

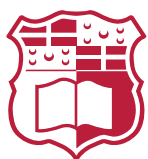
Innovative Pain Management Techniques

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November 2023

*Submitted in partial fulfilment of the requirements
for the degree of Master of Science in Artificial Intelligence.*



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Abstract

Pain is a prevalent issue in our everyday lives that can significantly affect our well-being. Subjective in nature, various elements affect an individual's perception of pain. The expanding use of pain analgesia presents numerous issues which can aggravate one's well-being. Non-trivial pain mitigating methodologies, which aim to alleviate pain without standard analgesia, are therefore required and being explored. Notably, distraction therapy, mindfulness, and meditation are all commonly employed methodologies effectively utilised for pain relief.

In the domain of digital health, technology is integrated to improve the quality of medical care. Numerous technologies can be employed for pain mitigation. Virtual Reality (VR) is used in a plethora of research about pain relief due to its immersive and distraction capabilities. Given that pain is multifaceted and complex, numerous variables must be considered in its study. A standard methodology is distinguishing pain as either chronic or acute. Apart from this, other factors such as individual demographics, medical condition, and pain intensity are all elements which might affect one's perception of pain. This work aims to further the research available in the domain of pain mitigation through the use of VR distraction therapy. Throughout this research, a personalised VR pain mitigation framework is proposed that harnesses the potential of user modelling, progressive content generation, and various VR experiences. The work utilises numerous user profiles consisting of well-known pain-characterising parameters mapped to several environmental elements the users prefer. Classifiers were trained on these profiles and used to generate a personalised environment. Progressive content generation techniques are utilised to create an environment at run-time entirely based on the user's profile. The solution builds an endless meditative space at run-time, consisting of vegetation, different environments, and animals, amongst other immersive elements. A survey tool was devised to evaluate the framework built, which captured the participants' characteristics and experience. An experiment was also run consisting of six anonymous participants. During the study, participants were exposed to both a standard and a personalised version of the solution for five-minute sessions. The results show that the average perceived pain intensity decreased by 68.9% from before the experiment session to after the last, significantly reducing perceived pain. Even though the standard environment effectively reduced pain intensity, the personalised environment further introduced a significant 27.5% reduction in perceived pain, displaying the efficacy such a solution has for pain mitigation.

Acknowledgements

Firstly, I would like to express my sincere appreciation to my supervisor, Dr. Vanessa Camilleri, whose knowledge and guidance helped in delivering an effective solution which harbours great potential in the domain of pain mitigation. I would also like to thank the participants who participated in the experiment and helped further our knowledge about such solutions through their comments and experiences. Finally, I would like to express my deepest gratitude to my loving family and close friends, who always provided their support throughout my life, serving as a good reminder of the reasons behind my efforts and perseverance throughout my journey.

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List of Abbreviations

2D Two-Dimensional.

3D Three-Dimensional.

AAT Animal-assisted therapy.

AI Artificial Intelligence.

AR Augmented Reality.

CBT Cognitive Behavioural Therapy.

CPU Central Processing Unit.

FPS Frames Per Second.

GPU Graphical Processing Unit.

GUI Graphical User Interface.

HMD Head-mounted Device.

IASP International Association for the Study of Pain.

MBSR Mindfulness-Based Stress Reduction.

MPQ McGill Pain Questionnaire.

PCG Procedural Content Generation.

RAM Random-Access Memory.

SVM Support Vector Machine.

VAS Visual Analog Scale.

VR Virtual Reality.

1 Introduction

1.1 Problem Definition

Pain is a vital sensation that warns organisms of bodily harm. The classification of pain can be approached from a multitude of perspectives. A common practice is discriminating it through duration, which can be categorised as either chronic or acute [1, 2]. The definition of pain is quite subjective. In 2020, the International Association for the Study of Pain (IASP) revised its definition as [3]:

“An unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage [3].”

Acute pain is often categorised by a sudden and intense discomfort that subsides quickly in hours or days. This is generally brought about by various factors such as injuries, illnesses, or even trauma [1, 2].

