Virtual Reality and Health Informatics for Management of Chronic Pain

by

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Abstract

Approximately 20 percent of people in North America suffer from chronic pain. Chronic pain is defined as pain that lasts more than 6 months and that persists beyond the healing of its putative cause. The complexity of the disease involves neurobiological, psychological and social dimensions, and as such, there exists no universal treatment for this disease. Besides pharmacological approaches to the management of chronic pain, digital media has not been widely used as a method of treatment in conjunction with traditional pharmacological approaches.

In this thesis, I designed and conducted several studies that constituted use of an Immersive Virtual Environment (VE) designed to assist chronic pain patients in self-modulating their pain, and ideally raise their pain tolerance. The VE, equipped with a biofeedback system, gives patients a chance to learn and practice mindfulness-based stress reduction (MBSR). One of the primary goals is to enable users to consciously train their emotional arousal, measured by galvanic skin response (GSR) in a healthy manner. The results suggest that Virtual Reality combined with biofeedback, and in conjunction with well-known MBSR, can decrease the pain reported by the patients.

• Keywords: Virtual Reality; Pain Management; Chronic Pain; Biofeedback; Social Media
Dedication

“To my lovely parents”
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# Table of Contents

Approval ......................................................................................................................... ii
Partial Copyright Licence ................................................................................................. iii
Ethics Statement .............................................................................................................. iv
Abstract.......................................................................................................................... v
Dedication ........................................................................................................................ vi
Acknowledgements .......................................................................................................... vii
Table of Contents ........................................................................................................... viii
List of Tables ................................................................................................................... x
List of Figures .................................................................................................................. xi

## Chapter 1. Introduction ............................................................................................... 1

## Chapter 2. Background ............................................................................................. 4
2.1. VR Technology ......................................................................................................... 6
2.2. VR for health and pain management ........................................................................ 8

## Chapter 3. VR technology for chronic pain management ........................................ 14
3.1. Sub Study 1: Right type of visual feedback for the biofeedback system .............. 14
3.2. Sub Study 2: Choosing the appropriate VR equipment ......................................... 18
3.3. Main Study: Virtual Meditative Walk ..................................................................... 20
    3.3.1. Biofeedback technology .................................................................................. 21
    3.3.2. Visual design ................................................................................................ 23
    3.3.3. Sound design and narration ......................................................................... 24

## Chapter 4. Experimental design & Results .............................................................. 27
4.1. Sub Study 1: Visual feedback types ......................................................................... 27
    4.1.1. Control group .................................................................................................. 28
    4.1.2. Progress bar .................................................................................................. 28
    4.1.3. Smiley face animation ................................................................................. 28
    4.1.4. Ambient feedback ....................................................................................... 29
    4.1.5. Procedure ..................................................................................................... 30
    4.1.6. Statistical analysis ....................................................................................... 31
    4.1.7. Sub Study 1: Visual Feedback Types Results .............................................. 31
4.2. Sub Study 2: The VR equipment comparison study .............................................. 34
    4.2.1. Sub Study 2: The comparison study results ............................................... 35
4.3. Main study: VMW ................................................................................................... 38
    4.3.1. Participants ................................................................................................... 38
    4.3.2. Conditions ................................................................................................... 39
    4.3.3. Apparatus ..................................................................................................... 39
    4.3.4. Procedure ..................................................................................................... 40
    4.3.5. Statistical analysis ....................................................................................... 41
    4.3.6. Main Study: VMW Results ......................................................................... 43
Chapter 5. Discussion ........................................................................................................ 45
5.1. Discussion on VMW .................................................................................................. 46
5.2. Conducting Studies on Chronic Pain Patients ......................................................... 49

Chapter 6. Conclusion and future works ........................................................................ 51

References ...................................................................................................................... 55

Appendix A. VMW Questionaire .................................................................................... 61
List of Tables

Table 4-1. Comparing feedback types pair-wise using Tukey HSD.............................. 33
Table 4-2. Study Conditions: two groups tested with different orders of the VR equipment................................................................................................................. 34
Table 4-3. The number of conditions and their participants........................................... 39
Table 4-4. Pain level reported by patients in each condition ........................................ 44
List of Figures

Figure 2-1. Oculus Rift, an affordable HMD designed for gaming in mind [28] .......... 7

Figure 2-2. In the Meditation Chamber, the user wears a HMD, and is guided by a narrator through muscle relaxation and meditation techniques. As a result, he is able to watch his stress level change in real-time. ................................................................. 9

Figure 2-3. Patient playing in Snow World VE while receiving burn wound care. .... 10

Figure 3-1. The DeepStream 3D display setup.......................................................... 19

Figure 3-2. Procomp Infinity biofeedback device along with GSR sensors ............... 22

Figure 3-3. Biograph application showing current GSR decreasing in time during a trial. .................................................................................................................. 23

Figure 3-4. Perspective showing the VMW path......................................................... 25

Figure 3-5. The beginning of the VR environment inside VMW............................... 25

Figure 3-6. The VE in the middle of the trial. .............................................................. 26

Figure 3-7. At the end of the trial, the user observes a relaxing landscape in which the grasses sway smoothly................................................................. 26

Figure 4-1. MindWave Mobile (side and front view)............................................ 27

Figure 4-2. The amount the bar is filled directly correlates with the participant’s relaxation state. An empty bar represents a state of agitation, and a fully filled bar represents the most relaxed state. ........................................... 28

Figure 4-3. The image gradually transitioned between these three images. ............ 29

Figure 4-4. The top left image (red) represents agitation. As the users relax, the image transitions to the bottom right image (blue), which represents the most relaxed state. This slow-moving animation does not offer any one area that demands more attention than any other area. .................................................................................. 30

Figure 4-5. Average relaxation level for each participant along with its standard deviation. The average relaxation level for each feedback condition is also represented ............................................................... 32

Figure 4-6. Visualization of data points for different participants in all conditions. .... 33

Figure 6-1. Workflow of a generic intelligent Agent ................................................. 53
Chapter 1. Introduction

According to [1], there are three categories of pain: 1) acute pain 2) cancer pain and 3) chronic pain. Acute pain is experienced as a result of a physical injury or a surgery and is a normal response to tissue damage that goes away as the injured tissue heals. Pain related to cancer results from tumor growth or the effects of chemotherapy. Chronic Pain is a pain that persists long after the expected healing time of an injury, or that has no identifiable cause but continues for at least six months [2]. Chronic pain is a complex neurobiological and psychological disorder where the pain response system responds in a hypersensitive manner so that the patient constantly suffers from on-going pain. It is important to note that chronic pain is considered a disease, in contrast to acute pain, which is a symptom of potential tissue damage. A considerable amount of world’s population suffers from this disease. In a study conducted in Europe, for instance, 19% of people reported suffering from pain on a daily basis for at least six months [3]. This percentage varies between 15-29% in Canada [4]. Although the prevalence of chronic pain appears high, its cause has not been found, and there is currently no cure. Therefore, managing pain is the focus for patients and the healthcare professionals who care for them.

Chronic pain is a complex disease. Over time, it is associated with a number of common sequelae, from insomnia, anxiety, depression and cognitive impairment to social isolation and decreasing mobility [5]. These may be categorized into the physical, psychological and social impacts of the disease. In addition to experiencing pain itself, a common physical impact of chronic pain is kinesiophobia, or fear of movement, which leaves many chronic pain patients reluctant to engage in physical activities. This reluctance is because patients find that the consequences of such activities are uncertain. Activity, for example, may worsen patients’ pain, or it may help them feel better. Commonly experienced psychological aspects of chronic pain are anger, anxiety, and depression [5]. Significant social implications related to chronic pain include social stigma and social isolation [6]. Many patients feel that others do not take their condition seriously, indeed, studies indicate that a surprisingly few family physicians are aware of
chronic pain or know how to treat it, and few members of the public have knowledge of it [5]. Therefore, other people may attribute the behavior of chronic pain patients as laziness or are hypochondriacs [7]. Moreover, because patients are less active, they may also participate in fewer social activities, causing them to feel isolated. Social isolation is not merely a negative feeling, but is correlated with higher rates of morbidity [7]. Together, these physical, psychological and social aspects of chronic pain have been proven to have negative effects on the daily routines, physical health, and physiological health [8] of patients – all of which decreases their quality of life.

Although pharmacological approaches are the most common treatment method for chronic pain, certain pain medications – opioids – have major side effects and can lead to dependency or addiction [9]. Dependency differs from addiction in that manner. This is important because misuse of opioids is a fast growing problem among other groups [10]. Additionally, few studies have been conducted in order to find out how digital media technology can help chronic pain patients to manage and alleviate their pain. One form of digital media technology that is promising is immersive Virtual Reality (VR). VR has proven to be effective in decreasing acute pain [11]. Although the exact mechanism of why VR is effective for acute pain is unknown [12], pain distraction is widely thought to explain VR’s success. However, no studies have been conducted to determine whether VR may also be helpful for chronic pain management. This gap in VR research is what this thesis addresses.

In summary, this thesis presents a novel approach for the management of chronic pain using VR and biofeedback technology along with the well-known mindfulness meditation technique of MBSR. The mindfulness practice of MBSR involves focusing one’s attention on on-going internal and external experiences, it is usually categorized as a meditation practice [13] [14]. The main research question is “Could VR be used to manage chronic pain?”. The way the VR+biofeedback approach is operationalized in this contribution is based on the MBSR practice as it is being widely used for management of chronic pain. To better address the research question, two sub studies were conducted. The first sub study helped me understand what type of visual feedback needed to be designed for the VR environment and the question I was seeking to answer was “what type of visual feedback is more appropriate in a relaxing biofeedback environment?”. The second sub study assisted me to learn what type VR equipment is more comfortable for chronic pain patients. The question I was seeking to
answer in the second sub study was “Comparing a hands free VR equipment with a famous Head-Mounted Display (Oculus Rift), which one induces less discomfort for the users?”

