version, I adapted a sense of ownership (SoO) and a sense of agency (SoA), rated on an 11-point NRS (from −5 to 5). The adapted questions are listed in Table 3.1.

6.2.2.6. Data Handling

All statistical analyses of the quantitative data were performed using SPSS version 22 (IBM) software (SPSS Software, 2020). For qualitative data, in-person interviews were first transcribed as electronic textual data. These data were then coded into categories based on preexisting knowledge or hypotheses. After comparing the results, the researchers highlighted significant patterns and summarized and grouped them into themes.

6.2.3. Results

6.2.3.1. Quantitative Findings: The Empathy Scale (Adapted Compassion Scale)

I used a paired t-test to analyze the differences between the before and after empathy ratings, total scores and subscale scores (Figure 6.5), kindness, indifference, separation, and disengagement (Pommier, 2011). For the adapted Empathy Scale, the total scores from the pretest (mean 47.33, SD 4.24) and the posttest (mean = 59.22, SD = 4.33) score did not reach statistical significance ($t_{17} = -1.41$, p=.07). However, I found differences in the subscales: the kindness subscale showed a statistically significant increase in the posttest (mean = 15.61, SD = 2.85) compared with pretest (mean = 17.06, SD = 2.65; $t_{17}=-3.97$, p=.01). However, indifference ($t_{17} = -1.52$, p=.14), separation ($t_{17}=0.75$, p=.46), and disengagement ($t_{17}=0$, p=.99) subscales were not statistically significant before and after the study. The mean and SD values of separation (pretest: mean = 11.11, SD = 1.64 and posttest: mean = 10.72, SD = 2.11), disengagement (pretest: mean = 11.61, SD = 2.17 and posttest: mean = 11.61, SD = 2.28), and indifference subscales (pretest: mean = 9, SD = 1.75 and posttest: mean = 9.83, SD = 2.46) in pretest and posttest are shown in Figure 6.5. Admittedly, the scores of the overall empathy and its 3 subscales (indifference, disengagement, and separation), which are different combinations of questions from the empathy questionnaire, did not change significantly. However, the statistical significance of the kindness subscale revealed that this aspect of empathy could be potentially altered in a VR game such as AS IF.

6.2.3.2. Quantitative Findings: The Willingness to Help Scale

The Willingness to Help Scale has a question that involves a real-world scenario regarding how likely one is to help a patient with chronic pain (Appendix A); it is intended as a means to evaluate the emotional and perspective taking aspects of a participant's empathy for patients with chronic pain. For the scores of the Willingness to Help Scale before and after the game intervention and from a t test analysis, a significant increase in the posttest score was observed (mean = 8.33, SD = 2.03) compared with the pretest score (mean = 7.17, SD = 2.28; $t_{17}=-4.51$, $p<.001$). The effect size for this analysis was found to be large, according to Cohen convention ($d=-1.06$). This statistically significant increase indicates that the game was able to increase participants' explicit willingness to help people with chronic pain.

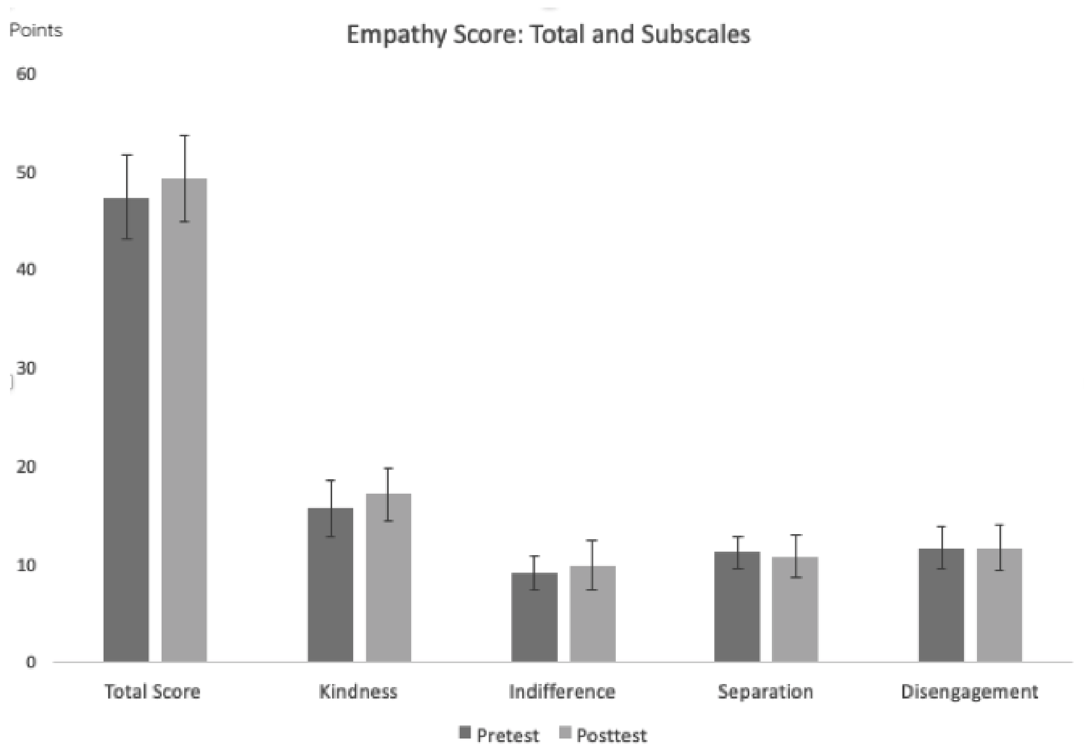

Figure 6.5 Mean values from the Empathy Scale with error bars before and after the study. From left to right: total score, kindness subscale, indifference subscale, separation subscale and disengagement subscale (y-axis: self-reported rating points from the questions in each category).

6.2.3.3. Quantitative Findings: The Wheel of Emotions

In their protocol paper for measuring empathy in VR, Carey et al (2017) recommended using the Wheel of Emotions Scale to measure the emotional aspects of empathy. Specifically, this instrument is intended for understanding affective empathy or the spontaneous feeling of oneness with another's emotions (Carey et al., 2017). Therefore, I reported the basic analysis of each participant's emotional changes before and after the study. Overall, 12 of the 18 participants changed from positive emotions (e.g., joy, love, and optimism) to negative emotions (e.g., sad, helpless, and scared). This may have been influenced by the AS IF experience. Six participants reported no changes, regardless of what their initial emotions were. However, half of the 6 participants first described their emotions as negative ones (e.g., sad, helpless, and scared). Therefore, most participants' emotions appeared to have changed from a positive to negative direction. Given that the virtual character's self-talk can be characterized by a sense of frustration and fear, these results suggest that *AS IF* fostered affective empathy.

6.2.3.4. Quantitative Findings: VR-Adapted Other in the Self Scale

A fourth set of tools was needed to understand cognitive empathy, characterized by understanding another's perspective while also maintaining a distinct sense of self. Regarding the relationship between the virtual avatar and the participant's self, 13 of the 18 participants reported feeling an overlap between their sense of self and the virtual avatar. Three participants felt completely distinct from the avatar, one participant reported not feeling any identity of himself (either inside or outside the game), and one participant reported feeling completely the same. Therefore, 14 of the 18 participants (74%) could relate the virtual avatar to themselves while playing AS IF. In general, the results from the VR-adapted Other in the Self Scale suggest that most participants felt the virtual body overlapped with their real identity—the perspective taking aspect of empathy. Therefore, most participants were able to take the perspective of the grandmother who suffers from chronic pain in AS IF.

6.2.3.5. Quantitative Findings: SoO and SoA

As one of the goals was to investigate whether embodiment in VR affected or correlated with changes in empathy, I collected posttest data regarding the participants' SoO (of the avatar) and SoA in VR. On average, participants' scores were higher than zero for both SoO (mean = 1.28, SE = .66) and SoA (mean = 1.5, SE = .625). In the SoO and SoA questionnaires, because the rating scale ranged from −5 to 5 (−5 means strongly disagree, and 5 means strongly agree with the statements), the mean values here show that the participants experienced a medium to slightly strong level of body ownership and agency over the virtual avatar.

6.2.3.6. Quantitative Findings: Correlation Analysis

Pearson correlation tests were also run to test the relationship between SoO and SoA, between the sense of embodiment (comprising SoO and SoA) and the Willingness to Help Scale, and between the sense of embodiment and the Empathy Scale (comprising 4 subscales). The results show that SoO is significantly correlated to SoA (r_{18}=0.83, p<.001), indicating that the participants' SoO strongly correlates with their SoA in AS IF. Although the correlation between SoO and Empathy Scale scores (p=.10) and the SoA and Empathy Scale (p =.11) did not reach statistical significance, the p values fell just short of statistical significance. Finally, the results from the Willingness to Help Scale had statistically significant positive correlations with the kindness subscale (r_{18}=0.63, p=.005) and statistically negative correlations with the indifference subscale (r_{18}=−0.53, p=.02).

Next, I discuss what the participants thought of AS IF and evaluate the strengths and weaknesses of the VR game. I also discuss which of the game's main features may be useful for future research.