Conversely, chronic pain can be categorised through its prolonged nature, persisting for a more extended period, ranging from months to years or even a lifetime. If left untreated, it can severely limit an individual's sense of well-being, exposing them to further physical, emotional and psychological complications [1, 2]. Although both categories of pain present several challenges, chronic pain can introduce additional complexities due to its prolonged duration, hindering the body's ability to regain its natural balance, commonly referred to as homeostasis [1, 2, 4, 5]. Understanding the nature of pain and its underlying mechanisms is essential in developing effective treatment strategies. The importance of implementing an effective treatment plan to promote an individual's health and well-being cannot be overstated. Various methodologies exist that can be used to monitor and alleviate pain. The most common are analgesic medications, surgical interventions, exercise regimens, and therapeutic interventions, among others [6]. Among these, medication stands out as the most frequently employed method for pain reduction, predominantly due to its efficacy, accessibility, and ease of use. Nonetheless, despite the numerous advantages associated with analgesics, there are also disadvantages, including potential side effects, financial burdens, and the risk of addiction, amongst many others [7, 8]. Utilising analgesics as a treatment highly depends on carefully evaluating the benefits and drawbacks these might induce [7]. Nevertheless, despite careful consideration of prescriptions, undesirable side effects can still occur. This concern is especially pertinent to individuals suffering from chronic pain since long-term medication usage increases the likelihood of encountering such adverse reactions [8].

Hence, it is apparent that individuals suffering from acute or chronic pain



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necessitate a practical solution that does not pose additional risks to their health and restores their sense of well-being and quality of life.

1.2 Motivation

Several non-traditional methodologies are being studied to reduce an individual's perception of pain, one of which is using VR [9]. VR introduces numerous advantages across several different domains, including that of digital health [10]. Such solutions provide a myriad of possibilities, allowing users to briefly escape reality and immerse themselves in various breathtaking environments depending on the solution being utilised. Considering that distraction therapy can lead to a notable 60% reduction in the perception of pain stimuli [11], VR emerges as a potentially powerful tool which can effectively reduce an individual's perception of pain in both acute and chronic cases. Throughout history, different cultures and religions have acknowledged nature's therapeutic and soothing benefits for various health concerns [12]. Studies suggest that spending time surrounded by nature can reduce an individual's perception of pain and possibly enhance recovery time [12, 13]. The potential animals hold in medicine is also imperative when discussing pain mitigation techniques [14]. Dogs, for example, have been instrumental in improving patients' mental health through Animal Assisted Therapy (AAT) [15] and assisting visually impaired individuals as guides, amongst other applications. While the research on this topic is quite limited, several studies indicate that engaging with animals may result in a decrease in an individual's perceived levels of pain [14–16].

Another avenue which generates interest in pain management is meditation [17]. Research indicates that breathing techniques and mindfulness exercises can effectively diminish pain stimuli while fostering an enhanced sense of well-being and control of one's self [18]. Therefore, it is evident that integrating these methodologies into one solution could generate further potential in the field of non-analgesic pain mitigation.

1.3 Aim and Objectives

Research has shown that VR distraction therapy, meditation, and exposure to nature can all improve an individual's perception of pain, as detailed in Chapter 3. However, individuals' pain threshold and pain characteristics may vary. Techniques such as user modelling can be utilised to personalise users' immersive VR experiences. This study investigates user modelling techniques in procedural content generation for VR experiences specifically intended to provide distraction from pain.

The highlighted work aims to address the following research question:

- How can user modelling be used for procedural content generation in VR experiences to provide personalised distraction therapy?

The following objectives have been established to attain the stated goal:

- O1: Determining user modelling techniques, including parameters characterising pain.
- O2: Adapting procedural content generation models to immersive experiences that reflect distraction therapy effectively.
- O3: Design a user evaluation plan to determine the effectiveness of the VR experience.
- O4: Developing a framework that brings together the various components of user modelling, Procedural Content Generation (PCG), and various VR experiences into one solution.

1.4 Proposed Solution

The proposed solution is split into two parts. The first is a script responsible for the project's user modelling aspect. This digests several characteristics from a number of user profiles, including an individual's age, race, pain type, pain location and pain intensity. These characteristics are then linked to that individual's preferred environment, denoting the level of light, sound, and greenery, amongst other elements. This serves as training data which is then used with several different classification-based machine learning algorithms, such as the Support Vector Machine (SVM). This script also displays a Graphical User Interface (GUI), which provides a form for the user to fill in. The data is then used with the algorithms mentioned to predict which environment attributes the new user would prefer. These predictions are consequently passed on to the second part of the solution, which generates the progressively generated VR environment. The VR solution is entirely based on the Unity3D engine and is primarily built in C#. PCG algorithms are implemented in this part of the solution and are tasked with creating the environment at run-time. This generates an environment based on the previously mentioned script's predictions. The endless environment is built entirely at run-time and depends on the algorithm's predictions. This methodology aims to fully immerse the user in an environment best tailored for them. The VR solution can create infinite, beautiful, never-ending settings and natural environments, capturing the beauty of the forest, endless deserts and snowy mountains, amongst many others. The user is also offered the opportunity to