The results of this thesis suggest that using mindfulness practice when exposed to a virtual environment could lead to a short-term decrease in pain. Chapter 2 provides a background review of similar research conducted in VR and acute pain management. Chapter 3 describes the general idea of user studies that led to the design of The Virtual Meditative Walk (VMW), our virtual environment. Chapter 4 describes the experimental design of the VMW virtual environment and all associated studies that were conducted along with the results. Chapter 5 presents the discussion on observations during the user studies and development of the VMW. Chapter 6 offers the conclusion and suggests the potential for future work in this area of research and introduces other technologies that may be developed to better help chronic pain patients manage their long term pain.
Chapter 2. Background

A study conducted by Breivik et al. explored how chronic pain affects physical and mental health. The study had a large sample size and broadly investigated different effects of chronic pain on patient’s lives. It showed the prevalence, treatment, severity and physical/social impacts of chronic in daily activities [15]. The researchers undertook a computer-assisted telephone survey among 46,394 patients suffering from chronic pain, and their study revealed interesting results. First, arthritis and lower back pain are the main causes of pain for patients. Although this study illuminates issues that are of primary interest for this thesis, like any study, it also reveals potential problems that plague research of this complex disease. First, chronic pain is widely thought to be an overall dysfunction of the pain system. Next, pain works in ways that remain unexplained; for instance, injury or dysfunction of one anatomical area can be “referred” to, or appears in other body parts, and how these connections work is unknown. Finally, an injury or illness that precipitates chronic pain may not exist or may not have been identified; this is called neuropathic pain. For these reasons, while attributing chronic pain to anatomical areas, such as back pain, arthritis and migraines may be a useful shorthand or focus, it ignores the systemic nature of chronic pain, which includes complex biochemical and physical processes. Moreover, it may reinforce a common problem that plagues discussions of chronic pain by non-experts: a tendency to revert to the common tendency to think of chronic pain as a symptom (i.e., acute pain), rather than as a systemic dysfunction.

The researchers asked questions about patients’ daily lives in order to find out how chronic pain impacts different aspects of life. For instance, one in four patients said that their pain had impacted on their employment. Only 31% of the respondents with pain were employed full time, while 13% were employed part time, 34% were retired and 22% were unemployed.
Consequently, to improve the quality of life in chronic pain patients, all of the physical, mental, and social aspects must be considered when developing assistive technologies for patients [16] [17] [18].

While treatment of severe chronic pain via pharmacological approaches is difficult to achieve with current trends in analgesic drugs [19], there are alternatives that may help patients manage their pain and control or reduce its intensity. Pharmacological approaches such as opioids that are broadly used for management of acute and chronic pain can have serious side effects such as psychological addiction. Moreover, the use of opioids for the long-term treatment of chronic non-cancer-related pain is also in question [20]. First, greater amounts are necessary over time to achieve the same pain relieving effects. Next, since these opioids are readily available, their abuse is a growing phenomenon, especially in North America. This may be one area where misunderstanding of the disease and stigma can be witnessed. Historically, opioids have been the most effective pain relieving medications that humans have used for at least a millennium. Thus, opioids have been prescribed for chronic pain patients since the disease was first identified [21]. Yet, despite their common use by chronic pain patients, they are not the most likely group to abuse them [22]. Patients, therefore, may suffer from stigma that assumes that they are or will become addicts, or that they are a main cause for rising rates of addiction. The proposed answer for the growing problem of addiction is to simply stop their use for all but the most obvious acute pain, like surgical pain. However, this leaves a large group of patients without other well-known, inexpensive and alternatives that are proven to be effective. Finally, opioid use is a complex problem, so other alternatives to manage pain, especially over time, could be beneficial in a number of ways.

Another well-known approach to chronic pain management is Mindfulness-Based Stress Reduction (MSBR). Jon Kabat-Zinn et al. conducted a study of 225 chronic pain patients while they practiced mindfulness meditation [23]. The researchers instructed patients to perform a formal meditation practice while lying down and/or sitting. The practice consisted of yoga exercises performed in a meditative and slow manner. The emphasis in this practice was on moment-to-moment mindfulness. The primary goal of MBSR is helping patients to reduce stress and improve their health and psychological state [23]. Rosenzweig et al. studied a group of patients suffering from different sorts of chronic pain during an 8-week MSBR program. The study measured bodily pain and
health-related quality of life (HRQoL); the results suggest that using MSBR can help people with arthritis and back pain to significantly change their pain and functional constraints [24]. Additionally, a number of studies suggest that the MSBR approach assists patients in changing pain, management ability, medical symptoms, and inhibition of daily routines by pain [25] [26].

2.1. VR Technology

In recent years, technology, and specifically computer science, has had a significant role in helping healthcare practitioners to diagnose medical conditions and helping to resolve them.

Immersive Virtual Reality, a subfield of computer science, consists of three-dimensional, computer-generated images (CGI) or simulations that respond to users' input [27]. The user can interact with the virtual environment using input devices such as a mouse, keyboard, sensors or motion detectors. The main goal of VR technology is the simulation of a real or fantasy world that enables a user to experience it as if it were a visually (and/or sonically) real space.

VR technology has a wide range of applications including gaming, medical, education, and military uses. One of the important aspects of VR is the sense of presence that defines how immersive it is from the user perspective, and how close it is to the real world. In an immersive VE, users ideally feel that they are inside the 3D CGI environment. The more the user experiences the sense physical presence in a VR environment, the more the environment is considered to be immersive. For instance, in an immersive VR flight simulator, users feel as if they are in a plane’s cockpit, operating the aircraft. Indeed, flight training was among the first applications of VR, and continues to be useful because VR gives a descent perceptual and sensory impression to the users.

Numerous technologies associated with VR have been developed to enhance the sense of presence; one of the most notable is head-mounted displays (HMDs). HMDs usually provide an acceptable sense of presence through the use of a 3D
stereoscopic displays and motion trackers. The 3D stereoscopic display, combined with motion trackers is a technique that creates the illusion of depth in visual perception by utilizing stereopsis for binocular vision. The motion trackers installed on the HMDs measure real-time rotation of the head and synchronize the simulated environment rotation accordingly. Therefore, rather than looking at a flat computer screen, as users turn their heads, the 3D scene updates in real-time, creating the illusion that one is inside the simulation. Until recently, HMDs have been prohibitively expensive, and so VR was relatively confined to university labs or industry R&D labs. Very recently, however, HMDs have become much less expensive, to the degree that they could be used in hospitals, clinics or at home. Figure 2.1 demonstrates Oculus Rift, a very popular and relatively affordable HMD (less than the cost of a high end iPad), equipped with a motion tracker.

![Oculus Rift](image)

**Figure 2-1. Oculus Rift, an affordable HMD designed for gaming in mind [28]**

The U.S. Navy has utilized Virtual Reality (VR) to train parachuters. Trainees are equipped with VR glasses while in a parachute harness, and the glasses expose the trainee to a simulated environment in which they learn how to control the parachute. A computer program monitors the movement of the risers triggered by the trainee and changes the environment accordingly [29].
In all of the aforementioned examples, VR engages perceptual and sensorial aspects of the users resulting in a more realistic environment. In such environment, the users dedicate more attention and have more sense of presence. In addition to gaming, military, and training purposes, VR has applications in the health care area.

2.2. VR for health and pain management

Although videogames have been one of the most prominent VR application areas, there have been an enormous number of medical studies concerning the use of VR technology in recent decades as well. Medical applications of VR have started to emerge in the past decade. The applications constitute rehabilitation, surgical simulators, training practitioners, and telepresence surgery [30][31]. These applications are coordinated via a simulated computer interface and embodiment of VR is a crucial part of the paradigm shift in the realm of medicine.

In 2007, researchers at the Georgia Institute of Technology Shaw et al. designed an immersive virtual environment (VE) named the Meditation Chamber to train people to control their physiological states to reduce their stress and consequently reduce their pain [32]. The researchers used biofeedback sensors to monitor arousal and then reflected the results in the VE. In other words, the users could “see” what was happening inside of their body in the simulated environment in real-time. The fact that the users could view the changes in their bodily activities in real-time enabled them to train their physiological states in a healthy manner. First users were performing a muscle relaxation technique and then meditation, guided by a vocal narrator. Therefore, they could see their stress levels changed in real-time; As a result of seeing their performance, or results of their efforts to reduce their stress and to meditate, their ability to modulate their stress levels or physiological state improved.

Generally, biofeedback is the process of retrieving biological information such as brain waves, heart rate, and skin conductance [33] and utilizing that information to update the status of a system or to inform the users. Galvanic Skin Response (GSR), for example, is a type of biological signal that is used to measure emotional and sympathetic responses in time such as stress, fatigue, fear, and anger by applying electrical current to the skin and measuring the resulting electrical conductance [19].
level of skin conductance changes with respect to sweat gland activity (i.e., different levels of sweating cause the electrical conductance to vary on the skin; the more intense the psychological arousal is, the more the skin conductance would be). GSR is a way of measuring electrical conductance of the skin. The electrical conductance generated varies based on the sweating on the skin.

The Meditation Chamber uses GSR as its primary biofeedback technology. Figure 2.2 depicts the Meditation Chamber setup during usage. During the meditation chamber session, users viewed a sunrise animation synced with users’ stress level and the animation changed accordingly. Deployment of this setup using an immersive VR enabled the users to dedicate more attention to the meditation progress. It also helped users to perform meditation in a more efficient manner by being aware of their progress. What I am seeking in this thesis is the potential of utilizing similar approach with a different paradigm for helping chronic pain patients to manage their pain using VR and biofeedback.

Figure 2-2. In the Meditation Chamber, the user wears a HMD, and is guided by a narrator through muscle relaxation and meditation techniques. As a result, he is able to watch his stress level change in real-time. Image from [32]

VR has also proven to be as effective as opioids in distracting patients from pain during burn wound care [11]. This is significantly important since it suggests that VR could be used as an alternative to opioids and to prevent potential side effects and
dependence. In 2011 Hoffman et al. designed a series of immersive virtual environments in which patients reported up to 50% reduction in operational pain. The main function of VR in those studies was to distract patients from the pain and move their attention to a virtual world with the goal of causing fewer neural signals to pick up attention available to pain. The researchers exposed the patients to a snowy VE called Snow World and let them play a game while receiving burn wound treatment. Patients interact with the game by throwing snowballs at game entities such as snowmen, penguins, igloos, and flying fish. Patients aim and perform the throw using a mouse or head tracking. The entities in the game collide and respond to the hits by shattering or playing a sound, for example.

The snow world VR environment proved to be effective in coping with acute pain, however, it strives to distract the patients from their pain and requires the system to be working in real-time. This setup might not be effective for chronic pain since patients have on-going pain cannot be distracted all day. Figure 2.3 shows Snow World + VR in practical use.