6.2.3.7. Qualitative Findings: Interviews Analysis

Although AS IF does not simulate the physical feeling of persistent pain, the game achieved its primary goals: to motivate the participants to reflect on experiences of patients with chronic pain and to raise empathy. One participant said:

"I think this can help me to understand more about patients. It definitely made me start thinking about how hard other day-to-day tasks would be for people with chronic pain." [P19]

Overall, participants considered the game interaction to be easy to follow and very intuitive. For instance, P05 said:

"The interaction was pretty good and very illustrative."

P08 and P09 said:

“The interaction is pretty straightforward.”

In general, none of the participants had trouble understanding or completing the VR game’s tasks. The two approaches of representing pain in VR had pros and cons in providing an immersive experience of a patient with chronic pain. Nonetheless, the VR game shows a high potential for fostering cognitive and emotional empathetic attitudes toward people with chronic pain. Next, I discuss the three themes that emerged and categorized from the participants’ interviews. The first two themes are feedback about the motion and visual approaches of representing pain in a VR game, and the third one discusses the important role of the game’s narratives in facilitating perspective-taking.

THEME 1: Representing Pain, Approach 1: Restricting Movement. From the interviews, most participants were aware that the physical limitations imposed in VR represented pain. However, a few participants initially reported that these restrictions felt more like a bug in the program. Overall, approximately one-third of the participants considered the randomly frozen hands/arms to be annoying and more like technical issues. For instance, P08 and P10 told us that:

“At first, I thought the arms had some delay compared to my real arms, and I thought it was technical difficulties. Then I realized it was the game setting.”

Nonetheless, to a certain degree, this mechanism did achieve the goal because participants’ emotional status changed, leading to an increased empathetic attitude toward the grandma patient.

“I felt like my movements were slowed down. Plus, I made a mess in the kitchen by dropping things. Emotionally, it was a little discouraging and lowered my confidence with being able to bake all by myself.” [P04]

“It was pensive. I was thinking like people with chronic pain, how it’s gonna be for them.” [P11]

The participants reported that their empathy was elicited when they felt that they were incapable of handling easy daily activities as a virtual patient. P10 said:

“Suffering pain and I should take a rest and slow down my movement later. I feel that everyone else could make a cake faster than me.”

Although 3 of the participants said they did not have emotional feelings about the grandmother, all agreed that the story in this game brought about an awareness. For the first time, participants said they started to think about what life would be like for patients with chronic pain. For instance, P16 said:

“Although I can’t feel any pain, I can feel the difficulty of [the] games’ tasks.”

Interestingly, some participants offered suggestions for improving the game, such as adding more and different forms of feedback regarding movement restrictions, such as a pain meter or digital pain diary. Some participants also suggested that if the granddaughter was visible, she could provide contrast with the physical problems the grandma experiences because of her chronic pain. For instance, P09 said:

“The limited movement also helps as I cannot move quickly, which is appropriate for a grandma at her age. But, it would be better if there is any contrast, for instance, having a very active child, or people who can move fast.”

THEME 2: Representing Pain, Approach 2: The Red Flashes Signaling Headaches. Generally, participants’ responses to the red flash effect matched my expectations. Specifically, the red flashes elicited some sense of pain, if only vaguely, through a visual effect. In total, participants reported 3 types of sensations when they saw this visual stimulus. The first type reported by the majority of participants was that the reddened world made them feel pain and headaches. For example:

“I did notice the red filter effect, and I can understand that the game was trying to express what the pain patient may have experienced.” [P03]

“It was very annoying, and I cannot think or move when the red shadow happens.” [P05]

“I feel very dizzy when the red flashes were coming out, and I cannot think anymore. My brain was entirely blank, and this can definitely represent pain to me.” [P08]

The second type of sensations participants experienced in response to the red flashes were not physical pain per se, but an idea of what the reddened environment was meant to be, and they felt bothered by it. For example, 2 participants mentioned that although they did not feel physiological pain:

“It can work as an indication to slow down my movement...but I do not feel any physical pain myself.” [P09]

The third type of response to the red flashes was an inability to make an association between the visual indication of an impending headache (or pain spike) with the patient’s pain experience. Two participants reported that they did not understand this idea and did not think it represented pain effectively.

THEME 3: The Narrative Strengthened Immersion. From participants’ feedback, the realistic visual depiction of the kitchen and cake making tasks strengthened the experience of being a patient with chronic pain:

“Everything in this game was so realistic and well-done. I was beginning to embody myself to the character and feel I was there. There were moments that I forgot that was me.” [P07]

In addition to the visual simulation, the audio of the grandmother’s inner voice or self-talk also strengthened immersion and empathy. For instance:

“It could put me into this situation by narrating that for me.” [P18]

“Yes, the narrator was expressive, and the voice felt very exhausted and tired. I think the audio was the most influential part and it directed the story.” [P13]

Overall, 14 participants reported that their affective changes emerged because of the game and described it using negative emotional words, including depressed, impatient, upset, frustrated, pensive, sorry, and pity. For instance, P01, P03, P04, and P11 said:

“I felt lonely in the game and frustrated while playing the game, but in the end, I am happy to finish the game and achieve the patient’s goal [cake making].” [P01]

Moreover, the ordinariness or daily life aspects of the tasks also appear to have succeeded in raising awareness of what life with chronic pain might be like. As P19 said:

“Normally, speaking of chronic pain patients, I usually think of the hospital or [them] laying on [a] bed. Baking a cake bring[s] me more awareness about how daily life could be so hard for them too. I won’t feel having empathy for them if not doing these tasks. Right now, I feel more related to the grandma in the game.”

Therefore, providing a connection to the virtual avatar—by performing realistic tasks and multimodal sensory input in VR—better situated the participants as if they were in the patients’ shoes. P11 mentioned that he was thinking of his mother’s chronic pain while inhabiting the grandma avatar. He felt frustrated, and his experience in *AS IF* reminded him how hard his mother’s life was.

6.2.4. Discussions and Conclusions

6.2.4.1. Principal Findings and Discussions

I explored a significant redesign and study results of a VR game, AS IF. It is aimed at motivating people who do not live with chronic pain (non-patients) to better understand the lived experience of chronic pain by increasing empathy. In general, the findings demonstrate that participants had greater degrees of empathy toward patients after playing the VR game. Furthermore, from the semi-structured interviews, I was able to gather essential feedback about the strengths and limitations of the current VR design, such as the effectiveness of pain representations.

Overall, after playing the VR game AS IF, participants scored significantly higher on the Willingness to Help Scale and the kindness subscale—an adaptation of the Empathy questionnaire. These two scores revealed that not only could one VR experience of AS IF raise people’s awareness of chronic pain but it could also increase their implicit and explicit empathy. Data from the kindness subscale showed implicit cognitive changes, whereas data from the Willingness to Help Scale revealed changes in explicit empathic attitudes toward patients with chronic pain. The other three subscales showed nonsignificant differences. Furthermore, the qualitative interview data show that most participants reported that playing this game helped them to understand what a chronic pain patient's life would be like, and that they had never thought about that before. I assume these findings may result from 2 potential reasons:

(1) indifference, disengagement, and separation are difficult to affect or change during a single, short period, as in this study,

and (2) the design of the VR game AS IF focused more on the perspective taking and emotional aspects of empathy, but it did not have specific game features that were meant to increase the four subscales.

The VR-adapted Other in the Self Scale suggested that most participants felt that the virtual body overlapped with their real identity. The findings from the VR-adapted Other in the Self Scale also overlapped with the interview results. Some participants said they felt embodied in the grandma avatar who has chronic pain through narrative storytelling, the immersive environment, and the game tasks. Thus, in the AS IF game, participants were able to understand the perspective of the grandma who has chronic pain.

The sense of embodiment scores showed that, on average, participants could sense owning and controlling the virtual avatar. However, the Pearson correlation test revealed no statistical significance between the sense of embodiment in VR (comprising SoO and SoA) and the Empathy Scale (posttest) or the sense of embodiment in VR and the Willingness to Help scale. I conjecture that 2 reasons might account for this nonsignificant outcome. First, there could be multiple factors that affected empathy levels besides embodiment, such as the narrative and the game's specific tasks (and the fun/frustration behind that). Hence, a single factor might not be strong enough to alter overall feelings of empathy. As mentioned in the interviews, participants suggested that tactile feedback might be a better way to indicate pain or the association of visual effects with pain. The second possible explanation could be that the game did not provide a strong enough sense of embodiment to reach statistical significance. In interviews, participants said they wanted the virtual avatar to more closely match their own gender and ethnicity and perhaps even body height and shape.

A few participants—a male and a participant whose skin color differs from the avatar's—reported they felt disembodied with the virtual avatar because of its divergent characteristics. Admittedly, the overall empathy scores and the 3 subscales (indifference, disengagement, and separation) did not change significantly. A crucial issue is how long it takes to affect and change empathy and what factors are important in facilitating such change. For example, implicit empathy may be difficult to change in a short time, in part because of its mental cost (Cameron et al., 2019).

However, in this study, the VR-adapted Other in the Self Scale findings suggest that participants identified with the VR avatar, insofar as the avatar was felt to overlap with their real self. Therefore, a perspective taking ability may be critical to being able to influence one's empathetic attitudes toward patients with chronic pain and painful experiences. From the qualitative interviews, two approaches to representing pain in the virtual body may also foster empathy. Although a few participants found the movement restrictions confusing, most reported it made them realize how pain would impact one's range of motion and emotion. Most liked the idea of using the red flashes to represent pain spikes and reported that the visual effect felt like a headache or pain (a synesthesia effect of transferring a visual sense to an emotional sense).