interact with various animals and enjoy the peaceful sounds of nature, amplifying their immersion in this unique experience. Depending on the user's preference, a meditative breathing exercise is also implemented, which can be initiated whenever the user desires through a spoken command.

The solution strives to provide a safe, personalised VR environment where users can endlessly roam and explore, effectively distracting them from discomfort and pain stimuli.

1.5 Contributions

This research contributes to the field of Artificial Intelligence (AI) and Digital Health by:

- Furthering the research for non-analgesic pain management and VR related pain mitigation techniques.
- Developing a solution which generates an immersive personalised VR environment unique for every user, effectively distracting the user from pain.
- Presenting a novel framework which encapsulates PCG, VR and VR environments, and user modelling techniques to deliver a personalised pain mitigation approach.

1.6 Document Layout

This chapter provides an introduction to the aim of this research and how it tackles the problem of pain mitigation, together with a general idea of the methodology used. Chapters 2 and 3 present all the necessary knowledge required to better understand the motivation behind this project and detail related studies that serve as a basis for this research. Chapter 4 provides a comprehensive overview of the methodology employed throughout the solution's design and development. Chapter 5 discusses and evaluates the results obtained through this research. Chapter 6 concludes the document, discussing any future improvements which can be made, obstacles that may have hindered the results achieved and a summary of what was accomplished throughout this research.

2 Background

This chapter covers the fundamental concepts introduced throughout this research. It begins by discussing pain and its physiology, as well as the available methods for assessing pain. Then, a thorough overview of the technologies used is provided.

2.1 Definition and Nature of Pain

As previously stated in Chapter 1, pain is a vital sensation that signals living organisms of any potential harm within the body [2, 3]. Accurately capturing the definition of pain is quite a complex task since many biological facets need to be considered. The 1979 Merskey definition of pain states that anything which feels like pain can be classified as such [3, 19]. As the definition of pain changed throughout the years, further emphasis was placed on its subjective nature. Pain is now regarded as an intrinsically complex personal sensation which cannot be directly measured by others [19]. To best capture the essence of pain, it is split into three categories that numerous physicians fail to recognise [20].

The first type of pain helps to detect potentially harmful tissue-damaging stimuli at their earliest, minimising damage and promoting action. This protective mechanism is known as nociceptive pain. It arises from sensing noxious stimuli such as contact with objects of extreme temperature or sharpness. It is a form of high-threshold pain, triggered solely when exposed to substantial and intense stimuli [20]. This protective mechanism draws immediate attention through the discomfort of the sensation felt, overriding most neural functions, urging the organism to act to overcome the external stimuli being experienced [20].

The second type of pain can be categorised as inflammatory pain, which commonly denotes some form of tissue damage and, just like nociceptive pain, is protective in nature. It plays a vital role in the body's healing process by inducing heightened pain sensitivity until the damage is wholly healed [20]. This increased sensitivity to pain discourages movement and engagement in any strenuous activity, further aiding recovery. Activated through tissue damage and infections, this category of pain stems from the immune system [20].

Lastly, we have pathological pain. Pathological pain is a maladaptive type of pain stemming from either neuropathic damage to the nervous system or neural dysfunction through which little to no noxious stimuli are present, but the pain is still expressed. Some common examples of conditions which cause such pain are Irritable Bowel Syndrome and Fibromyalgia, where these life-impeding conditions have no known noxious stimulus bringing them into effect [20]. This way of categorising pain

aids in our understanding of how vital pain is in our lives, our dependence on it, and its role in helping us respond to our surroundings, acting as a crucial tool for our adaptation and survival. Issues arise, however, when the pain is no longer informative and is present continuously throughout our lives.

To further understand the nature of pain, the following section takes a deeper dive into its physiology and the changes our body experiences during a pain response.