![Image](image.jpg)

**Figure 2-3. Patient playing in Snow World VE while receiving burn wound care. Image from [11].**

Das et al. at University of South Australia designed an acute pain modulation VR for children with burns [35]. They conducted a clinical trial on children undergoing treatment for burn pain. 6 boys and 3 girls played a game in a VE during the treatment. The children used a HMD (IOGlasses HMD with a SVGA video resolution of 800 × 600 16 million colors) to control a first-person shooter camera and mouse to shoot monsters in the game. The researchers found that VR could improve pain management for children with burns. They also found that children acted less distressed and appeared calmer
during treatment when exposed to VR. The researchers used the self-reporting face scale to record the amount of pain children were experiencing. The pain level was quantified from 0 to 10. Mean pain score difference between pharmacological analgesia and pharmacological analgesia coupled with VR was 3.2 and reported significant utilizing paired t-tests.

Similar to Hoffman’s et al. studies, this system required real-time usage of the patients and cannot be as effective for management of chronic pain. Additionally, usage of HMD might introduce some limitations since some patients have burns on their face or cannot tolerate the weight of the HMD.

In another application, Murray et al. in 2007 at the University of Manchester deployed an immersive VR as a solution to treat phantom limb pain [36]. They exposed three patients with phantom limb pain to the VE and transposed their healthy limb movement to a virtual limb. Although the study was preliminary in nature, the researchers found that users felt a sensation morphing into the muscles of the phantom limb and stated that patients reported a decrease in phantom pain. The participants using the environment made a hint that they experienced a transferral of sensations into the muscles of the phantom limb. The researchers also claimed that the effect of relief might have roots in pain distraction. This supports that pain distraction and attention distribution could be a significantly useful approach.

Furthermore, in 2013 Shiri et al. created a novel VR + Biofeedback system for treatment of paediatric headache [37]. Headaches in children are very common, can decrease quality of life for children and can trigger stress. Additionally, overuse of pharmacological treatment of headaches has side effects and is not very efficient in the long run [38]. These problems motivated the researchers to create an alternative treatment using VR and biofeedback. They used the ProComp Infinity by Thought Technology to obtain the GSR levels of the patients with chronic headache in 10 sessions each lasting 30 minutes. The GSR was then processed and used to affect the VE that the users were exposed to. In the protocol, the users were instructed to perform relaxation techniques and as they became more relaxed, the VE showed a happier picture of them. The visuals were based on a series of photos taken from the users before the actual experiment.
The researchers reported that during the intervention, patients with migraines experienced a significant decrease in headache pain using Visual Analog Scale (VAS). There was also an increase in patients’ quality of life (QOL) by monitoring QOL measurement factors in time. The researchers used the PedsQL model for measurement of the pediatric quality of life inventory [39].

![Image](image.png)

**Figure 2-4. Distracting patients using a VE to assist them in decreasing their dental anxiety. Image from [40].**

In 2013 at Plymouth University, Dijkstra et al. implemented a novel VR environment to help both general dental practitioners and patients in dealing with dental anxiety and unpleasant dental procedures [40]. The researchers exposed 69 dental patients who displayed different levels of dental anxiety (e.g., fear of treatment) to a VR environment composed of natural scenery (figure 2.4) in order to distract them while they received dental treatment. Patients’ anxiety level was recorded using an online dental anxiety questionnaire before the experiment. The goal was to distract the patients from their current anxious state, to help them form a vivid memory of their care, and to be
more encouraged to follow-up their dental care in the future by reducing their dental anxiety. Participants were assigned to one of 3 conditions 1) no VR: participants had a HMD on with a black screen 2) active VR: participants had a controller while walking in the VE 3) passive VR: Participants had a HMD on and watched a pre-recorded walk in the VE. During the study, patients listened to a pre-recorded audio that narrated a dental treatment (doctor talking to the patient and their interactions) while present in the VE.

Results of the study suggested that VR distraction could be utilized as an intervention for a care plan in which patients’ previous experiences could potentially have a negative effect in their behaviour regarding future dental visits. This is important since it enables us to understand the cognitive model by which VR distraction functions. Additionally, what makes VR a crucial part of this research is sense of immersion. Using VR, the researchers were able to simulate a dental treatment session and give the impression to the patients as if they were present in another environment. The study was partaken in a simulated environment because of ethical reasons. This means that it is not clear whether the VR distraction is as effective in a real dental treatment setup.

The background work indicated that VR has been effective for acute pain treatment. The literature also supported the fact that biofeedback can help patients be self-aware of their pain and anxiety and be able to regulate them in a healthier manner. The VR environments developed for acute pain treatment might not be as useful for chronic pain management. This is because the main approach in VR for acute pain is to use the VE for pain distraction so that the users are immersed in an environment resulting distraction from their pain. On the other hand, it is not possible to distract chronic pain patients from their pain all the time. Thus, there is a gap for a solution that can help chronic pain patients benefit from similar technology. Additionally, most of the biofeedback systems designed to help people regulate their anxiety or pain by relaxation, do not follow a systematic approach such as MBSR for biofeedback training. Consequently, a VE equipped with the right well-known systematic pain management approach could potentially help patients to manage their pain in a more robust and effective manner.
Chapter 3. VR technology for chronic pain management

The literature supports the idea that technology, specifically VR, can be effective in decreasing and managing acute pain [11]. Could VR be used to manage chronic pain as well? VR designed to address acute pain often utilizes distraction as the approach for managing and decreasing pain; however, unlike acute pain, chronic pain is continuous and the patients might experience it for the rest of their life. Since it is not practical to distract a chronic pain patient for 24 hours a day, another approach must be used. Mindfulness meditation is a well-known approach for pain management that does not aim to distract patients from their pain. Rather it assists them to be aware of their pain and manage it. On the other hand, there is concern that patients might not take mindfulness meditation seriously or might be discouraged from pursuing treatment after failing to see short-term effects. We designed a system that would help people perform meditation by exposing them to a VE during the process. Using the VE, we visually displayed their progress during mindfulness meditation. Consequently, the patients would be aware of any success even it was not on a large scale. We used biofeedback to monitor patients’ emotional and sympathetic responses to change the visual presentation in the VE. The main research question we were seeking to answer was, “can VR combined with biofeedback be used for managing chronic pain?”. To design a system that would be able to answer this question, we conducted two sub studies that contributed to the final design of our VR environment (main study).

3.1. Sub Study 1: Right type of visual feedback for the biofeedback system

In this study I wanted to know what type of visual feedback is more appropriate for biofeedback system whose aim is to help people relax. I hypothesized that “Ambient visual feedback that distributes user attention during relaxation is more effective than a non-ambient feedback”. The assumptions underlying differing approaches to interface
design result, in part, from how attention is managed and categorized using theories from media studies. We proposed the term ‘intraface’ to refer to biofeedback, or other interfaces that are designed to support users who direct their attention inward to their inner physiological states [41]. These intrafaces are intended to support the users’ task of learning how to change their inner or interoceptive states. Early biofeedback devices displayed a graph, a wave, or a sonic tone as their working intraface. More contemporary biofeedback devices offer a number of ways in which the information can be represented including numbers, graphs, smiley faces or more abstract images. In our contribution, the role of representing feedback data in abstract forms is compared in an experiment using Neurosky’s brain signal acquisition device. The device picks up the brain signals associated with relaxation, attention, and blinking. Although preliminary, the results suggest that mapping biofeedback data from a brain-computer interface (BCI) to highly abstract ambient animations is more effective for relaxation than mapping it to a highly familiar symbolic smiley face icon or to a progress bar. We propose that the relative success of the abstract ambient animation can be explained by the fact that this representation of biofeedback data is in the form that requires the least amount of outward attention to process (i.e. ambient animation distributes the attention of the users). Designing biofeedback interfaces that avoid externalizing a users’ attention enables users to continue to direct most of their attention to their inner physiological states. Because this task can be relatively difficult for new practitioners, the design of the intraface with regard to how it handles visual feedback information should require as little attention as possible from the viewer.

In order to assess whether users are able to focus better on their interoceptive states if their biofeedback data is represented as abstractions, we conducted a user study. The study used a BCI that monitored meditation status originating from the brain during relaxation. This BCI then maps brain activities to a visual representation for users feedback. Twelve participants were exposed to three types of feedback: a progress bar showing relaxation levels, a smiley face showing more happiness when in a more relaxed state, and an abstract ambient feedback changing color smoothly as the users meditated. As the control group, four people were monitored without being exposed to any feedback. Each group viewed a different representation of biofeedback data to convey their state of relaxation. The results showed that subjects achieve a higher level of relaxation when they used an ambient feedback visualization compared to the other
conditions studied. We suggest that this has to do with the role that visual attention plays in each of the treatments. For the smiley face feedback condition, the visual stimulus could be strongly attended to, namely the curve of the mouth and the color of the face.

Moreover, the smiley face is a schematic face, and is thus a highly familiar symbolic cue. Cues like these are often referred to as a gaze cue, as they appear to be processed faster and more accurately than others. They are thought to be so well-learned – even overlearned – that although responses to the cues may seem reflexive, they are actually automatic [42]. If this is true, and if gaze cues are more related to goal-directed attention than stimulus-directed attention, then why does ambient feedback function better to support users’ attention to their interoceptive processes? First, unlike direct cues, gaze cues persist for relatively long periods of time, and do not produce inhibition of return [43]. Second, the human face is the most important social stimulus that people process [44], and is fundamental to social cognition. Thus, schematic faces actually function to direct attention, or by “popping out,” call attention to themselves. Although schematic faces are thought to support task-oriented attention [45], the biofeedback task used in our study may be so qualitatively different from those used in other attention studies that the faces function as a unique case. Put another way, when the task is to try to focus one’s attention inward, toward one’s interoceptive senses, the recognition of a face, no matter how schematized, implies that that we are impelled to look back at its highly salient visual features. In this case, the schematic face functions more like a stimulus that cannot be easily ignored. In addition, the fact that the stimulus is a face means that it bears visual features perceived as a facial feature, one that users can attend to in a focused manner.