Besides facilitating non-patients' (game players who are health care givers or family members of patients with chronic pain) empathy toward patients with chronic pain, I believe that a VR game such as AS IF has the potential to benefit patients and other researchers. Chronic pain experiences are notoriously difficult to describe and are often out of the experiential scope for most people. Hence, VR is one method that may provide clinicians and family members or friends who play a caregiving role with a deeper understanding of a patient's chronic pain condition. VR appears to have the potential to change the player's mind significantly (Bailey et al., 2016) and to stimulate perspective taking and/or behavioral changes that are associated with empathy toward others like patients (Longo et al., 2008; Schäfer et al., 2016). For instance, in previous research, Platt et al (Platt & Piatt, 2011, p. 201) showed how empathic communication, such as clinicians' awareness of the patients' affective states and showing appreciation of the patient's feelings, may reduce patients' feelings of isolation (Halim et al., 2019). In addition, the findings, experiences, and design suggestions from this paper may directly benefit other researchers in the future developing empathic games for patients with chronic pain specifically or for patients who must manage similarly invisible chronic conditions. Given the aging population, this may be particularly useful as an approach to medicine shifting from treating acute conditions to managing chronic conditions and promoting wellness. Some of the participants questioned, "Was my pain sensation the chronic patients' pain too?" Although it is impossible to make this determination in this study, I assume that the sensations were not the same. For one thing, chronic pain is unique and difficult to describe, let alone recreate specific perception. For another, the interview findings suggested that current gameplay increased the participants' awareness of chronic pain patients' situation through the narrative, visual, and audio feedback in AS IF.

6.2.4.2. Study Limitations

This study also had a few limitations that may affect the empathy outcomes and bring a risk of bias regarding the conclusions. First, the sample size for this preliminary study was small, and a larger number of clinicians will be tested once the prototype is revised and prepared for clinical deployment. Next, to avoid overwhelming participants with assessment instruments, the level of immersion in VR was not measured, so I do not know if there are potential relationships between immersion and changes in empathy.

Moreover, I only conducted a preliminary, in-laboratory study using questionnaires and interviews to evaluate changes in empathy, and no real-life assessment has been implemented. One of the scales used in this study, the Empathy Scale, was an adapted version of Pommier's Compassion Scale. The validity of the revised scale was used directly in both studies without getting statistical evidence. Further, the measurements from this empathy scale might be limited to the "willingness to help" and emotional aspects, which don't fully overlap with the empathy responses. Therefore, empathy wasn't being comprehensively measured and I only identified significant improvements on the Separation subscale in the first study and the Kindness subscale in the second study. Future studies should consider including other standard scales to better understand participants' potential empathy changes. Moreover, this study didn't measure chronic pain patients' feedback; thus, its effects on reducing their social stigma remained unknown, which could be explored in future research.

However, evaluating the pragmatic aspects of the VR game is definitely something I am planning. This involves running a practical test immediately after the subsequent study, asking participants to donate a portion of their study compensation to a hospital's foundation or a nonprofit organization for patients with chronic pain. Finally, I did not have a control group and did not conduct a follow-up study to see if any long-term empathy behavioral changes persisted. Investigating these factors to determine whether they affect changes in empathy are important next steps.

6.2.4.3. Comparisons with Prior Work

For a long time, researchers have been looking for evidence about how the sense of embodiment in VR may impact one's cognitive perception (Bailey et al., 2016). Various potential impact factors of virtual embodiment on empathy (perspective taking) have been investigated, notably, attitudes toward racial bias (Behm-Morawitz et al., 2016, p.), gender bias (Lopez et al., 2019), and age (Banakou et al., 2013; Tajadura-Jiménez et al., 2017). I explored the relationship between SoO, SoA, and empathy through correlation tests. However, although participants reported a medium-level SoO and SoA over the virtual body, no significant relationship was discovered. In summary, to put non-patients in the shoes of patients with chronic pain, players inhabit a virtual body of a patient with chronic pain who attends to everyday tasks in the VR game AS IF. It simulates several experiences common to chronic pain: physical limitations of movement and a patient's verbally articulated self-talk. The visual-motor synchronicity of a player's full-body movements mirrored by the avatar appears to elicit identification with the avatar. The results from the mixed methods study revealed that the game was effective in improving implicit and explicit empathy. Furthermore, the findings showed that the game raised the emotional and perspective taking aspects of players' empathy. However, no associations were found between the sense of embodiment (SoO and SoA) and the empathy scales in this game. On the basis of the analysis of participants' feedback, in future work, I plan to:

- iterate the design features and study protocols according to participants' feedback.
- conduct a randomized controlled study with a larger sample size that is more diverse in terms of gender and age.
- implement tactile feedback in the controllers (or body sensors) that matches the game tasks, and I would also prepare virtual avatars of different genders and ethnicities.

6.3. Chapter Summary

In this chapter, I adopted an iterative process for creating and assessing an embodied VR game called AS IF, which I designed to foster empathy toward people with chronic pain. In Study 1, I introduced the design features and user evaluation. I recruited 15 healthy participants and measured their empathy levels before and after the study. The results indicated that AS IF, successfully simulated the experience of a chronic pain patient and enhanced empathy significantly in healthy people. Participants' feedback on the game's task design motivated me to iterate the prototype and revise the study method to enhance user experience.

Therefore, in Study 2, I described the updated game and the study design. I recruited 18 participants, and my findings suggested that the new version of the game had useful affective and perspective-taking aspects and improved implicit and explicit empathy. The kindness subscale from the Adapted Empathy Scale and the Willingness to Help Scale showed a significant increase in empathy levels, which was confirmed by *a t*-test analysis of scores before and after the game.

In both studies, I adopted a mixed methods approach and compared the empathy-related outcomes in pre- and post-testing. I summarized participants' feedback on how pain can be communicated by and presented in an avatar, and I analyzed the impacting factors (narrative and perspective taking) critical to enhancing empathy.

The studies validated the effectiveness of the approach taken by AS IF and offered promising design suggestions for developing embodied VR games to foster people's empathy toward patients with chronic pain.

Chapter 7. Embodied Design in VR for Analgesia and Empathy

In Chapter 1, I asked how virtual embodiment can affect people's perception of pain and address the BPS challenges that chronic pain patients face. In this dissertation, I developed different VR systems and examined their avatar features and design features' effects on users' sense of embodiment. To understand how virtual embodiment correlates to perception changes, I manipulated the appearance and motions of virtual bodies and examined participants' embodied experiences and the associated changes in perceptions or, put another way, how pain patients embodied in a healthy virtual body will experience pain and how healthy people embodied in a painful virtual body will experience empathy. To explore these ideas, I conducted a series of studies and analyzed my data, keeping the following research questions in mind:

- Can the virtual embodiment approach effectively (a) support pain patients in modulating their pain and (b) foster empathy toward their conditions?
- What are the potential correlations between embodiment and pain levels and between embodiment and empathy levels?
- What are the design recommendations and suggestions for future research on VR embodiment, pain, and empathy?

7.1. Summary of Findings

In Chapter 1, I defined this dissertation's conceptual model of pain and how VR enables an embodied experience that can affect pain and empathy. After identifying the research problems, I situated my research questions along two trajectories: VR for pain modulation and VR for empathy facilitation. In Chapter 2 and Chapter 5, I reviewed the literature on definitions of embodiment and its clinical applications in pain modulation; I also examined research on VR analgesia (Chapter 2) and empathy (Chapter 5) separately, focusing on studies' embodiment approaches, research methods, potential impacting factors, and underlying mechanisms.

Chapters 3 and 4 explored the role and effectiveness of virtual embodiment in pain modulation from the BPS aspect of pain. In Chapter 3, I reviewed an embodied VR environment and described two of my research experiments that evaluated how avatars' appearances and motions affect healthy people and patients' embodiment and pain. Study 1 was conducted with healthy people exposed to pain stimulus, and Study 2 was conducted with CRPS patients. The results of both studies demonstrated that being embodied in a virtual body has an analgesic effect. Seeing embodied virtual arms in VR from a first-person perspective significantly reduced participants' self-reported pain ratings compared to the control conditions in which the virtual arms did not appear. Moreover, the results also showed that manipulating the motions and visual realism of the embodied virtual arms can strongly affect SoO and SoA. Nevertheless, I did not find a significant effect of synced movement on pain reduction in either population. Interestingly, for CRPS patients, the lower-level visual realism (abstract tube) conditions elicited significantly lower ownership but significantly better analgesic effects than the realistic virtual arms conditions.

In Chapter 4, to evaluate virtual embodiment's long-term effects on chronic pain modulation, I conducted a narrative literature review and analysis of the existing VR and AR approaches in the context of PLP, and I reviewed a longitudinal case series experiment with five PLP patients. The findings from this review suggested that very few studies explicitly measured embodiment or the controllability of phantom limbs' movements and that the effects of virtual embodiment on PLP modulation has not been sufficiently investigated. Therefore, I created a VR system that could mirror the movements of PLP patients' intact hands with the phantom hands in VR. I found that repetitive exposure to VR interventions leads to reduced PLP and improvements in anxiety, depression, and SoO and SoA. Importantly, I also found that users' ability to move their phantom limbs improves because of the shortened motor imagery of the impaired limb. My study proved the potential of using the virtual embodiment approach in long-term pain alleviation and the motor imagery method to measure PLP patients' phantom limb movement and agency in future research.