2.2 Physiology of Pain

Pain is a complex experience which involves both physical and psychological responses. Whenever our body encounters a painful stimulus, it instantly reacts to this nociceptive pain. This first response is handled through specialised receptors (specialised cells which respond to sensory stimuli) biologically referred to as nociceptors. These transmit electrical signals through the body's nerve pathways to the brain [21] as seen in Figure 2.1.

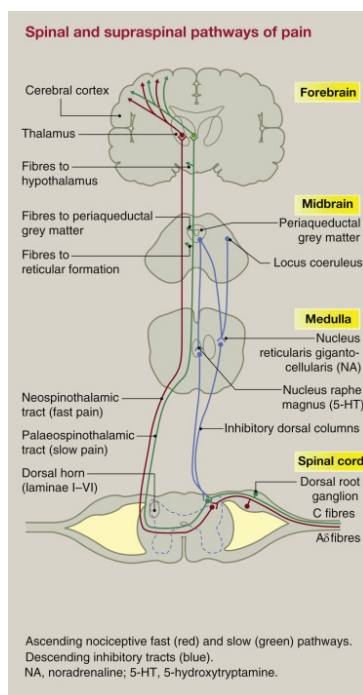


Figure 2.1 Spinal and supra-spinal pathways of pain, reproduced from [21]

The brain then processes the signal and decides based on the information received. Following this, the body responds with a motor response, which aims to resolve the noxious event [22].

Even though this is a vastly complex phenomenon, the experience of pain is much more complicated than a relay of information from the body, spinal cord, and brain.

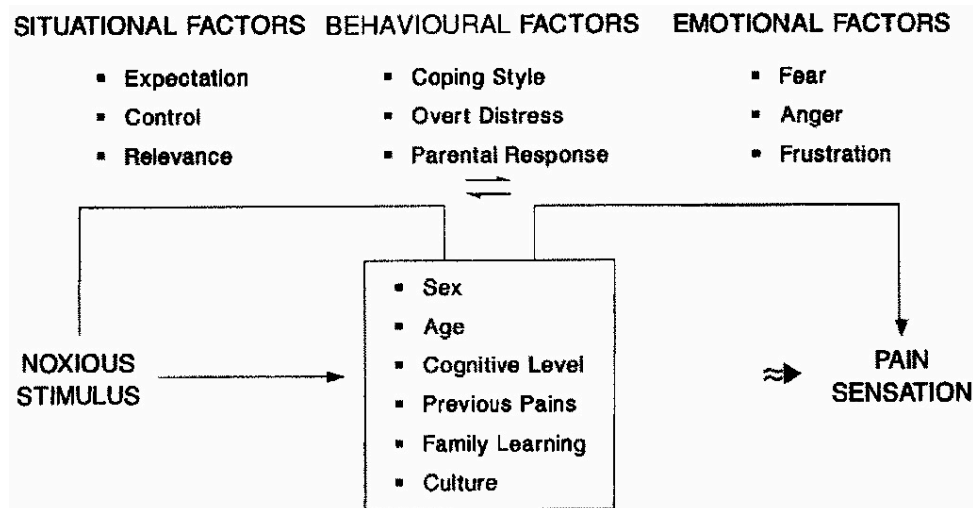


Figure 2.2 Roles of psychological factors in pain perception, reproduced from [23]

2.2.1 Psychological and Emotional Aspects of Pain

As outlined, pain is a multi-faceted biological wonder which is extraordinarily complex. It can be influenced by several factors, one of which is the brain itself [23]. This malleability in the nociceptive framework is seen in the body's varying response when exposed to the same amount of tissue damage [23]. Numerous psychological and environmental factors affect the brain's perception of pain. These take effect through the complex interplay of nociceptive and non-nociceptive signals within the body's pathways, which can be influenced by external factors that have nothing to do with the pain itself, such as emotions, anxiety, and physical discomfort [23]. Given the numerous facets which can affect an individual's perception of pain, measuring it solely based on the noxious damage at play does not serve as an accurate methodology. Research shows that individuals experiencing pain would react differently based on several key aspects, including prior pain experiences, gender, age, cognitive levels and relevant contextual and physical factors [23]. The roles these factors serve are further described in Figure 2.2. Research shows that these personal traits are consistent in their influence on one's interpretation of tissue damage [23].

In comparison, as described in Figure 2.2, contextual, emotional and behavioural factors are not as stable and highly depend on the specific scenario. Although volatile, these factors profoundly affect how an individual experiences and perceives pain. This is particularly seen when there is no apparent tissue damage [23].