In contrast, the ambient video distributes visual attention across a wider range of the visual field. In addition, this feedback has no specific element to focus on. Also, the biofeedback changes slowly and continuously, frame-to-frame. Slow changes are difficult to attend to, particularly when the changes are taking place in visual stimuli that do not contain a clearly identifiable central object of interest. Thus, in the ambient feedback condition, attentional resources that could be devoted outward to highly salient visual features can be instead directed inward towards managing the internal sense of relaxation, with occasional reference to the color and general appearance of the ambient video.
The NeuroSky EEG sensing device generates the numerical measures of relaxation. The relaxation measure for the sensing device was developed at NeuroSky’s labs by having a number of subjects enter a relaxed state, then recording a sequence of raw sensor readings while the subjects were in this state. A neural net recognizer was trained on this set of subject data, and the output of this trained neural net is the relaxation reading. The advantage of using this device for our study was that we did not have to train our own machine learning system to recognize raw readings as “relaxed” or otherwise. However, the disadvantage of using NeuroSky’s recognizer is that we had to trust that the NeuroSky device accurately measures what it claims to measure. Thus, we plan in future work to compare NeuroSky’s measures with data from other biofeedback devices.

We observed that subjects almost always attended to the progress bar and to smiley faces, but not to the ambient animation. For reasons that are unclear, subjects tended to look at the animation, close their eyes, and look back at the animation from time to time, ostensibly for updates from the feedback. It is unclear whether this resulted from the type of feedback representation: the progress bar and smiley face may have appeared to users to be more “formal,” while the animation may have been perceived to be more informal, especially since one-to-one data mapping did not appear to be evident.

Differing approaches to interface design operate on underlying assumptions of how attention is directed and managed. We draw upon a theory from media studies that have characterized these approaches as transparent windows into the information displayed, or as mirrors that demand that users pay attention to the interface itself, in some cases including reflections of users themselves in the interface. Interfaces designed for contexts that support users usually demand the unfamiliar task of directing users’ attention inward, to their physiological processes, as if biofeedback should call as little attention to the users as possible. This enables users to maintain focus on their inner states, and on their ability to learn how to change them. Biofeedback presents a challenge in that the feedback tends to split attention between the representation of the feedback and the users’ inner states.

Results of our study suggested that mapping biofeedback data from a brain-computer interface (BCI) to highly abstract ambient animations is more effective than
mapping it to a highly familiar symbolic smiley face icon or to a progress bar. The relative success of the abstract ambient animation over the schematic face or progress bar may be due to the fact that ambient representation of biofeedback data requires the least amount of attention from the users. Therefore, biofeedback interfaces should be designed so that they require the least amount of attention, supporting the need of users to handle the task of directing the majority of their attention towards their inner physiological states. This study helped us to better design the visual feedback for our VE by distributing users’ attention during the VR experience. In subsequent chapters, the study will be referred to as “Visual Feedback Types”.

3.2. Sub Study 2: Choosing the appropriate VR equipment

Several technologies exist which enable developers to build stereoscopic immersive environments. To engage users in a more efficient manner, we were especially interested in making our Virtual Environment (VE) immersive. HMDs are a common choice for displaying immersive VEs and have evolved increasingly in recent years. We also considered using HMDs as our visual medium; however, during focus groups in which we acquired patient’s opinions regarding our study, some issues attracted our attention. Some chronic pain patients suffer from static mechanical allodynia, where they feel pain in response to light touch or pressure. This means that having a HMD on their face is not preferable for them.

Additionally, HMDs are usually heavy and patients cannot bear them for long periods of time, making them impractical. There have been notable improvements regarding this issue, especially after the Oculus Rift was introduced. Still, that HMD as of writing this thesis, was not ready to be utilized by consumer markets and lacked the resolution needed for an acceptable immersive VR experience. Hopefully, Oculus Rift’s recent acquisition by Facebook will help it to reach consumer markets in coming years.

Furthermore, in some cases the level of immersion increases in a way that actually causes nausea for users. This is particularly important to us since chronic pain patients are even more sensitive to such phenomenon than the general public. Motion sickness in VR usually occurs when there is no real physical action, even
though it is induced in the VR [46]. In this case, motion sickness is referred to as visually induced motion sickness.

To address these issues, we considered using a 3D-enabled display developed by Firsthand Technology called DeepStream 3D. The display, despite being close to the users, does not need to physically touch the users. We installed the device on a movable adjustable arm in order to relieve the users from bearing the weight of the HMD, while the device rested just in front of the viewer’s eyes. Figure 3-1 demonstrates our setup in use. We hypothesized that “DeepStream induces less discomfort comparing to Oculus Rift HMD”

![Figure 3-1. The DeepStream 3D display setup](image)

To ensure that this setup is more effective than other accessible HMDs, a study was led by Xin Tong et al. in our research laboratory to find out if DeepStream 3D is more convenient for users [47]. During the study we compared DeepStream to Oculus Rift HMD in terms of physical discomforts. Initially we hypothesized that DeepStream would induce less physical discomfort. To assess this hypothesis, 20 participants from a convenience sample were recruited to participate in an Oculus Rift vs. DeepStream comparison study. The experiment was meant to examine the
users’ experience of HMDs and a 3D display to figure out which one provided the most optimal experience.

The results suggested that participants using the Oculus Rift HMD had a higher level of visually induced motion sickness comparing to DeepStream; however, follow-up discussions with the participants indicated that the HMD felt more immersive and participants also reported a greater degree of freedom for movement. Additionally the fact that the users did not have to sit still in front of DeepStream for a long period of time was also found to be more convenient.

This study helped us to choose the more appropriate VR display for a VE that would suit chronic pain patients' needs. The study will be addressed as “The Comparison Study” in subsequent chapters.

3.3. Main Study: Virtual Meditative Walk

Upon finding out which type of biofeedback system, feedback type, and VR equipment we needed, we designed a VE which we called “Virtual Meditative Walk” (VMW). VMW is an immersive VE that aims to help chronic pain patients self modulate their pain, ideally to decrease pain, and also to increase measurable aspects of quality of life. I hypothesized that “VR in conjunction with biofeedback and MBSR helps chronic pain patients manage their pain”. The system assists patients in performing mindfulness meditation while being exposed to a VE and having their stress level monitored. Chronic pain patients tend to have higher level of stress that is measurable using GSR technology, and the more pain there is, the more likely it will contribute to patient stress levels. Consequently, being able to control stress can help patients control their pain. The well-known practice of mindfulness meditation helps patients regulate their stress levels in a healthy manner. During meditation sessions, we monitored GSR levels of patients and used this data to control the dynamics of the VE in real-time. This real-time biofeedback system allowed patients to see their progress as they performed mindfulness and encouraged them to pursue the practice. During a session, the patient saw a foggy forest, with the fog representing the patient’s GSR level. As the stress level
went down, the fog faded away, and this indicated that the patient was in a meditative state. The fog indicated the cause and effect mechanism of biofeedback in the VE. Based on the sub study 1, the fog animation was designed with abstraction in mind. The fog aimed to distribute the attention of the user while showing the changes of GSR in real-time.

Although not documented, earlier design of the VMW had the fog dissipating in reverse. That is, the fog would increase as the user relaxed. It was assumed that this would work because for walking meditation (with out technology), users must be able to see their surroundings, but they just attend to "milestones" or familiar paths, trees or objects; the rest of their attention is devoted to intentionally focusing on breath, stepping, specific sounds, or so on. Pain Studies Lab members at SFU who practice walking meditation described it as "knowing where I am walking, but almost as if the path and forest were blurred or hazy." Thus, we felt that having the fog indicate (dissipates) that the user is relaxing would be better since there would be less to pay attention to. However, when anecdotal studies were conducted with lab members, it was quickly obvious that this was not the case because more fog caused users, esp. female users, a mild sense of uncertainty and concern. That is, because they couldn't see the path and forest well, they felt they had to be more attentive. Being more attentive defeats the purpose of relaxation as the first sub study observations indicated that the more attentive the users are during relaxation, the less relaxed they would be.

I hypothesized that by performing this practice, patients would be able to better manage their pain. With more practice, patients would become better at managing their pain by putting it into the background of their mind. As of writing this thesis, there existed no universal way to treat chronic pain or to make the pain truly go away; however, I hypothesized that the pain could be self-modulated using biofeedback and VR. In a VR setting, the social and physical limitations imposed by chronic pain are somewhat mitigated, and the patients in our studies could perform their daily routines with a capability similar to what they experienced before developing their chronic illness.

3.3.1. **Biofeedback technology**

We used the Procomp Infinity biofeedback device to measure GSR level of the patients in real-time. The device was created by Thought Technology and supports
various inputs such as EEG and heart rate variability. However, we only utilized the GSR slot for the purpose of the VE we developed. Figure 3.2 demonstrates the device along with its GSR sensors strapped to user’s fingers.

![Procomp Infinity biofeedback device along with GSR sensors](image)

**Figure 3-2. Procomp Infinity biofeedback device along with GSR sensors**

The Procomp Infinity biofeedback device comes with an application called Biograph that enables users to see GSR signals in real-time. Figure 3-3 demonstrates a Biograph real-time signal. Additionally, Thought Technology provides an SDK to allow developers to code against device input sensors and read data flows in real-time. The functions needed are embedded inside a Microsoft Windows Dynamic Link Library file (DLL). The DLL enables programmers to open network sockets for data communications, which is what we used to create a bridge between GSR sensors and the VE. Since the communication channel is based on TCP/IP standard, the data can be exchanged among different platforms and devices, even in remote distances if necessary. The VE, which was designed and coded in Unity game engine, used the socket we developed to access stress levels of users during several user studies.
3.3.2. **Visual design**

The VMW was designed using 3D Studio Max and Maya applications and imported into Unity as assets for further development. Unity is a game engine that enables developers to build cross-platform games. It supports a wide variety of platforms including Windows, OS X, Linux, iOS, Android, Xbox, Playstation, in addition to many web browsers. This flexibility would give us a high degree of freedom to port our system to any platform in future.

In our study, the VMW takes place in a calm, 3D simulated forest with a lengthy dirt pathway for the users to walk along. The users experience virtual walking by seeing the VE through a first-person camera view as they walk along the path. Figure 3-4 demonstrates the animation path of first-person camera. As the session starts, the camera traverses along the path in 20 minutes while the patient is instructed to perform mindfulness meditation. Generally, 15 up until 20 minutes is a common duration for MBSR practice [48][49][50]. Inside VMW VE, 12 minutes of the trial is accompanied with the MBSR narration and the rest of the session is accompanied by an ambient relaxing music and visuals. Figure 3-5, figure 3-6, and 3-7 show images from the beginning, the middle, and the end of the trial respectively. Additionally, an animation was created within the environment that resembled fog. During the walk, the VE changes between a
clear to a foggy forest. This state of the animation is controlled by the data flowing from the TCP socket.