In Chapter 6, I use the virtual embodiment approach to address the social stigma that chronic pain patients face. My goal was to embody non-patients in the perspective of a pain patient's virtual avatar so that they could see and experience life in a painful body. By immersing non-patients in a narrative scenario, I aimed to foster their understanding of and empathy toward pain patients. I created an embodiment game called AS IF and iterated the game design based on participants' feedback. I described the pilot study in which I evaluated the proof-of-concept idea of using an embodied game to foster empathy. Findings from the pilot test showed that the game effectively improved users' willingness to help chronic pain patients, but it did not show a significant increase in empathy. After receiving promising feedback, I redesigned the game tasks, interactions, and parts of the narrative and evaluated them in a second user study. The findings of the second mixed study revealed participants' feedback about how to present pain in the virtual avatar, the game tasks, and the narration. A significant increase was observed in the Willingness to Help Scale and the Kindness subscale, one of the five subscales of the empathy measurement.

7.2. Summary of Dissertation Contributions

7.2.1. Greater Insights and Design Recommendations

Concerning the biological, psychological, and social aspects of pain, my dissertation contributes an empirical understanding of virtual embodiment's effects on one's perception from two trajectories. This includes understanding how manipulating avatar features affects one's sense of embodiment and pain perception with different pain etiology as well as whether and how embodied VR experiences can foster empathetic attitudes toward pain patients. These insights can further our scholarly understanding of how embodied VR experiences alter people's perception of pain and practice of empathy and can inspire future research in this domain. Moreover, these insights can benefit marginalized users and chronic pain patients, and they can shape the design space of virtual embodiment environments and clinical applications.

7.2.2. Technical Implementations

This dissertation offers the design and development details of multiple embodied VR systems, which benefits the virtual embodiment research fields by suggesting more feasible equipment setups and implementation approaches. In the research presented in Chapter 4, I used a Leap Motion sensor and mapped the motion data to the virtual avatar with both healthy participants and pain patients. This system setup is not novel for industrial applications. However, it offers a cost-effective way of realizing synchronous movement and can improve participants' SoA over the virtual arms. In the research presented in Chapter 5, I mapped the movement of PLP patients' intact arms to their virtual arms so both could act in a mirroring way. For this study, I synchronized the controllers' motion in VR for reconstructing the entire virtual arms' motion. Again, this system offers a cheaper way of realizing mirror therapy in VR when most previous studies adopted expensive and complex systems, such as data gloves or motion capture sensors and bodysuits. In the research presented in Chapter 6, I first utilized Microsoft Kinect to capture the entire body movement and map it to the virtual avatar for completing game tasks (i.e., solving a puzzle). After migrating the prototype to a VR environment, I adopted the same method presented in Chapter 5 to set up the movement of the virtual avatar, achieving the full-body motion features with VR controllers. To foster participants' visuomotor experiences of pain, I introduced visual features to the avatar and restricted its range of motion; researchers can refer to this method going forward.

7.2.3. Study Methods and Results

The scientific findings from the studies presented in chapters 4, 5, and 6 also highlighted the value of virtual embodiment in altering patients' cognitive experiences of pain as well as the perspective taking of marginalized users (i.e., chronic pain patients). Although this dissertation's methods and results follow the standard protocols of prior studies, I demonstrated potential new application scenarios in order to understand PLP patients' phantom limb movement through mental imagery tasks in Chapter 5 and a combination of multiple empathy measurements in Chapter 6. Often, designers and practitioners pursue a high level of visual realism when designing VR scenes for pain modulation, while embodied experiences and perception changes are discounted. The results presented in Chapter 4 remind us that low visual realism may have a better analgesic effect for CRPS patients.

7.2.4. Conceptual Design Framework

Finally, my work contributes to the conceptual framework of designing embodied VR experiences to foster changes in users' perceptions. For the virtual embodiment and pain-modulation trajectory, the four attributes of presence illusions, pain etiology (participants), and avatar features (VR content) should be included in the framework, and they should be carefully implemented on a case-by-case basis. For the virtual embodiment and empathy trajectory, components that strengthen participants' perspective taking, such as visual details or multimodal feedback, and narrative storytelling should be considered as the background context of the design framework. I discuss the roles of embodiment in pain modulation and empathy generation more in-depth in the following section. I also propose a conceptual framework for designing embodied VR for pain modulation and empathy generation in future research.

7.3. Designing Embodied VR for Analgesia and Empathy

The Impact of Seeing a Virtual Body on VR's Analgesic Effects. In addition to the discussions of the three experiments in chapters 4 and 5, I will further analyze the impacts that seeing a virtual body or avatar has on VR's analgesic effects from three perspectives. First, what are the effects of seeing a virtual body on virtual embodiment and pain modulation? Second, what are the avatar features that can affect virtual embodiment and pain modulation? Third, does pain etiology affect how avatar features work in embodiment and VR analgesia? My discussion explores three theories that could explain why virtual embodiment affects pain.

What Are the Effects of Seeing a Virtual Body on Virtual Embodiment and Pain Modulation? This dissertation's findings suggested that the seeing a virtual body in VR elicits varied levels of virtual embodiment (ownership and agency) and analgesic effects in all VR experimental conditions. All experimental conditions significantly reduced pain when compared to the control condition, regardless of pain types. However, various states of the avatar features elicited significantly different levels of ownership and agency.

What Are the Avatar Features that Can Affect Virtual Embodiment and Pain Modulation? As noted in subsections 2.3.1 and 2.4.1, most experiments have mainly manipulated the appearances and motions of virtual bodies (or body parts) to affect one's sense of embodiment and associated changes in pain. The appearance of the virtual body includes components such as skin color and transparency, body size and shape, and points of view (first-person versus third-person perspectives). Researchers have generally manipulated the movement of virtual bodies in three ways and in relation to the real-world body: static, synchronized, and asynchronized movements. Both appearance and motions changes can alter one's sense of embodiment, and these two factors can have a joint effect. Physical sensations, such as touch, can also be used to enhance the overall SoO (Botvinick & Cohen, 1998; de Jong et al., 2017; Ehrsson et al., 2005). However, the effect of touch in VR on embodiment and potential changes to pain levels have not been explored in the literature and require further exploration. To conclude, visual and motor modalities should be considered as the primary avatar features that alter one's perception of embodiment.

Does Pain Etiology Affect How Avatar features Work in Embodiment and VR Analgesia? Much like Matamala-Gomez et al. (2019a), I found that pain etiology does not affect people's sense of embodiment, but it does affect the way virtual embodiment works to reduce pain. Based on my two studies presented in Chapter 4, CRPS patients feel ownership and agency over the virtual arm to a similar degree as healthy subjects, which also aligns with Matamala-Gomez, Diaz Gonzalez, et al.'s work. As the authors noted, this can be supported by the fact that the brain regions associated with multisensory integration are preserved in CRPS patients in the same way as healthy people. Indeed, prior research showed that phantom limb pain patients who are missing one limb still feel ownership and control over the virtual limb that mirrors the movements of their intact limb (Osumi et al., 2018; Tong et al., 2020). This phenomenon revealed that pain etiology does not affect CRPS and PLP patients' sense of embodying a virtual body when compared to healthy people.

Findings from this dissertation and other studies indicate that pain etiology affects how visually induced ownership modulates pain, which is not the case for embodiment. Most studies have been conducted with healthy people exposed to pain stimulus. Their results suggest that SoO can positively affect pain reduction by manipulating the virtual arms' appearance and motions. For instance, Martini et al. (2015) observed participants' body ownership illusions decreased when the virtual body became more transparent, but they did not find any pain threshold changes. However, when a similar transparency factor was tested with CRPS and PNI patients, Matamala-Gomez et al. (2019a) revealed the different ways pain was affected by the appearance of the virtual arms. They found that increasing transparency increased ownership and pain in PNI patients, but it decreased pain in CRPS patients. In a second example, although increasing the body size negatively affected healthy participants' SoO, it did not impact their subjective pain ratings (Romano et al., 2016). When the same study was conducted with patients, interestingly, increasing body size increased pain ratings in CRPS patients but not PNI patients (Matamala-Gomez et al., 2019a).

Further, my study with CRPS patients conflicted with Zanini et al.’s (2017) research with healthy participants. In the study presented in Chapter 4, I observed a negative correlation between ownership and pain reduction in CRPS patients when manipulating the visual realism of the virtual arms; the realistic arm condition had higher ownership ratings but less analgesic effects than the abstract tube condition. This was contrary to Zanini et al.’s findings, as they observed significantly better analgesic effects with the realistic arm condition than the abstract tube condition. As for motion-induced agency, I did not find any significant differences in pain modulation between healthy subjects and CRPS patients in my study or in the literature, as it is a null effect. In short, although healthy people and patients share similar perceptions of ownership and agency over the same virtual body, pain types affect the association between one’s sense of ownership and pain.

Given all of the above, questions must be asked to find out why my findings did not support my hypothesis that embodiment positively correlates with pain reduction. In Study 1, why did significantly higher ownership levels not affect the pain of healthy participants but elicited significantly higher pain levels in CRPS patients? In both Study 1 and Study 2, why did higher agency levels not elicit significant changes in pain? Below are three possible answers.