The impact of age on the perception of pain

Pain is a sensation most individuals experience from a very young age [21]. Studies show that a child's understanding of pain is highly dependent on their age. Children

experience rapid cognitive progression as the body develops, which plays a vital role in understanding the stimuli being felt. As with most things in life, the more we are exposed to something, the better we understand it. This is the same for pain. As children grow, they experience more and more things which are relatively new to them, one of which is pain. According to McGrath [21], at approximately five years old, a child is able to describe pain in further depth, describing sensations such as location, frequency, and intensity. As one grows, their experience in life enables them to describe pain in much more detail, taking both physical and emotional aspects into consideration [21]. Therefore, it is evident that age is a significant factor in an individual's perception of pain.

The impact of gender on the perception of pain

The role gender plays when it comes to the perception of pain has been a researched subject for several years. Unfortunately, throughout the years, studies have produced inconclusive results when it comes to this due to unreliable data, insufficient evidence, and contradictory investigations [21]. Recent studies, however, provide further insight into the matter, with research showing that between the two genders, females tend to exhibit a greater sensitivity to pain and are more susceptible to experiencing clinical pain [24]. Certain conditions, however, are known to be more prevalent in one gender than the other [21]. In addition, studies have observed discrepancies in the response to pharmacological and non-pharmacological pain interventions between genders. It is worth noting, however, that these results are still inconclusive due to the lack of consistency and varying outcomes achieved because of distinct treatment types and pain characteristics [24]. It is now known that gender plays a role in the perception of pain due to a handful of biological factors amongst many others. These include a different distribution of hormones in the peripheral and central nervous system, different genotypes such as the melanocortin-1 receptor gene and the mu-opioid receptor gene, and the different endogenous opioid function [21, 24].

The relationship between one's upbringing and experiences with perceived pain

As previously outlined, one's upbringing has a substantial influence on their psychological function. This is seen in the perception of pain in particular. The environment in which we are brought up shapes our knowledge and is fundamental to a child's development and social understanding. By observing and imitating their parents or guardians, children acquire a wide range of behaviours, coping mechanisms, expressions, and attitudes, which shape their personalities and influence their future interactions with the world [21]. This is clearly seen when a child is injured. In such instances, children typically respond in accordance with their parents' responses. If the

parents react alarmed, the child may magnify the pain and potentially perceive the injury as more severe than it truly is. These early relationships with parents, guardians and siblings are vital information bases in shaping a child's pain perception. An understanding family that dedicates time to their loved ones will cultivate a sense of comfort and reassurance that members feel comfortable in [21]. These qualities promote proper communication within the family, making it easier for one to deal with any potential physical or psychological pain [21]. In addition, children also learn about the potential secondary gains associated with expressing pain. These can include escaping anxiety-inducing situations at work or school or even receiving extra care, attention, or affection. As they witness the results of their pain-related expressions, they begin to understand the advantages such behaviours may bring and might start to employ them for their own advantages [21]. Given that one's upbringing varies depending on the culture one is raised in, race and culture play a vital role in an individual's perception of pain [25]. Past encounters and experiences are crucial in developing an individual's pain perception. These past experiences serve as a good foundation for one to gain a solid understanding of the various aspects of pain, encompassing its sensory characteristics, emotional impact, and value as a warning signal. As individuals come across a type of pain they have never experienced before, they assess and interpret it based on their past encounters. They gauge the intensity and discomfort of their current pain by comparing it to sensations they have previously felt [21]. In essence, the complexity of pain perception is a multi-faceted phenomenon that cannot be distilled into a single determinant.

As outlined in Chapter 1.1, pain can be split into three major categories: acute, recurrent, and chronic pain [21]. Throughout this research, the term pain mainly refers to chronic pain. The following subsections introduce both acute and chronic pain, clearly distinguishing between the two while also presenting the relationship between stress and pain.

2.2.2 Acute Pain

Acute pain, defined by its transient nature, is short-term pain typically classified through brief, noxious stimuli. This mainly occurs as a response to sudden illness or injury and exists to alarm the body in order to protect it from further harm. It usually subsides within several days or weeks once the body heals. As one can see, acute pain is vital for an organism's survival and well-being. It serves as an essential warning mechanism while helping organisms adapt to their environment [21].