The VMW Unity project gets its input from the TCP socket that I coded. As mentioned earlier, the socket carries GSR information reported by Procomp Infiniti in real-time. At the beginning of the trial, the VMW establishes an average from the incoming GSR over one minute and constantly monitors changes. As the GSR level increases, the fog in the VE fades, representing a less relaxed condition for the users. As the users’ stress decreases, the fog fades in a gradual fashion, accommodating for meditative states.

3.3.3. Sound design and narration

The audible narration in the VMW heavily influenced how the graphics were decided upon. The track used in the VMW was carefully selected from hours of mindfulness meditation audio tracks derived from the pain management series by Kabat-Zinn. The Narration is 12 minutes long and instructs listeners to focus on both their breathing and their inward experiences while following mindfulness practices. The goal of mindfulness practice is to delve deeper into one’s awareness of how the mind and body are united and how the mind itself can be a factor in stress-related disorders such as chronic pain. MSBR utilizes yoga as the channel to stop both halt and reverse the effects of a sedentary lifestyle, especially for people suffering from chronic pain. The MSBR practice was initiated at University of Massachusetts Medical Center in 1979 and is now being practiced in 200 clinics across the world [51].

In addition to mindfulness meditation narration, we embedded an ambient audio track of relaxing music inside the environment to enhance the experience for the listener and to further assist them in reaching a more meditative state.
Figure 3-4. Perspective showing the VMW path.

Figure 3-5. The beginning of the VR environment inside VMW.
Figure 3-6. The VE in the middle of the trial.

Figure 3-7. At the end of the trial, the user observes a relaxing landscape in which the grasses sway smoothly.
Chapter 4. Experimental design & Results

In this chapter I describe the experimental design approaches I took when conducting studies leading to VMW study. The goal of each study was described in the previous chapter.

4.1. Sub Study 1: Visual feedback types

We used MindWave Mobile from NeuroSky Inc. to acquire neural brain activity associated with relaxation state. The device has been designed for practical applications of BCI, and consists of a dry electrode that picks up EEG signals and transmits data to the receiving end via Bluetooth technology (fig. 4.1).

![MindWave Mobile (side and front view)](image)

Figure 4-1. MindWave Mobile (side and front view).

Participants were taken from a convenience sample comprised of sixteen male and female university students between the ages of 21 and 26 (M = 23, SD = 3.49) with no previous meditation or biofeedback experience. They were recruited using Doodle event manager. Participants were briefed about the experiment via email before arrival.
To assess different types of visual feedback in a brain-triggered system, I designed a between-subject experiment. The independent variable was the type of feedback or control group that the participants were randomly exposed to and the dependent variable was the level of relaxation in a percentage reported by NeuroSky’s MindWave Mobile. I developed three visual types of feedback using the Processing programming language. The three feedback types consisted of a progress bar, an animation of cartoon face, and a slow moving abstract animation.

4.1.1. **Control group**

In this group, participants were instructed to relax by breathing deeply and trying to keep their mind free of distractions. They were not exposed to any visual feedback during the relaxation process.

4.1.2. **Progress bar**

Participants of this group were instructed to look at a progress bar which showed how relaxed a participant was during relaxation (fig. 4.2). The more relaxed the participant was, the more the progress bar filled. A fully filled progress bar indicated the most relaxed state, and the bar was presented on a scale from 0 to 100.

![Progress bar](image)

Figure 4-2. The amount the bar is filled directly correlates with the participant’s relaxation state. An empty bar represents a state of agitation, and a fully filled bar represents the most relaxed state.

4.1.3. **Smiley face animation**

In this group, the percentage of relaxation affected the animation of a cartoon-like smiley face. When the participant was less relaxed, the face looked sad, dark, and gray.
As the participant reached a more relaxed state, the face became happy, light and more colorful (fig. 4-3).

![Image](image.png)

Figure 4-3. The image gradually transitioned between these three images.

### 4.1.4. Ambient feedback

The relaxation level in this group was mapped to a video that changed color with respect to participant's relaxation status. The original video constituted abstract animations and was meant to be the main focus of participant's attention (fig. 4-4). As the participants moved from a non-relaxed state to a relaxed state, the colors of the video changed from red to orange to green to blue respectively. The goal in this mode was to display the feedback in a passive and implicit yet informative manner.
Figure 4-4. The top left image (red) represents agitation. As the users relax, the image transitions to the bottom right image (blue), which represents the most relaxed state. This slow-moving animation does not offer any one area that demands more attention than any other area.

4.1.5. Procedure

I randomly assigned each participant to a feedback type and recorded relaxation levels as a percentage for five minutes. The sampling rate provided by NeuroSky MindWave is presented as one data point per second; hence there were 300 data points for each participant at the end of the trial. This was saved as plain text file for further analysis. NeuroSky MindWave conveys the patient’s relaxed mental state with percentages by utilizing a proprietary algorithm called eSense. According to NeuroSky, eSense is constituted of artifact rejection and machine learning methods that can distinguish between higher cognitive mental states such as meditation and attention. The manufacturer of MindWave conducted an extensive study to distinguish when participants are in a calm and relaxing state from when they are agitated by providing relaxation levels with percentages [52]. As opposed to conventional raw EEG that requires pre-processing along with machine learning techniques to classify mental states, this output is used for practical application-oriented studies.
4.1.6. **Statistical analysis**

I initially averaged 300 data points for each participant into a single value representing the relaxation level. The independent variable in this study is the type of the visual feedback that the user is exposed to. The dependent variable is the averaged relaxation level during the entire session ranging from 0 to 100 (0 means the least relaxed, 100 meaning the most relaxed state reported by the EEG device). To test for potential significant differences among means of relaxation levels, I ran a one-way analysis of variance (ANOVA) test. To further investigate the effects of each feedback, I ran a pair-wise Tukey HSD test in order to compare all pairs of feedback types.

4.1.7. **Sub Study 1: Visual Feedback Types Results**

Primary observations of data are demonstrated in figure 4.5. The results suggest that the participants who are exposed to ambient feedback have the highest level of relaxation compared to the other visual feedback scenarios and the control group (Mean= 77.61%). The Smiley Face mapping (Mean=68.89), Progress Bar (Mean =58.68), and the control group (Mean=46.78) are rated less relaxed, respectively.

The results of the one-way ANOVA suggest that there was a significant effect of independent variable feedback type on the dependent variable relaxation level for four conditions F(3,12)=23.74, p<0.0001 at the p value <0.05. Figure 4.6 demonstrates the results of analysis for all of the conditions.

The results of pair wise Tukey HSD test suggest a significant difference between ambient feedback and other feedback types. Table 4-1 provides the results of the Tukey test along with the statistical significance at p value <0.05. The test results also support the idea that the difference between progress bar mapping and the face mapping is not statically significant with regards to our study.
Visual biofeedback treatment groups

![Graph showing average relaxation level for each participant along with its standard deviation. The average relaxation level for each feedback condition is also represented.](image)

**Figure 4-5.** Average relaxation level for each participant along with its standard deviation. The average relaxation level for each feedback condition is also represented.
Figure 4-6. Visualization of data points for different participants in all conditions.

Table 4-1. Comparing feedback types pair-wise using Tukey HSD.

<table>
<thead>
<tr>
<th>Feedback type 1</th>
<th>Feedback type 2</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient</td>
<td>Control group</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Ambient</td>
<td>Progress bar</td>
<td>0.0013</td>
</tr>
<tr>
<td>Ambient</td>
<td>Face</td>
<td>0.0139</td>
</tr>
<tr>
<td>Face</td>
<td>Control group</td>
<td>0.0029</td>
</tr>
<tr>
<td>Face</td>
<td>Progress bar</td>
<td>0.5205</td>
</tr>
<tr>
<td>Progress bar</td>
<td>Control group</td>
<td>0.0329</td>
</tr>
</tbody>
</table>
4.2. **Sub Study 2: The VR equipment comparison study**

In this study, two different VR display technologies were compared in terms of sense of immersion, fatigue, and comfort. The goal was to choose the better type of VR equipment that was appropriate for the main study so that least amount discomfort is experienced by chronic pain patients.

In this study Tong et al. utilized a repeated-measure design pattern to assure that participants would be exposed to all treatments (i.e., using the DeepStream and Oculus Rift). My main contribution in this study was to setup the DeepStream display, help with the questionnaire and study design, and assist the other researchers to conduct the sessions. Considering the fact that the use of one condition can potentially affect the outcomes of another, the order in which the participants were exposed to different conditions was also considered as an independent variable making two-way mixed ANOVA our statistical analysis approach. The variable that we measured as the dependent outcome was the participant’s level of motion sickness during their VR experience.

Upon arrival, participants were given a preliminary introduction to the study. They took turns trying both the Oculus Rift and the DeepStream devices, trying each for ten minutes with a five-minute break time. During each session, participants were exposed to the VMW simulated environment and filled out a questionnaire after each condition. Table 4-2 indicates two treatment conditions.

<table>
<thead>
<tr>
<th></th>
<th>First Session</th>
<th>Second Session</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group #1</strong></td>
<td>Oculus Rift</td>
<td>DeepStream</td>
<td>5 female / 5 male</td>
</tr>
<tr>
<td><strong>Group #2</strong></td>
<td>DeepStream</td>
<td>Oculus Rift</td>
<td>5 female / 5 male</td>
</tr>
</tbody>
</table>
After each session, each participant filled out a questionnaire by which the study investigators gathered data and performed appropriate statistical analysis. The questionnaire was inspired by the Simulator Sickness Questionnaire (SSQ) introduced in [53] (the questionnaire poses 16 questions regarding general discomfort, stomach awareness, fatigue, and various other relevant factors -- headache, eye strain, difficulty focusing, nausea, sweating, difficulty concentrating, fullness of head, increased salivation, dizzy with eyes open, dizzy with eyes closed, vertigo, blurred vision, and burping). The type of the VR equipment which the users were exposed to was the independent variable in the study. SSQ was the dependent variable for measuring general discomfort. Additionally, sense of immersion, field of view, and visual effects were the dependent variables for measuring immersion discomfort. The three main components that contributed to the SSQ calculation were oculomotor problems, nausea, and disorientation. Additionally, participants rated five statements related to sense of immersion, screen resolution, field of view (FOV), tightness, and weight during Oculus Rift session. They also rated three statements related to sense of immersion, screen resolution, and FOV during the DeepStream session. All discomfort questions were formed as statements rather than questions, and participants rated them using the likert 11-point scale, with 0 meaning “not at all” and 10 meaning “very much”.