It is possible that attention distraction is the underlying explanation of the virtual embodiment analgesia approach and that there may be a threshold value of attention needed for pain alleviation. In Study 1, both the static hand and sync hand conditions featured a virtual body and attracted more of the participants’ attention than the control condition, which featured an empty virtual room. Therefore, both experimental conditions elicited significant pain reduction when compared to the control group. In Study 2, the abstract tube condition offered participants’ a more novel experience than the realistic arm condition. Although the realistic arm condition elicited significantly higher levels of ownership, it required less attention than the abstract tube condition, which led to less of a pain reduction. Regarding the relationship between agency and pain, it is possible that whether or not the virtual hand moves synchronously with the real one, simply seeing the virtual arms causes participants to reach the attention threshold for analgesia and no further effect will appear thereafter. This explains why motion-induced agency did not affect pain changes at all. Therefore, attention theory and its threshold level for analgesia could explain the negative association between embodiment and pain changes. To date, no research has compared the analgesic effect of the traditional distraction approach to the embodiment approach. Future research should compare the effect of seeing only a virtual body and seeing no body but having an interactive virtual environment to understand the effectiveness of each approach.

The other theory that can answer the above questions is *predictive coding* proposed by Friston and Kiebel (2009), and later adopted by Riva et al.'s (2018) to explain how embodiment might work in VR. According to the authors, predictive coding suggests that the brain actively maintains an internal model (simulation) of the body and the space around it; this model provides predictions regarding expected sensory inputs and tries to minimize the amount of prediction errors (or surprises). In other words, predictive coding assumes that our brains create embodied simulations to effectively regulate and control our bodies in the world (Friston & Kiebel 2009, Riva et al., 2018). In Study 1, I conjectured that the brain was able to adopt the new look of the virtual arms in the two experimental conditions and that it drew on the simulations to map the real arms to the virtual ones to minimize prediction errors. Because the virtual arms were seen from a first-person perspective and looked healthy, the participants could generate a model to fit in that specific body, which reduced pain levels. Again, in Study 2, the brain tried to adopt the new look of the abstract tubes and realistic arms and map them to participants' perceptions of their real arms. Realistic arms looked and felt familiar to the brain, but the brain was not aware of the mappings between the abstract tubes and real arms, nor could it predict how perception would or should change. The goal is to have the brain's predictive coding model make the participant feel that their virtual arms are real. In this case, people's perception of pain seems to be reduced when no source of it is presented in the virtual body. Therefore, the abstract tubes had better analgesic effects than the realistic arms. In both cases, movement and its elicited agency had nothing to do with the arms' healthy appearance, so they did not impact how the brain predicted and perceived pain.

The last explanation is that the visual body network overlaps the pain network in the brain, and having a visual perception of one's physical body could have an analgesic effect if it activates the brain's visual body network, as suggested in Longo et al.'s (2012) neuroimaging study. The authors compared two conditions in which participants were either viewing their hands or an object. They found that laser-induced pain ratings are significantly lower while people look at their hand than when they look at the object.

Such an analgesic effect was positively correlated with an increase of functional connectivity between the visual body network (i.e., the posterior parietal cortex) and the areas in the pain matrix, such as the primary and secondary somatosensory networks, the anterior cingulate cortex, and the insula (Longo et al., 2012). In Study 1, the visual body network may have been activated in both the static arm and synced arm conditions, and that activation may have contributed to pain reduction in the pain network. Since long-term chronic pain sufferers usually have a distorted pain network (Lotze & Moseley, 2007; Moseley, 2005), the effect of a visual body network on pain might be different in patients than in healthy people. Study 2 was conducted with CRPS patients; thus, the activated visual body network did not affect the pain network the same way as it did in Study 1.

Further, in Study 1 and Study 2 mentioned in Chapter 4, the incongruences between the visual representations of the body parts and the sensations (i.e., the static movement condition) could have elicited a sensory conflict and suppressed afferent information—a process Longo et al. (2009) called “deafferentation” (p. 20). In my experiments, it is possible that the inconsistencies between the real bodies’ movements and the avatars’ movements were blocked by the deafferentation mechanism, so the same extent of implicit embodiment was induced in participants. Therefore, significantly increased agency in synced movement conditions did not improve analgesic effects. However, more evidence (such as fMRI data) is needed to understand whether agency in synchronous and asynchronous conditions affects the neural patterns of the visual body network activation and its connectivity with the pain network.

Researchers have suggested that related areas in the brain modulate pain and the processes of nociceptive information in the descending pain pathways (Gold et al., 2007). To conclude, all three explanations could elicit perception changes in attention and bodily awareness, and they each support the top-down modulation theory of pain. However, each takes a different perspective: attention mechanism, predictive coding mechanism, and brain networking. Further studies are required to test all explanations and identify which is operative or most operative. I provide more details regarding potential future research in Subsection 7.4.2.

7.3.1. Design Recommendations

Regarding design recommendations for future research and VR applications for pain management, I developed a set of best practices inspired by this dissertation's findings and the literature.

- Show patients a healthy-looking avatar or parts of a virtual body that correspond to real parts of their bodies that are in pain, regardless of virtual realism (tubes/arms), as this plays a significant role in increasing their sense of embodiment and decreasing their pain levels.

- Carefully consider and manipulate the avatar's appearance according to the effects that various characteristics have on pain because pain etiology affects the way virtual embodiment engenders analgesia. The embodied avatar's visual characteristics can alter users' SoO; skin color and transparency and body shape and size are all important. However, SoO is not always positively correlated with pain reduction levels, and each visual characteristic has different outcomes for different types of pain.

- Continue to explore the ways of motion-elicited agency in different pain patients. The avatar's movements significantly affect people's SoA but not their pain. Prior studies gave healthy people considerable control over virtual bodies and compared the resulting analgesic effects with a low control condition. Studies in Chapter 4 compared CRPS patients' pain levels in high control and no control conditions. Neither revealed any significant reduction in pain levels. However, the case series in Chapter 5 indicated that mirrored movement of a phantom limb plays an important role in reconstructing PLP patients' distorted body image.

- Be aware that physical interaction and embodiment have interrelationships with each other. If the interactive tasks are related to changes in the avatar's appearance, users feel an elevated sense of embodiment and reductions of pain. I would recommend future research to further explore how performing interactive tasks may alter people's sense of embodiment and pain by comparing it to a non-interactive condition.

- Investigate the impact of social communication and social presence on pain.

7.4. Communicating Pain and Facilitating Empathy in Embodied VR

The findings from the two studies in Chapter 6 demonstrated that embodying healthy participants in a chronic pain patient's avatar can foster cognitive empathy (i.e., perspective taking) and affective empathy (e.g., the kindness subscale of the Adapted Empathy Scale and the Willingness to Help Scale). In this subsection, I further discuss the results of both studies, analyze virtual embodiment's role in generating empathy, validate the impacting factors, and propose design recommendations for future VR empathy applications, and I do this with consideration of three aspects: avatar features, narrative, and virtual presentations of pain.

7.4.1. Impacting Factors of Embodiment's Effect on Pain

Seeing an avatar and feeling embodied in it are necessary conditions to engender perspective taking, and avatar features affect users' levels of embodiment and self-identity. Participants from both studies reported that embodying the avatars was necessary for them to take the perspective of a chronic pain patient and play the role of such a patient throughout the tasks. Further, based on participants' feedback in both studies, the embodiment's first-person perspective is more effective in eliciting the embodiment illusion than a third-person perspective. Although results from Study 2 did not reveal any significant correlations between virtual embodiment and empathy levels, the findings suggested that the embodied characteristics (avatar appearance and movements) impacted participants' sense of embodiment and their perception of their identity. For instance, full-body synchronized movements gave participants a high level of control (i.e., agency) over the avatar through the Kinect (Study 1) and the HTC VIVE's sensor capture system (Study 2). The avatar was a chronic pain patient and an elderly grandmother in her 60s. The avatar's outfits (clothes and shoes), body figure (height and weight), skin patterns, and even hair were realistically modeled after a real person. Embodying such a vivid avatar gave participants a concrete idea of the patient's identity, which matched the virtual context or environment. Specifying this avatar's identity answered the question implicitly posed to participants: who am I (the embodied avatar)? However, the con is that a solid identity can break some users' experience of immersion if their self-identification clashes with the avatar. For example, in Study 2, one participant with dark skin reported that the avatar's white skin drew his attention and made him feel uncomfortable. Similarly, a tall male participant reported feeling disembodied because the avatar's slim and short body did not map to his real body. Researchers have not studied how identity misalignments—the connections between the real body's physical characteristics and the appearance of the avatar—affects sense of embodiment and elicited empathy. Therefore, future research should explore how users' sense of embodiment and empathy are connected to whether they identify with avatars' appearances.

Combining multiple modalities communicates the embodied avatar's pain in a way that matches the narrative context. In both iterations of the AS IF game, I implemented visual components and movement features in the digital world to mimic how pain works in the real world. The virtual arms' unhealthy skin presented a long-term symptom of chronic pain, and the occasional special visual effects (reddened arms and fisheye effects in Study 1, and reddened arms and red flashes in Study 2) communicated the acute pain spikes that patients felt. Meanwhile, synchronized movements gave participants a high degree of control over the avatar. Further, movement restrictions were occasionally added to represent issues pain patients' have with their range of motion. Although some participants understood these limitations as a consequence of living with chronic pain, others thought they broke their control of the avatar while they were interacting with objects and the environment, and they misinterpreted the limitations as programming glitches.