2.2.3 The Relationship Between Pain and Stress

Chronic pain and chronic stress are closely intertwined. Individuals suffering from chronic pain are much more susceptible to stress due to the challenges and limitations such conditions expose them to. Prolonged stress, on the other hand, can potentially aggravate physical discomfort and contribute to the development of chronic pain, such as muscle tension, spasms, inflammation due to increased cortisol levels, and altered pain perception [26, 27].

Whenever experiencing a stressor or pain, the body loses its state of equilibrium. This is commonly known as homeostasis, which is the body's state of balance and harmonious function. To overcome the stressors faced, the body undergoes several physiological changes. This is done through a number of changes in biological function, such as in the cardiovascular process (increased heart rate) and increased breathing rate. With these changes, the body increases its chances of overcoming the stressor and thus re-calibrating back to a homeostatic state [1, 2, 4, 5]. If the stressor endures and the body never manages to achieve homeostasis, it is susceptible to other illnesses such as cardiovascular diseases, anxiety, and depression. As one can see, this creates a malicious cycle of illness and distress, which is very difficult to break through without the necessary support [28].

With one in five people (based on studies based in Scotland) suffering from a form of chronic pain [29], having an effective way of dealing with chronic pain is a necessity which cannot be ignored.

2.2.4 Chronic Pain

Chronic pain, as outlined, takes longer to subside. Pain is classified as chronic once it persists for three months or longer. While injuries or diseases are commonly the reasons behind this type of pain, additional factors such as the involvement or shock suffered by other organs or body parts might propagate the pain even further. A notable example is the nervous system. Depending on the injury, the nervous system might sustain damage beyond recovery, superseding the body's natural ability to recover [2]. Sustaining damage to such a vital part of the body's core functionality threatens one's independence and can produce pain in other body parts. In addition to this, the perceived pain experienced in chronic pain syndromes tends to be amplified, making it considerably more challenging for the individual to lead a normal, healthy life as long as the pain persists. Identifying the cause of this discomfort is no easy task, as chronic pain can manifest without any noticeable injury [2]. Given the implications such conditions cultivate, implementing a proper methodology tasked mainly with mitigating chronic pain is essential.

While analgesia and opioids have been used throughout the years to minimise pain, such medication comes with several limitations that cannot be ignored. Even though analgesics are unarguably one of the most efficient methods to promptly relieve pain, issues such as medication cost, side effects, dependency and addiction exist. Using medication for a prolonged period, as commonly required for chronic conditions, presents a number of risks and elevates one's chances of experiencing side effects, further encouraging the cycle of unending pain and discomfort.

2.3 Pain Assessment and Measurement

Pain can be very subjective and highly dependent on one's psychology, amongst other factors. This subjectivity naturally presents a necessity for there to be effective methodologies one can use to measure pain. Throughout the years, numerous tools have been developed that aim to capture the multi-faceted nature of an individual's pain and back up the diagnosis, ensuring that a proper assessment is made [30]. These psychometric tests exist in many forms, most commonly being numeric scales and self-assessment questionnaires. Given that numeric scales are simple and reliable, self-assessment pain scales are the current gold standard when it comes to evaluating pain intensity [30]. The VAS and the numeric scale rating are widely researched pain scales that can effectively assess pain. If a patient struggles to assess pain numerically, the VAS might be a good option because of the visuals it provides. The same idea exists for children, which, through drawn faces, helps juniors better understand what is being asked for, as seen in Figure 2.3.