4.2.1. Sub Study 2: The comparison study results

Motion Sickness (Descriptive Analysis)

Figure 4.7 from [47] represents the preliminary results from experiment treatments. The oculomotor and disorientation symptoms in the HMD were clearly visible. Additionally, all of the motion sickness measurements of DeepStream — nausea (M = 3.23, SD = 3.61), oculomotor (M = 6.15, SD = 4.71), disorientation (M = 4.35, SD = 4.37) were lower than the HMD — disorientation (M = 7.44, SD = 6.24), oculomotor (M = 8.28, SD = 6.06), and nausea (M = 4.98, SD = 4.41). Consequently, results suggested that HMD induced more motion sickness in users in comparison to DeepStream.
Other usability comparisons (Descriptive Analysis)

Figure 4-8 from [47] represents the preliminary results regarding usability discomfort for two experiment treatments. The results suggest that participants experienced less discomfort using DeepStream display ($M = 6.85$, $SD = 1.67$) in comparison to the HMD condition ($M = 5.10$, $SD = 2.69$). Interestingly, participants considered the field of view (FOV) ($M = 6.75$, $SD = 2.42$) and sense of immersion of the HMD ($M = 6.00$, $SD = 3.20$) more comfortable in comparison to the FOV ($M = 5.35$, $SD = 2.37$) and sense of immersion ($M = 4.40$, $SD = 2.85$) for DeepStream. Furthermore, it was clear from the results that DeepStream had no weight or tightness while the HMD presented some level of discomfort due to its tightness ($M = 2.60$, $SD = 3.55$) and weight ($M = 3.50$, $SD = 3.62$).

Motion sickness (Inferential Analysis)

Based on discomfort levels as self-reported by participants, two-way mixed ANOVA was utilized to test whether the type of VR displays and the sequence in which they were displayed to the users resulted in a statistically significant difference in effect on participant discomfort.
Figure 4-8. Usability measurements for two conditions.

Based on the SSQ measurements, DeepStream immersive display had a significantly lower SSQ value than the HMD (M = 13.73, SD = 12.01), F(1, 18) = 7.45, p = .014, r = .63 when compared to the HMD (M = 20.70, SD = 16.41). Consequently, the results suggested that motion sickness in DeepStream was significantly lower than HMD. According to SSQ measurements, the main effect of the sequence in which DeepStream and HMD were presented to the users was not significant — F(1, 18) = 2.18, p = 0.827, r = .53.

**Sense of immersion (Inferential Analysis)**

The main effects of two conditions of immersion discomfort as reported by the participants were significantly different. The DeepStream display had a significantly lower sense of immersion comfort in comparison to the HMD F(1, 18) = 5.21, p < .05, r = .69. Additionally, the main effect of the sequence of the displays relative to immersion discomfort was not significant — F(1, 18) = .34, p = .56, r = .60.

This study compared two different 3D stereoscopic displays in terms of discomfort. Based on the results and our observations, the Oculus Rift HMD provides a much better sense of immersion. However, it lacks adequate resolution. The Oculus Rift adds weight tolerance burdens for the users, creates a feeling of tightness, and induces virtual nausea. In comparison, DeepStream does not have these problems, which are crucial to consider when conducting studies on chronic pain patients. Generally
speaking, for non-patient, regular VR users, the Oculus Rift would be a better choice of device. For chronic pain patients, the choice depends on the specific type of pain that the end-user normally experiences. For allodynia patients or people who cannot tolerate any extra weight on their head, it is better to use DeepStream as the 3D display. However, in the conditions where weight and the sense of touch are not an issue and where sense of immersion is of importance, the Oculus Rift would be more favorable.

4.3. Main study: VMW

After properly understanding how the design of a VMW should be implemented, I designed an experiment to test my hypothesis. Similar to any other medical practice, studies conducted over long periods of time are required to prove the long-term effects of our approach on pain. That is, however, outside the scope of this thesis. Still, I designed the study in a way that would be amenable to a long-term repeated measure design approach.

4.3.1. Participants

The participants in the study were thirteen chronic pain patients aging from 35 to 55 (mean=49, SD=8.2) who were recruited using flyers and the assistance of Dr. Pam Squire located in Vancouver, British Columbia. As part of the process, all participants signed a consent form to ensure that their participation was completely voluntarily and has no effect on their current relationship with their doctor. Based on statistical measures, the best number of participants relies on how much statistical power researchers are seeking. If a researcher cannot conjecture that, the best approach would be to conduct their study on as many participants as possible. I had no prior statistical data and as a result I aimed for twenty participants. I believed this to be a realistic sample given the timeline available for the study. However, I later realized that conducting the study on patients took significantly more time that I anticipated. Difficulties arose due to different factors such as patients feeling pain while sitting for a long period of time, patients finding the environment to be unappealing, or patients finding the required questionnaire to be frustrating. Some patients were also unable to
use computers to fill out surveys. These factors resulted in us conducting the study on thirteen patients which we believe to be an acceptable amount considering similar VR user studies. The source of pain for participants was mostly from their lower back, legs, hips, neck, and shoulders.

4.3.2. Conditions

The independent variable in VMW study was exposure to VR. Seven participants practiced mindfulness meditation while being exposed to VR, while the other six acted as the control group and only listened to mindfulness meditation. This was to ensure that if there were any changes, they are not solely made by mindfulness but also by engagement with the VE.

Table 4-3. The number of conditions and their participants

<table>
<thead>
<tr>
<th>Condition</th>
<th>Number of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mindfulness practice with VR</td>
<td>3 Male / 4 Female</td>
</tr>
<tr>
<td>Mindfulness practice with no VR</td>
<td>3 Male / 3 Female</td>
</tr>
</tbody>
</table>

4.3.3. Apparatus

I used DeepStream from Thought Technology as our 3D display for traversing the VMW environment. For the stereoscopic experience I used 3D vision, a tool from NVidia that enables users to experience a 3D environment using shutter glasses along with the drivers that provide stereoscopic vision for any Direct3D graphics including Unity 3D games.
The reason I chose DeepStream as the VR equipment originates from the sub study 2. The results of the sub study 2 indicated that DeepStream provides more level comfort for the users. On the other hand, DeepStream had less sense of immersion and FOV. For the purpose of this study, comfort of chronic pain patients was one of my priorities otherwise the results might had potentially been biased. The DeepStream 3D display provided a descent resolution, had no touch with the skin, and introduced no weight burden. One of the main problems with DeepStream was that it was not flexible in terms of movement and most of the users had to bend in order to view the display. This could induce pain itself since a lot of patients could not sit in a bending manner for the entire session. To tackle this issue, I made some changes to the original DeepStream by installing it on a heavy-duty movable arm. The moveable arm was adjustable horizontally and vertically and could be moved easily. Therefore, before every trial, I adjusted the display for patients to enhance their comfort.

![Participant using DeepStream](image)

**Figure 4-9. Participant in the VMW study using DeepStream and NVidia 3D**

### 4.3.4. Procedure

Upon arrival of the participants, I introduced them to the study and presented them with the consent form giving them a chance to consider all the pros and cons of the
study based on the guidelines enforced by the SFU ethics board. After the approval of each participant, I presented them with the pre-trial questionnaire that consisted of questions asking about their pain experience and its impacts on their physical and social life. There are a number of approaches that can roughly measure the pain experience such as the McGill pain questionnaire and the pain disability index as well as a NRS. I planned to use the McGill pain questionnaire and NRS methods since they are well known and accurately expressed the pain in a quantified manner. After patients rated their pain level and its intensity, they were randomly either assigned to the control group or the VR group to practice mindfulness meditation.

The control group listened to the mindfulness meditation while being equipped with GSR sensors and sitting on a chair in a relaxing manner. Although the data from the control group was saved, it was not used since there was no biofeedback involved in this condition. The data was saved merely to keep the conditions as similar as possible given the difference of the VE in one condition. The mindfulness practice took twelve minutes for each participant, and the participants rated their pain level afterwards using the same questionnaire as was used prior to the session.

The VR group also listened to mindfulness meditation practice during the session, but was also exposed to VMW VE for twelve minutes while I observed their GSR level and updated the environment based on the flow of real-time skin conductivity (i.e., the environment was updated based on their stress level). The goal was to help participants to regulate their inner emotional states towards a healthy manner. As their skin conductance level dropped, the fog in the VMW eventually faded away and as conductance increased, the fog faded in. After the session, the participants rated their pain level once again.

4.3.5. Statistical analysis

I planned to calculate the pain before and after the session using two methods independently.

The McGill Pain Questionnaire: This method includes three rudimentary categories of descriptors — affective, sensory, and evaluative. The questionnaire contains an intensity meter as well as other elements that can determine the characteristics associated with
pain. Patients use the questionnaire to express their pain subjectively. This scale was initially created to provide a quantitative method to measure pain [54]. The questionnaire calculates a pain score between 0 and 78 (0 meaning no pain and 78 meaning maximum amount of pain). The intention was to retrieve one McGill scale before and one after the session and compare the mean of differences with the control group condition to find out if VR and biofeedback can be affective for pain reduction.

11-point Numerical Rating Scale (NRS): One of the classic methods for self-reporting pain in patients, the participants simply rated their pain from 0 to 10 before and after the VR or Control group condition. 0 means no pain and 10 means worst pain possible. The “No Pain” and the “Worst pain possible” labels were provided for the patients in the questionnaire in order to help them rate their pain on the same scale in a subjective manner. Since chronic pain has physiological, neurobiological, psychological, and social roots, it is very difficult to come up with a unified method to measure the pain. Additionally, the pain experience is subjective and variable on daily basis, which makes measurement a very complicated process. However, researchers usually use NRS as one of main pain assessment instruments [55][56][57][58][59][60]. NRS is also easy to understand, fast to fill out, does not need translation for international use, and does not introduce significant cognitive load for chronic pain patients.

I used the calculated means of differences between pain ratings before and after session in a t test to see if there was a statistically significant difference between the patients in the control group and the ones in VR group.