These two studies validated the idea that visual effects (e.g., unhealthy skin, fisheye and red flash camera effects) can communicate the symptoms of pain to healthy people, but manipulations of the movement factor should be carefully considered to avoid breaking the embodiment illusion and perspective taking. Besides visual and motor feedback, audio cues and physical feedback were suggested by participants, such as weights added to participants' real bodies to hinder movements. In short, this dissertation's findings recommend using a multimodal approach to communicating the avatar's pain; however, it should be noted that manipulating movement requires exploration and evaluation. By combining multimodal sensory and motor stimulations with a first-person perspective visual input, the experience can lead users to feel actively engaged in a controlled virtual environment and to behave in a realistic manner, adopting new attitudes and modulating cognitive biases and behavioral responses (Bertrand et al., 2018).

Narratives are essential to sharing pain patients' experiences and other vulnerable groups in embodied VR and should be explicitly integrated into the game. If the embodied VR provides users with a perspective to take, the narrative component should provide content and experiences specific to that perspective. Game designers and researchers use a ludology lens to define narrative (Koenitz, 2018). Usually, narrative in games refers to all aspects that contribute to the telling of a story, and it has occasionally been used to describe the story itself. Narratives answer the question of why users, once embodied, are in a particular place, what they should do, and what the purpose of their actions is. Therefore, VR narratives allow users to enter a virtual scenario that represents a story, which is more effective than passively watching a 360-degree shot of the environment.

In AS IF, the narrative was integrated into the participants' game tasks and delivered in different ways across the two studies. Both approaches adopted a linear and embedded (predetermined) way of presenting the narrative but did so through different game tasks. In Study 1, players were asked to solve puzzles and connect dots using physical movements (Figure 6.1B), and the narrative was delivered via a puzzle-solving task. First, participants experienced pain patients' physical challenges and range of motion issues when they moved their upper limbs to solve puzzles. Then the underlying story of a pain patient and the game's goal implicitly emerged while completing the task (in the game, the grandma avatar has promised her granddaughter that she will bake a birthday cake). Participants' affective empathy was elicited because of the frustrating experience of completing the puzzle-solving task. However, participants suggested that designers explicitly integrate the narrative into the game tasks so their attention was focused directly on the story rather than the puzzle. Therefore, in Study 2, I changed the game task from puzzle solving to direct manipulation so the participants could interact with the objects and directly complete the steps of baking the cake. This comparison of narrative delivery approaches indicated that explicit storytelling and game tasks elicit greater empathy than an implicit and indirect approach.

7.4.2. Design Recommendations

Below, I summarize design recommendations and study directions for future research focused on using embodied VR to generate empathy.

- Show participants an avatar (or parts of its body in pain) in pain with visual and motor cues (such as unhealthy skin, limited range of motion, and other potential pain symptoms) from a first-person perspective, as this is significant in increasing healthy people's sense of embodiment and enhancing their empathy levels. Manipulations of the avatar's appearance enhance users' perspective taking of the body in pain.

- Keep movements between participants real and virtual selves synchronized, as this is critical to perspective taking and interacting with the virtual content from that perspective. However, as the findings in Chapter 6 suggested, disrupting synchronized movement can break immersion and may not be perceived as a symptom of pain.

- Integrate pain patients' (or a vulnerable population) experience into interactions that communicate narrative, as this improves participants' empathetic attitudes. The narrative should present pain patients' challenges and experiences, and the narrative components should include visuals, audio, narration, and game tasks.

- Social communications and physical interactions should be designed as part of the narrative and contribute to pain patients' experiences.

- The extent to which participants align their own identity with that of the avatars they embody should be further explored, as this affects their empathy toward pain patients. To do so, researchers should consider ways of designing the avatar's appearance, including skin color and body shape and height, all of which should be modeled after the user's real self.

7.4.3. Bodily Resonance: Toward a Unified VR Design Framework for Pain and VR for Empathy

This dissertation's main focus was to understand the effect of avatar embodiment on pain modulation and empathy generation. In other words, it explored the broader questions of virtual embodiment: can a real body resonate with a virtual body (bodily resonance) so the brain can believe what the virtual body sees and make sense of it, leading to cognitive and affective changes? If so, how do such changes happen, and what are the impacting design factors? Answers to these questions will provide a framework that guides researchers in their design of embodied VR applications for pain modulation and empathy generations, and it will help researchers comprehensively examine the impacting components.

Bodily resonance is the "comparison between cognitive representations of our own self-image and that of the other" (Bedder et al., 2019, p.1). Self-image representations encode personal features in neural networks (particularly physical and bodily ones, such as gender, skin tone, hair color, and more abstract characteristics, such as group memberships). The cognitive mechanistic account of bodily resonance states that "during subsequent perception of another agent, total output from the self-image network is proportional to the degree of overlap between that agent's features and the encoded self-image" (Bedder et al., 2019, p. 2). Virtual embodiment shows that our self-image representations are highly plastic and that they can influence social cognition by modifying pain and generating empathy after a VR experience. Therefore, I here introduce this concept to my proposed design framework and envision that reaching bodily resonance will be important for empathy and certain types of pain, such as PLP, though perhaps not CRPS.

In chapters 4 and 5, I presented my creation of a healthy avatar that patients can embody to self-manage their pain. Similarly, in Chapter 6, I presented my creation of an avatar in pain that healthy people can embody to elicit their empathy for patients' pain and emotional challenges. Upon scrutiny of the design processes, VR's pain and empathy uses share similar design components, including (1) participation of the real body, (2) VR content, (3) illusions of being in a place and/or a virtual body, and (4) perception (pain or empathy). Drawing on support and evidence from my own studies and the literature, I here provide design frameworks of pain applications (Figure 7.1A) and empathy applications (Figure 7.1B), and I discuss how each component functions and impact each other.

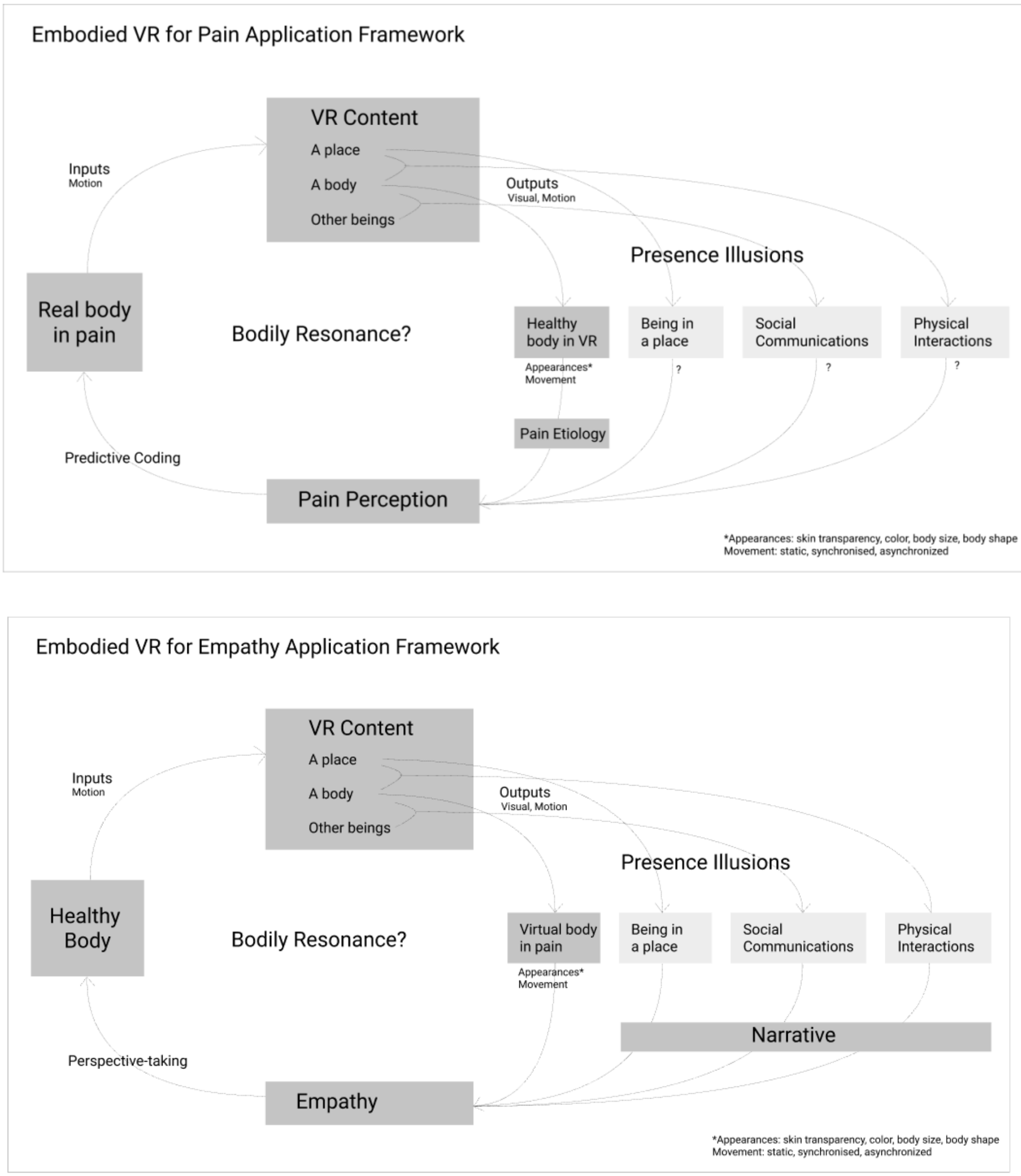

Figure 7.1 Top: Embodied VR for pain application framework. Bottom: for empathy application framework.