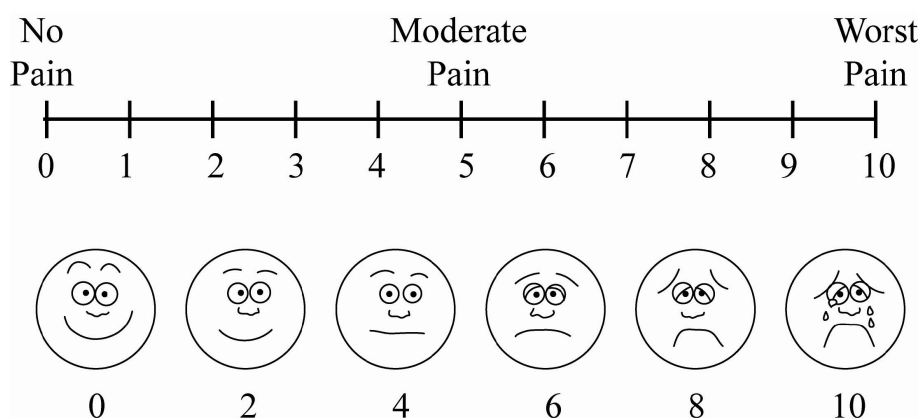


Figure 2.3 VAS variation

Looking at various questionnaires, the McGill Pain Questionnaire (MPQ) is a prevalent tool which provides a deeper understanding of the sensory attributes that come with pain. Existing in short and long formats, the MPQ is a validated tool proving that the essence behind numerous pain conditions can be effectively captured through

distinct descriptors [30]. Disability scales, such as the Multidimensional Pain Inventory and Brief Pain Inventory, provide reliable measures of how chronic pain affects a person's physical and social function [30]. Emotional scales, like the Beck Depression Inventory and Profile of Mood States, help assess an individual's emotional well-being [30].

Given that chronic pain can induce a variety of emotions, such as anger and anxiety, such a tool is incredibly beneficial to capture this aspect of pain, which other tools, such as the VAS, would fail to capture. On a global scale, the Patients' Global Impression of Change considers multiple aspects of a patient's life, such as general well-being and fatigue. This comprehensive evaluation allows professionals to understand a treatment's effectiveness better, capturing not only an individual's quality of life but also sheds light on any side effects experienced, improvements made and treatment convenience [30].

2.4 Pain Mitigation

There are numerous methodologies one can employ to manage pain. The most commonly used pain mitigation techniques generally involve the use of analgesics.

2.4.1 Analgesics

Analgesics are a group of medications that specifically target pain. Entry-level analgesics such as paracetamol, aspirin or anti-inflammatory drugs offer fast and effective relief to anyone experiencing mild to moderate pain levels. When pain is more serious, opioids or steroid-based anti-inflammatory drugs are most commonly employed [31]. While analgesics are an effective way to deal with pain, long-term use suggests higher chances for an individual to experience unwanted side effects, which can be not only uncomfortable but also fatal at times. The side effects experienced vary based on multiple factors. Most notably, these depend on the type of medication used, dosage and treatment longevity. While side effects for paracetamol are relatively rare and negligible most of the time, other medications such as aspirin and anti-inflammatory drugs all present a chance of unwanted short-term side effects like nausea, headaches and heartburn. Side effects of a more severe nature are also possible and must be taken very seriously if ever experienced, primarily due to the long-lasting impact these might have. Such side effects include an increased risk of a heart attack, stroke and kidney failure. Opioids, such as codeine and morphine, can not only cause a number of unwanted effects but have a higher chance of leading to medication dependence and addiction, which can also be fatal [31].

2.4.2 Non-Analgesic-Based Pain Mitigation Techniques

Given that analgesics present several undesired effects, other pain mitigation techniques should be looked into for individuals suffering from chronic pain, especially since such pain demands a long-term pain mitigation strategy. Numerous other non-medication-based methodologies exist which can be employed to control pain. It is worth noting that using an amalgamation of such methodologies displays better results [31]. Using heat or cold packs, for example, effectively reduces body swelling and can even relieve chronic muscle and joint discomfort. Engaging in physical therapies like walking, stretching, and other physical exercises can gradually improve one's perceived pain and also aid in mobility [31]. Massages can also be employed for soft tissue injuries but should not be relied on to relieve pain for chronic pain conditions. Relaxation techniques, such as mindfulness, yoga and meditation, help reduce perceived pain, rooting the individual and helping them further understand the pain [31]. Cognitive Behavioural Therapy (CBT) equips individuals with numerous strategies which reshape their thoughts and behaviours about pain, making it a valuable tool for managing chronic pain independently [31]. Finally, distraction therapy is another technique which plays a substantial role in diminishing perceived pain.

2.4.3 Distraction Therapy For Pain Mitigation

Distraction is a well-known tool for pain mitigation depending on the nature and intensity of the pain [32]. Given the strong ties perceived pain has with an individual's psychology, voluntary distraction can be an effective method to increase pain tolerance and reduce pain [32]. Although the effect distraction has on chronic pain might be inconclusive, [33] reports that distraction therapy successfully decreases pain by 20% to 50% in 90% of patients. Its effectiveness is also documented by the Lucile Packard Children's Hospital, where VR-based distraction therapy is employed for pediatric patients to reduce their pain and anxiety [33].