I only asked patients to self-report their pain before and after the trial. The reason that I did not ask patients to report their pain during the practice was because it takes time for the users to get used to the idea of biofeedback and MBSR and it is usually effective if MBSR is practiced for at least 15 to 20 minutes. As a result asking patients to self-report their pain during smaller chunks of time was not useful for answering my research question.

Although GSR data was used to control the biofeedback system in VMW, it was not used to compare pain levels. The main reason is because GSR is not equal to stress level or anxiety although they could influence it. The assumption in VMW is that to immerse the user in the VE so that stress level has the major influence on the GSR.
However, in the real world that is not possible since the mindset of the users and artifacts affect the GSR data. Consequently, the raw GSR data was not used for comparing two conditions.

4.3.6. Main Study: VMW Results

Descriptive analysis

Figure 4-10 demonstrates the descriptive mean chart of self-reported pain by patients in the NRS (dependant variable) before and after the session for each condition. For the NRS, preliminary results suggest that on average, VR was more effective in management of pain and its intensity (mean=4.71, SD=1.88) comparing to the non-VR condition (mean=7.3, SD=2.73). Table 4-4 shows individual pain levels reported by patients before and after the session along with their designated condition.

Table 4-4. Pain level reported by patients in each condition

<table>
<thead>
<tr>
<th>Group</th>
<th>Pain level reported before trial</th>
<th>Pain level reported after trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>VR</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>VR</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>VR</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>VR</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Control</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>VR</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>VR</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>VR</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Control</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Control</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Control</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Control</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 4-10. The means of pain level before and after session reported in NRS. Each error bar was constructed using a 95% confidence interval of the mean.

**Inferential analysis**

I used the difference of the reported pain level before and after the trials to indicate the reduction in pain, i.e., the difference is the level of pain reduction. I also used a one-way analysis of this difference to calculate the t test for the means of the pre-session and post-session pain level. There was a significant difference in the pain level for Control (M=0.16, SD=1.16) and VR (M=2.71, SD=1.88) conditions; t (10)=2.96, p < 0.05. Results suggest that VR and biofeedback had an effect on pain reduction for chronic pain patients.
Chapter 5. Discussion

In this section I describe and discuss the major finding in the studies I conducted. I also provide my qualitative observations that appeared important for understanding the research flow and developing further technologies for chronic pain management. It is now clear that chronic pain has disrupted life of a considerable amount of people in North America. It is also proposing a considerable financial burden on both the patients and the governments.

In order to develop a practical and effective biofeedback VEs that can help chronic pain patients manage their pain I conducted two sub studies before the main study. The sub studies were meant to make the VMW functionality as robust as possible, thus patients would accept it as an alternative treatment for management of chronic pain. In the visual feedback types sub study, I learnt that the more the biofeedback system distributes the attention, the more relaxed the users would feel. That means if the users attend to a specific visual element in a computer-simulated environment, it will decrease their level of relaxation. That may explain why a lot of people close their eyes when they try to relax or meditate. On the other hand, if visual elements change in a slow and ambient style, it will distribute the attention of the users, resulting a more relaxed state. Using this approach, we can keep the visual cues in a biofeedback setting while assisting users to reach a relaxed state.

Additionally, during various focus groups and interviews with chronic pain patients, I realized that equipment used in VR could be a barrier. Patients may feel nausea, discomfort, and even be unable to handle the weight of the currently used HMDs. To address this issue, my colleagues and I conducted the second sub study to see how we can solve this issue. We compared a hands-free VR display that we hypothesised as a more comfortable solution as opposed to a common HMD available on the market. As we hypothesized, users found the hands-free VR equipment more comfortable, however, it had less sense of immersion comparing to the HMD. I accepted
this trade-off since the comfort of the chronic pain patients due to their sensitivity was one of my priorities.

Two sub studies shaped how the main VR environment should be designed and developed. The feedback in the main study was an ambient one with attention distribution in mind. The equipment to display the VR environment proposed a comfortable setup for the patients in order to prevent potential extra pain inducing stimuli.

5.1. Discussion on VMW

Using the NRS, the results suggested that VR could be potentially useful in helping chronic pain patients to manage and decrease their pain. The method worked because VR, in conjunction with biofeedback and mindfulness meditation, allows patients to see a mirrored version of themselves in a simulated environment and to learn the skill to control their inner emotional states in a healthy manner. One of my goals was to use this method to aid patients in accepting their pain as part of daily life if they were unable to make it disappear using current medical practices. A similar everyday example would be eye floaters that some people see as intruding within their normal vision. The floaters occur as the jelly-like substance inside one’s vision. They can be annoying and frustrating at first, however, it is possible to develop strategies to live with the floaters and put them into background of one’s mind. It may even be possible for those with eye floaters to see normally as if the floaters did not exist. The progress in pain management however, is much more difficult, which is why the field requires multidisciplinary approaches to assist patients in steering pain towards the background of their attention.

Results of the main study would have been even more concrete if scores from the McGill pain questionnaire were also included. During the study, most participants were not willing to complete the McGill pain questionnaire before and after the trial. From my observations, participants found it to be confusing, hard to grasp, and cumbersome to complete. As a result, participants skipped questions or chose random answers simply to finish the task. Consequently, there is a large amount of missing data relating to the McGill pain questionnaire, making this method impractical to use. 10 out of 13 participants filled out merely 30 percent of the questions. The rest 3 filled out about 40
percent of the questionnaire. Alternatively, I had embedded one other approach to collect the desired data, i.e., the NRS. This problem revealed an important consideration; due to the pressure that chronic pain patients are under, any questionnaire that they fill out must be as concise as possible. It should also be as straightforward as possible thus it causes the least amount of cognitive load for patients.

The NRS indicated that patients reported lower level of pain after the VMW practice, however, how does this pain difference report matter? A single trial in VMW might be not as effective in long-term for chronic pain management. A patient might report less pain after the trial but experience his usual pain 4 hours after the trial. However, the VMW aims to help chronic pain patients to learn the knowledge that they can manage their pain operationalized by the MBSR practice. By doing the practice on daily basis, patients can be self-aware of their pain, be able to sustain its level, and ideally decrease it in the long run. The pain reduction reported by NRS is an early step in proving that VR+Biofeedback could be effective in management of chronic pain.

Since Facebook acquired Oculus Rift HMD, there is a renewed interest in VR, and it has a better chance than it has ever had to become affordable while still maintaining its unique features. The most important things designers in the area should consider is:

1. Designers developing VR for chronic pain management should not assume that all chronic pain patients could be classified to some common normative characterization. Unlike diseases such as diabetes, less is known about causes of chronic pain, and there are no cures.

2. Another point designers must take into account is to enhance the sense of immersion while maintaining patients’ comfort. In the setting I provided, the patients had the most level of comfort, however, the sense of immersion was decreased. This could potentially result patients to distract from the VE. This distraction could lead to less productivity during MBSR, potential artifacts in the biofeedback data, and decrease the efficacy of the entire VE setup.

3. A very important factor that designers must consider when developing further technologies is Quality of Life (QoL) measurements. In addition to evaluating a chronic pain management technology against pain reduction, it is also crucial to see how the
developed technology actually makes a difference in patients’ daily life. It also must take into account the social enhancements on chronic pain patients’ lives.

4. One of the major issues that designers must pay attention to is assisting chronic pain patient in physical activities engagement. Some chronic pain patients are afraid of physical activities because they are unaware that if the activity will decrease the pain or would make it worse. This fear is referred to as kinesiophobia. Designers could combine assistive fitness technologies with VR to encourage chronic pain patients engage in physical activities. For instance, patients could actually walk during VMW on a treadmill with high safety measurements.

The validity of GSR as the indication of pain-oriented stress for controlling the biofeedback is also an important issue. I observed the GSR of patients increasing during higher intensity of pain and decreasing as they started meditating in the VR. There were also situations in which the patient reported high level of pain, but they did not necessarily have a high level of GSR. This disparity can be misleading for the biofeedback system coordinating the dynamics of the VR. Other biological observations such as heart rate variability and EEG signals can also be used in conjunction with the GSR to increase the validity and accuracy of the readings and biofeedback coordination.

There were two reasons that I did not choose EEG as the biofeedback mechanism in my studies. 1) EEG technology is extremely vulnerable to noise. This would impact the VE and make it almost impractical for VMW. To use EEG as the cause and effect mechanism, a system is required to monitor numerous electrodes installed on the brain. Additionally, an online noise reduction mechanism along with custom machine learning algorithms is required to interpret the signals originating from the brain. The mentioned research problems are out of the scope of this thesis and therefore EEG was not used for VMW. 2) A considerable number of patients did not feel comfortable wearing a EEG head-band during the study. This would result in a large-scale opt out from the study and a lot of missing data.

All the mentioned studies and researches aimed to introduce the VR technology in general and later on specifically in health domain. Based on the results, attention distraction and biofeedback plays an important role for regulating physiological activities, managing pain, and coping with psychological disorders (e.g. PTSD and anxiety). This
signifies that VR could be helpful for helping patients physically/psychologically, save cost, and decrease potential medication abuse.

5.2. Conducting Studies on Chronic Pain Patients

While I was conducting the VMW study on chronic pain patients, I realized that there are matters that one must pay attention to when conducting studies on chronic pain patients. This is crucial since following a number of guidelines could significantly boost the efficacy and outcome of a study. Additionally, these guidelines would result in potentially less biased results that are also more reliable when quantified. Approximately 90% percent of these observations come from the user studies I conducted and 10% originate from the focus groups we hosted in the Pain Studies Lab.

One of the matters that make conducting user studies on chronic patients extremely challenging is that developing technology is merely half of what is required. The other half of one’s effort should go to preparing the mindset of the patients in order to encourage them to believe in the practice, to join medical user studies, and to continue to come in for their sessions. In order to be able to encourage patients, the researcher must know how to communicate with them and truly show that they care while understanding the patients physically, psychologically, and socially. Despite the designated time for the study, there were times that patients continued to talk with me for up to an hour explaining their pain experience and its implications on their daily life. 8 patients stayed after the trial and asked how they can maintain practicing the VMW. 3 patients were in a hurry to leave after the experiment was finished. 2 patients were very observant and they actually were interested in knowing how the system works under the hood. The patients need to know that you as a researcher care about them and respect their words. The researcher also needs to make the patients feel believed. For instance, chronic pain patients regularly fill out pain reporting questionnaires and us asking the patients to fill out the questionnaires again might make them think that we suspect their sincerity. Consequently, they should be reminded that the instruments are for our use and we do not doubt their condition.