Figure 7.1A demonstrates my proposed design framework for pain-focused VR applications. Below, I explain each component and how future researchers can use this design framework.

(a) The real body is a patient in pain and provides inputs to the VR system via motion sensors, biofeedback sensors, or controllers.

(b) The VR content falls under four categories—a place or environment, a body, interactions in the place, and interactions with objects in the place—which are related to the four presence illusions.

(c) The content and modalities elicit a virtual embodiment illusion and the other three types of illusions. Manipulating avatar features, such as the avatar's appearance and motions, can significantly alter patients' perception of owning and controlling the virtual body. Bodily resonance occurs when patients feel a great level of embodiment over the virtual body, how pain etiology affects pain when the real body resonates with the virtual one has yet to be discovered.

(d) Embodiment and other presence illusions impact changes in pain, potentially because of three theories discussed in Subsection 7.3.1 (predictive coding, attention, and overlapped brain networks and pathways of embodiment and pain).

Figure 7.1B illustrates my proposed design framework for empathy-focused VR applications and, apart from (b) above, is similar to the previous framework. Below, I provide a detailed explanation of the similarities and differences.

(e) The real body is a healthy person and provides inputs to the VR system through motion sensors, biofeedback sensors, or controllers.

(f) The VR content falls under four categories—a place or an environment, a body, interactions in a place, and interactions with objects in this place—which are related to the four presence illusions.

(g) The content and modalities elicited virtual embodiment illusion and the other three types of illusions. Manipulating avatar features, such as an avatar's appearance and motions, can significantly alter patients' identification with it (cognitive empathy, or perspective taking). In addition to embodiment, illusions of being in a place, physical interactions, and social communications can contribute to the narrative of the vulnerable group's experience and foster affective empathy. Bodily resonance occurs when people feel a great level of embodiment in the avatar, and it is important in the facilitation of perspective taking.

(h) Embodiment and other presence illusions impact changes in empathy, potentially due to perspective taking.

Above interpretation primarily explained the potential roles of virtual embodiment; next, I examine the four attributes of presence illusions and their potential roles in changing pain and/or empathy.

Sense of being in a Place. Cummings and Baileson (2016) suggested that VR environments provide users accurate spatial awareness within a confined play area. No matter which VR applications people experienced in the experimental studies reviewed in Subsection 3.2.1, the VR applications contained an environment, or a scene, that facilitated the illusion of being in a place. Although few studies have measured people's sense of being in a place or its correlation with empathy changes explicitly, the virtual scene and its associated sense of being in a place are prerequisites for embodying an avatar and interacting with an environment to experience an empathetic perspective. The illusion of being in a place also establishes the realism of a narrative about a selected vulnerable group. For instance, Neyret et al. (2020) created an experiment group of male participants embodying female avatars in a virtual bar where they were harassed by a group of virtual male avatars. The researchers' goal was to examine whether experiencing the perspective of a female victim who has been sexually harassed could impact participants' action conformity under group pressure. Situating participants in a virtual bar put them in a place where sexual harassment frequently occurs and thus enhanced the narrative's realism.

Sense of embodiment. As discussed in Subsection 3.1.2 and Subsection 3.2.1, perspective taking is the primary underlying reason for people's perspective taking ability toward vulnerable populations. Therefore, seeing a scene from the perspective of an avatar is a must-have component of a VR intervention. When people are put in the perspective of an avatar whose identity differs from their own, they feel embodiment and perceive themselves as owning and controlling the avatar. In the literature (Banakou et al., 2013; Cummings & Bailenson, 2015; Petkova & Ehrsson, 2008), sense of embodiment seems to be the most critical of the four illusions when it comes to altering people's perceptions. For instance, when embodying a four-year-old avatar, adult participants overestimated the size of objects when compared to another group of adults who embodied in an adult avatar scaled to the same height as the child (Banakou et al., 2013). In this example, the virtual scene and the physical interactions (study tasks) were the same in both conditions, but whether participants were embodied in a child or adult avatar led to a significant change in their visual perspectives. Similarly, Rosenberg et al.'s (2013) experimental group participants were more engaged in helping behaviors when embodied in a superhero with the power of flight than participants in a control group that flew as helicopter passengers. In studies that used embodied VR to reduce gender and racial bias (Banakou et al., 2016; Lopez et al., 2019; Maister et al., 2015; Peck et al., 2013), researchers found that people who embody different avatars (female or male and white or black) have significantly different biases toward women or black people. In short, changing a person's virtual body may also change their mind. In this effect, the sense of embodiment has the potential of encouraging people's behavioral and attitudinal changes, which can be explained by the underlying effect of perspective taking (Maister et al., 2015).

Sense of physical interaction. Engagement with a virtual environment influences the VR experience (Schuemie et al., 2001). Some researchers have suggested that interactivity in VR leads to greater empathy levels. For instance, Nicovich et al. (2005) found that interactivity with the environment increases empathy and sense of presence. In another example (Hamilton-Giachritsis et al., 2018), researchers virtually embodied adult participants in a child's avatar whose virtual mother interacted with them negatively or positively. They found that experiencing negative maternal behaviors increases empathy levels more than experiencing positive maternal behaviors. In that experiment, the illusions of an embodied avatar and virtual place were the same for both conditions, and the differences in interactivity significantly altered the empathy outcome. Although empathy can be elicited with 360-degree videos and no interactivity (Weinel et al., 2018), no researcher has examined how it differs in an interactive environment. So far, most interactions have been between participants' avatars and other avatars that are parts of narrative plots; very few researchers have explored how interactions or experimental tasks with virtual objects impact empathy. Therefore, the sense of physical interaction and its impact on empathy levels is an important yet underexplored field, particularly when it comes to interactions that involve another virtual avatar.

Sense of social presence. The social presence illusion is similar to the sense of physical interaction in terms of its role in altering a person's empathetic attitudes. As discussed above, most interactions documented in the literature were between an embodied avatar and other avatars, and participants felt that they were in the VR environment with another person. Empathy is a key construct in social relationships; therefore, social presence could be a critical factor in altering empathetic changes. In the example mentioned above (Hamilton-Giachritsis et al., 2018), social interactivity (e.g., positive versus negative) played an important role in facilitating empathy. As for social presence's effects on pain, there is no direct evidence showing their relationships.

To summarize, more evidence and studies are needed to validate this framework (Figure 7.1) and to better justify the potential impacts of four presence illusion factors on pain and empathy in future research. Further, although ownership and agency are both attributes of embodiment, few empathy and pain studies have measured them separately, nor has their correlation to empathy changes been explored. Therefore, future experiments manipulating ownership and agency are also necessary to enhance understandings of their roles in eliciting pain and empathy.

7.5. Conclusions and Future Work

7.5.1. Conclusions

Embodiment is a construct through which we can understand how we see ourselves as people and how our minds interface with our bodies. VR is perfectly suited to the study of embodiment as a form of technology because its core offering is embodied simulations. This dissertation examined the effects of virtual embodiment on analgesia and empathy to resolve the BPS challenges of people living with chronic pain. The findings showed how altering embodied characteristics affects pain and empathy in various contexts.

My first research trajectory involved studies with healthy people exposed to pain stimulus, CRPS patients, and PLP patients and revealed that pain etiology significantly alters how virtual embodiment affects pain. The appearances of the avatars were associated with all participants' SoO, but its correlation with pain was found in CRPS participants. Altering avatar motions did not have a significant effect on any participant's experience. My second research trajectory proved that the narrative component is critical in sharing the experience of pain. Different approaches to visualizing long-term pain and short-term spikes successfully communicated the perspective of a pain patient, but changes in synchronized motions could break the embodied illusions.

Finally, although the underlying mechanisms of using embodied VR for pain modulation and empathy generation require further exploration, this dissertation summarized the potential avatar features that affect pain and empathy, and proposed novel frameworks with design recommendations to inform future embodied VR environments, research questions, and study methods.

7.5.2. Future Work

Further research should be conducted to improve our understanding of the underlying mechanisms that cause different behavioral effects both during and after virtual embodiment. Below, I propose future research agendas based on my findings, and I have divided these into two categories: embodied VR applications for pain modulation and embodied VR applications for empathy generation.

7.5.2.1. Embodied VR Applications for Pain Modulation

Future researchers should recruit larger sample sizes to validate this dissertation's findings, and they should include people with more types of chronic pain to better understand why pain etiology affects the correlations between virtual embodiment and pain. In addition to SoO, the manipulation of SoA should be carried out in varied ways (e.g., motion induced, touch induced, or visually induced), and its effect on pain should be examined to explore the underlying mechanism of how embodiment works to help users modulate pain. Further, future research should compare Hoffman et al.'s traditional pain distraction approach (Hoffman et al., 2001, 2007, 2011) to this dissertation's embodiment approach to further understand the effectiveness of each as well as the situations that can optimize VR's analgesic effects.

7.5.2.2. Embodied VR Applications for Empathy Generation

Future studies should implement and test a multimodal feedback system to communicate pain through visual, audio, and tactile sensations. A controlled study in which participants experience AS IF in an experiment condition and another media (such as watching a video or reading a story about chronic pain patients' challenges and life situations) in a control condition will better evaluate the potential value of embodied VR. Further, follow-up behavioral tests should be arranged in the post-study period to learn the potential long-term impacts that embodied experiences have on empathy.

For both research trajectories, longitudinal experiments are required to validate the long-term effects of VR on analgesia and empathy generation. In addition to self-reported ratings used to measure the explicit sense of embodiment, implicit embodiment should also be measured with behavioral tests to produce greater insights into how embodiment affects pain and empathy. Further, biofeedback, such as HRV, EEG, or GSR data, should be collected to assist in analyzing the perception changes of pain and empathy. In the end, all four types of illusions should be measured and collected to study the possible interrelationship between each other and how they affect perception and behavioral changes.

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Appendix A. Research Questionnaires for AS IF Studies

1. Pretest Questionnaire

[Note: the following 16-item questionnaire is based on the "Compassion Scale" (Pommier, 2011), modified for Chronic Pain]

HOW I TYPICALLY ACT TOWARDS **P**EOPLE **W**ITH **C**HRONIC **P**AIN (PWCP)*

* Chronic Pain is defined as any pain that lasts longer than six months. With chronic pain, signals of pain remain active in the nervous system for months or even years. This can take both a physical and emotional toll on a person.

Please read each statement carefully before answering. To the left of each item, indicate how often you behave in the stated manner, using the following scale:

1. If PWCP cry in front of me, I often don't feel anything at all.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

2. Sometimes if PWCP talk about their problems, I feel like I don't care.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

3. I don't feel emotionally connected to people in chronic pain.

Almost Never | Almost Always

1 **2** **3** **4** **5**

4. I feel detached from PWCP if they tell me their tales of woe.

Almost Never | | | | Almost Always

1 **2** **3** **4** **5**

5. If I see someone with chronic pain going through a difficult time, I try to be caring toward that person.

Almost Never | | | | Almost Always

1 **2** **3** **4** **5**

6. I will tune out if PWCP tell me about their troubles.

Almost Never | | | | Almost Always

1 **2** **3** **4** **5**

7. I will like to be there for PWCP in times of difficulty.

Almost Never | | | | Almost Always

1 **2** **3** **4** **5**

8. If I see PWCP feeling down, I feel like I can't relate to them.

Almost Never | | | | Almost Always

1 2 3 4 5

9. Sometimes I am cold to PWCP if they are down and out.

Almost Never   Almost Always

1 2 3 4 5

10. I don't concern myself with PWCP's problems.

Almost Never   Almost Always

1 2 3 4 5

11. My heart goes out to PWCP who are unhappy.

Almost Never   Almost Always

1 2 3 4 5

12. If I saw PWCP are feeling troubled, I usually will let someone else attend to them.

Almost Never   Almost Always

1 2 3 4 5

13. I don't think much about the concerns of PWCP.

Almost Never   Almost Always

1 **2** **3** **4** **5**

14. I can't really connect with other PWCP when they're suffering.

Almost Almost

Never Always

1 **2** **3** **4** **5**

15. I try to avoid PWCP who are experiencing a lot of pain.

Almost Almost

Never Always

1 **2** **3** **4** **5**

16. If PWCP feel sadness, I try to comfort them.

Almost Almost

Never Always

1 **2** **3** **4** **5**

The following question ask you to imagine a scenario and what you would do accordingly.

You're preparing for an important interview for tomorrow. However, a friend who have chronic pain ask you if you can help with a ride to airport (a 2 hour drive each way). Please indicate how willing are you to help the person?

1 2 3 4 5 6 7 8 9 10

Not at all Very willing to help

The following questions will ask you some personal information regarding chronic pain and demographic information. Your answer is completely anonymous. And we will keep these information in secure condition.

Do you know of any families or friends who had ever been diagnosed with chronic pain?

a. Yes b. No

Have you ever been diagnosed with chronic pain before?

a. Yes b. No

b.

Could you tell us your age?

____

Could you tell us your gender?

a. Female b. Male c. Other d. Prefer not to disclose

2. Post-test Questionnaire

HOW I TYPICALLY ACT TOWARDS **P**EOPLE **W**ITH **C**HRONIC **P**AIN (PWCP)

Please read each statement carefully before answering. To the left of each item, indicate how often you behave in the stated manner, using the following scale:

1. If PWCP cry in front of me, I often don't feel anything at all.

Almost Never — Almost Always

1 **2** **3** **4** **5**

2. Sometimes if PWCP talk about their problems, I feel like I don't care.

Almost Never — Almost Always

1 2 3 4 5

3. I don’t feel emotionally connected to people in chronic pain.

Almost Almost

Never Always

1 2 3 4 5

4. I feel detached from PWCP if they tell me their tales of woe.

Almost Almost

Never Always

1 2 3 4 5

5. If I see someone with chronic pain going through a difficult time, I try to be caring toward that person.

Almost Almost

Never Always

1 2 3 4 5

6. I will tune out if PWCP tell me about their troubles.

Almost Almost

Never Always

1 2 3 4 5

7. I will like to be there for PWCP in times of difficulty.

Almost Almost

Never Always

1	**2**	**3**	**4**	**5**

8. If I see PWCP feeling down, I feel like I can't relate to them.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

9. Sometimes I am cold to PWCP if they are down and out.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

10. I don't concern myself with PWCP's problems.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

11. My heart goes out to PWCP who are unhappy.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

12. If I saw PWCP are feeling troubled, I usually will let someone else attend to them.

Almost Never				Almost Always
1	**2**	**3**	**4**	**5**

13. I don’t think much about the concerns of PWCP.

Almost				Almost
Never				Always
1	**2**	**3**	**4**	**5**

14. I can’t really connect with other PWCP when they’re suffering.

Almost				Almost
Never				Always
1	**2**	**3**	**4**	**5**

15. I try to avoid PWCP who are experiencing a lot of pain.

Almost				Almost
Never				Always
1	**2**	**3**	**4**	**5**

16. If PWCP feel sadness, I try to comfort them.

Almost				Almost
Never				Always
1	**2**	**3**	**4**	**5**

The following question ask you to imagine a scenario and what you would do accordingly.

You’re preparing for an important interview for tomorrow. However, a friend who have chronic pain ask you if you can help with a ride to airport (a 2 hour drive each way). Please indicate how willing are you to help the person?

1 2 3 4 5 6 7 8 9 10

Not at all Very willing to help

3. Post-test semi-structured Interview Guide

Do you have any difficulties while playing the game? If so, what they are?

What do you think about the game interaction, such as controlling your avatar or interacting with the game objects, connecting the dots, etc.?

Can you describe how the virtual physical limitations on your avatar made you feel? While playing the game, what were your physical sensations, if any? While playing the game, what were your emotional experiences, if any?

How do you feel about the “fisheye” lens effect and glowing limbs as a visual representation for chronic pain?

In your opinion, does the game reflect the real patient’s sufferings, i.e.: put you into the shoes of chronic pain patients? Why or why not?

How would you design or redesign this game if you were the game designer?

Appendix B. Published Papers from My Dissertation

Here, I listed out the citations to the peer-reviewed papers that were published about my dissertation. I also briefly introduced my roles and contributions in each paper.

Phantom Limb Pain Case Series (Chapter 4.2): **Tong, X.,** Wang, X., Cai, Y., Gromala, D., Williamson, O., Fan, B., & Wei, K. (2020). "I Dreamed of My Hands and Arms Moving Again": A Case Series Investigating the Effect of Immersive Virtual Reality on Phantom Limb Pain Alleviation. *Frontiers in neurology*, *11*, 876. In this research, I was the lead researcher who designed and conducted the study with patients, developed the VR environments, analyzed the data, and wrote the entire manuscript.

AS IF initial game idea (Chapter 6): Jin, W., Ulas, S., & **Tong, X.** (2016, May). AS IF: A Game as an Empathy Tool for Experiencing the Activity Limitations of Chronic Pain Patients. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 172-175). In this project, I teamed up with the other two colleagues from Pain Studies Lab and contributed equally to the initial ideation and development of AS IF. We presented this project together at CHI 2016 Student Game Competition at San Jose, US.

AS IF first round of user testing (Chapter 6.1): **Tong, X.**, Ulas, S., Jin, W., Gromala, D., & Shaw, C. (2017, May). The design and evaluation of a body-sensing video game to foster empathy towards chronic pain patients. In *Proceedings of the 11th EAI International Conference on Pervasive Computing Technologies for Healthcare* (pp. 244-250). I led the revision of AS IF and developed a new game environment, conducted the study together with two other colleagues and wrote the entire manuscript.

AS IF second round of user testing (Chapter 6.2): **Tong, X.**, Gromala, D., Ziabari, S. P. K., & Shaw, C. D. (2020). Designing a Virtual Reality Game for Promoting Empathy Toward Patients with Chronic Pain: Feasibility and Usability Study. *JMIR serious games*, *8*(3), e17354. In the second revision, I developed the VR version and redesigned the game tasks. Further, I conducted the study and wrote the entire manuscript.

The two studies in Chapter 3 and the literature review described in Chapter 4.1 are in submission when writing this dissertation.