Another issue I noticed during the VMW user study was that a number of patients had problems remaining seated for the duration of the session, as this position induced pain.
3 of the participants told me that they were exhausted sitting during the entire session and the rest were comfortable sitting. This could potentially affect their judgment for rating their pain after the study. Therefore, it would be ideal to present the environment in a way that would allow patients to perform mindfulness meditation in a VE while standing or lying down. Another way to tackle this issue is to consider having short intermissions and split the practice into two sessions. This will give patients a chance to go for a quick walk or readjust themselves to their seats.

It is also important to consider the kind of pain the patients have. For instance, 2 patients had severe neck pain, thus they could not efficiently hold their neck still for the required period of the user study. The 2 patients had to slightly move their necks for resting purposes.

The level of immersion in the VE is also a noteworthy factor. 3 of the patients mentioned that the 3D display made them feel present in the VE resulting a better meditation experience. On the other hand, 2 patients told me that they experienced mild nausea from the middle of trial to the end. This recaps the fact that using a VR equipment that features deeper level of immersion is not probably the best choice for chronic pain patients. To best address the issue, a user study could assist in understanding whether sense of immersion actually results to a better meditation experience. In the study, the level of the VR immersion is the independent variable.

A treatment for pain management must usually be tested a number of times in medical trails in a repeated-measure manner. This requires the patients to follow up all the treatment trials, however, because of the limitations created by the pain, they are sometimes reluctant to pursue all the user studies. To tackle this issue, researchers must provide a convenient situation for the patients (e.g. flexible hours, convenient locations, transit bonus, etc.). Researchers must also help the patients to understand the potential treatment as fully as possible. If the patients are educated about a certain practice, they develop a passion for the cause and there is a better chance that they will follow up the incoming user studies.

Understanding patients mentally and physically could significantly enhance the research results and help chronic pain patients in living with their pain and ideally decrease physical/social implications of chronic pain on their lives.
Chapter 6. Conclusion and future works

Through this thesis, I described a number of approaches and studies that I developed to help chronic pain patients manage their pain using VR, mindfulness, and biofeedback technology.

The comparison study revealed that the DeepStream 3D stereoscopic display had less physical discomfort for the users and induced significantly less motion sickness for them. The usability comparison between the DeepStream and Oculus Rift VR systems indicates potential ways to enhance the properties for VE equipment that have less physical discomfort. This means lighter displays, better FOV, and higher resolution. Although it was indicated that DeepStream was better in terms of physical comfort and usability, Oculus Rift has great potential for pain management/distraction with small fixes. Both displays are still in the development stage and their manufacturers are constantly upgrading the hardware and software for a better user experience. One of the future goals of this particular study is to conduct the same usability comparison on chronic pain patients after applying the feedback from the current study in order to see what patients have to say about each display.

The results of Biofeedback Type experiment indicated that the more the feedback distributes the attention, the more relaxing the VE will be. This study used the MindWave EEG device that encapsulates raw EEG signals into a level of relaxation originating from the brain. While this removes all the machine learning and noise removal efforts, the validity of the relaxation mapping being returned by NeuroSky’s API is not clear. One of the potential future works in this area is to use the raw EEG signals and observe the relaxed state by open source well-known algorithms. Additionally, the types of feedback can be enhanced to be even more abstract and have other sensory elements such as biofeedback-oriented sound. Finally, based on the experimental design, a bigger sample size would increase the validity of the results reported in the study.
Using the results of several preliminary studies, I designed a biofeedback environment to help chronic pain patients observe their inner senses in a visualized manner while learning how to control them. Results of the study suggested that VR and biofeedback combined with mindfulness meditation is a helpful method for decreasing pain. One of the major future works in testing the validity of VMW VE would be to increase the sample size to at least twenty people and add more sessions to the study. This would change the experimental design to a repeated-measure design, which would enable us to better evaluate VR and biofeedback as a skill that can be enhanced over time. VMW has great potential for pain self-modulation and that can be increasingly exploited if mindfulness meditation skills are improved over time.

Another aspect of VMW that could be extended would be the graphics and feedback types used. Some patients reported that they were bored or tired of the monotone environment and some did not notice the changes in fog density very clearly. While the reason for the lack of sudden changes in the virtual environment and feedback was to allow for constant distribution of the attention of the participant, improvements can still be made to the environment and the visual feedback.

One of the main problems relating to the participants was low computer literacy or high level of cognitive load at the time of the experiment. I believe that instead of using new online forms, classic hard-copy forms should be printed and offered to participants. An interesting topic of research would be how to design very intuitive tablet-based questionnaire that any individual with no knowledge of computer science would be able to fill out.

Lastly, studying pain assessment in VR is of great importance. Before performing any further user studies, I believe that pain assessment questionnaires must be rigorously revisited. Additionally, as the literature supports [61], at least two methods of pain assessment are recommended to be used in the evaluation of any treatment.

After user studies on chronic pain patients and medical trials have been completed, our goal is to deploy VMW in hand-held devices such as tablets and smart phones. As mentioned earlier, VMW is designed and developed in Unity, which is a cross-platform game engine that enables us to run VMW on different devices. The commercialized version of VMW runs on hand-held devices and would enable patients
to enhance their mindfulness skills in a self-paced manner. The reason for this future works recommendation is to push VR technology from research laboratories to the end-users. To achieve this goal, one of the best approaches is to migrate the current VE to the devices patients own.

To further expand the biofeedback navigation in VMW, Intelligent Agents (IA) can be used to increase the performance of user experience and accuracy. IAs are software applications with predefined scripts and responses that can perceive the environment in which they are operating, and can perform certain actions autonomously. Agents get information relating to their operating environment from so-called sensors. The IA’s perform reasoning and further processing on the input, and can then affect the environment using elements called effectors in order to reach a goal [62]. Figure 6.1 demonstrates a generic agent workflow.

![Figure 6-1. Workflow of a generic intelligent Agent](image)

An agent uses sensors to perceive an environment and autonomously operates based on actuators toward a goal. They learn or use the knowledge they have to operate. For instance, an alarm agent in a health care setup would have the hospital as its environment, critical care indicators such acute care physiologic monitoring system as sensors, and a “trigger the alarm system” as the action. The goal of the agent in this case is to notify health care practitioners of emergency situations. IAs are based on a concept of Artificial Intelligence (AI), and are programmed to interact with humans. They are initiated by a knowledge base that includes a dictionary of possible different queries, responses, and gestures, enabling the agent to respond to human input in a human-like manner. The IAs support actions such as the obtaining and manipulating of information distributed in a large number of information systems. In other words, they are used to observe an on-going situation, autonomously making decisions on actions to be compatible with the domain that they are operating in, and then executing those actions.
on the environment. In VMW, an IA can be developed to sense different biological inputs such as heart rate variability, GSR, and EEG and make smarter decisions for changing the dynamics of the VE. For instance, by observing the brain signals that are associated with relaxed state of mind and monitoring GSR signals simultaneously, the agent can double check if the data inputs are valid and contain the least amount artifacts. The GSR in this case may indicate higher level of stress and by cross referencing it with the EEG signals, the agent can report to the biofeedback system whether this indication is correct or not. By having more input signals, the agent could even act more intelligently by performing voting algorithms. As a result, the abstract visual feedbacks that the users experience in the VE tend to be more accurate and closer to users' inner physiological states.
References


Appendix A.

VMW Questionnaire

Pain Assessment (McGill pain questionnaire)

Some of the following words below describe your current pain. Choose the words that best describe your pain in each question. Leave out any category that is not applicable.

What does your pain feel like? (Temporal)

- Flickering
- Quivering
- Pulsing
- Throbbing
- Beating
- Pounding

What does your pain feel like? (Spatial)

- Jumping
- Flashing
- Shooting

Incisive pressure

- Sharp
- Cutting
- Lacerating

What does your pain feel like? (Punctate pressure)

- Pricking
- Boring
- Drilling
- Stabbing
- Lancinating

Constrictive pressure

- Pinching
- Pressing
- Gnawing
- Cramping
- Crushing

Traction pressure

- Tugging
- Pulling
- Wrenching
Brightness

- Tingling
- Itchy
- Smarting
- Stinging

Dullness

- Dull
- Sore
- Hurting
- Aching
- Heavy

Sensory miscellaneous

- Tender
- Taut
- Rasping
- Splitting

Tension

- Tiring
exhausting

Autonomic

Sickening

Suffocating

Fear

Fearful

Frightful

Terrifying

Punishment

Punishing

Gruelling

Cruel

Vicious

Killing

Affective-evaluative-sensory: miscellaneous

Wretched

Blinding

Evaluative
- Annoying
- Troublesome
- Miserable
- Intense
- Unbearable

Sensory: miscellaneous

- Spreading
- Radiating
- Penetrating
- Piercing

Sensory: miscellaneous

- Tight
- Numb
- Drawing
- Squeezing
- Tearing

Sensory

- Cool
Which word or words would you use to describe the pattern of your pain?

Tell us how does your pain change with time.

Do the following items increase or decrease your pain?
- Cold
- Damp
- Weather changes
- Massage or use of a vibrator
- Pressure
- No movement
- Movement
- Sleep or rest
- Lying down
- Distraction (TV reading etc.)
- Urination or defecation
- Tension
- Bright lights
- Loud noises
- Going to work
- Intercourse
- Mild exercise
- Fatigue
Which word describes your pain right now?

How Strong is Your Pain?

- ○ Mild
- ○ Discomforting
- ○ Distressing
- ○ Horrible
- ○ Excruciating

Which word describes your pain at its worst?

- ○ Mild
- ○ Discomforting
- ○ Distressing
- ○ Horrible
- ○ Excruciating

Which word describes your pain when it is at its least?

- ○ Mild
- ○ Discomforting
- ○ Distressing
- ○ Horrible
Which word describes the worst toothache you ever had?

- Excruciating
- Mild
- Discomforting
- Distressing
- Horrible
- Excruciating

Which word describes the worst headache you ever had?

- Excruciating
- Mild
- Discomforting
- Distressing
- Horrible
- Excruciating

Which word describes the worst stomach-ache you ever had?

- Excruciating
- Mild
- Discomforting
- Distressing
- Horrible
Pain assessment

Please rate your current level of pain from 0 to 10 (0 meaning no pain and 10 meaning maximum amount of pain)

- ☐ Excruciating