This type of pain mitigation is becoming more prevalent in research. The following section aims to introduce VR and what it entails, as well as highlight its use cases and importance in the digital health domain.

2.5 Introduction to Virtual Reality

VR can be described as the employment of computer-generated environments and simulations that one can artificially interact with within a Three-Dimensional (3D) space. The beauty behind this technology lies in its ability to immerse the user within a completely different environment with little to no limitations. From a young age, humans explore different ways to express their imagination. Ranging from paintings, panoramas, and 3D movies, creative minds have many times dared to explore and further the possibilities available to deliver an immersive and captivating experience to their audience. This love for illusionary spaces dates back to the 18th century when panoramas were used to immerse the audience within various landscapes and scenes through large paintings [34, 35].

The introduction of computing in this domain furthered the immersive possibilities one could achieve. In the 1960s, Sunderland created the first ever head-mounted 3D display headset [34]. In 1966, Sunderland moved to Harvard University, at which he later developed a groundbreaking tethered display for computer images [34]. This heavy head-mounted apparatus utilised goggles and mirrors to create a comfortable 3D visual environment. It could track the wearer's gaze and ensure that the right images were displayed for the users' field of vision. This pioneering device offered a highly immersive virtual experience while still allowing the user to move around [34]. Nowadays, VR devices have made remarkable progress. With peripherals such as the 'Oculus Quest 2' headset weighing under 505 grams [36], it is clear that the usability of such devices has been dramatically improved. Consisting of just a lightweight headset and two controllers depending on the type of equipment being used, it is evident that significant advancements have been made in the domain of VR [34, 36]. Modern-day headsets are generally equipped with numerous sensors which help further immerse the user within the environment by tracking movement and other data [34]. The movements are mapped within the environment, changing the scene displayed as per the user's new position. The controllers, on the other hand, allow the user to interact with the environment. By following the user's hand movements and controls, the user can grab, move and manipulate the virtual environment as desired, depending on what the virtual environment allows.

2.5.1 Applications of Virtual Reality

Virtual reality has many applications, one of the most common uses being entertainment. With numerous solutions being developed with VR capabilities in mind, using VR for leisure has been dramatically simplified. While playing games on a standard display is entertaining, being fully immersed in the game's virtual environment

can be an exhilarating experience. Another use case for VR is socialisation. Through numerous applications explicitly built for social activities, individuals can communicate and physically interact ‘face-to-face’ without being in the same room. This technology promotes life-like interaction, which goes beyond the experience provided in a video call. Individuals suffering from physical limitations can forget about such disabilities momentarily and temporarily live out a different reality by meeting and interacting with people in ways they previously could not [34].

Another prominent use case lies within the domain of education [34]. Through VR, educators teaching potentially life-threatening tasks such as aviation or surgery can use simulators which simulate real-life scenarios with life-like accuracy. This promotes confidence in students, rendering these stressful tasks much less stressful. Through this reduced risk and anxiety, students can learn faster and feel much more confident once they try the exercise in real life. On another note, the immersion presented in such technologies presents opportunities for attention-grabbing solutions that educators can utilise to teach in a captivating way. Students suffering from attention-related challenges would undoubtedly find these solutions highly beneficial. In a classroom setting, these innovative approaches could help encourage greater interest and engagement, especially among those who usually find it difficult to focus. It is therefore evident that VR solutions provide numerous benefits in the field of education.

2.5.2 Exploring Side Effects Caused by Virtual Reality

As previously outlined, VR brings about numerous benefits which one can harness and take advantage of. It is worth noting, however, that the possibility of adverse side effects exists when using such a technology. The most commonly experienced effects fall under the umbrella term ‘virtual reality sickness’, which encompasses symptoms such as nausea, loss of balance and dizziness [37]. Even though these side effects are typically temporary and reversible, proper precautions must be taken to minimise these outcomes as much as possible. This is done using known VR best practices such as frequent breaks, reducing exposure to blue light, and immediately stopping use if any of the above symptoms are experienced [37]. Given the benefits VR provides, especially concerning its immersive capabilities, researchers are trying to incorporate this technology into the domain of digital health.

For an individual to use VR, a solution needs to be developed that supports the technology required to harness VR capabilities. In this research, an environment unique and personalised for its user is generated at runtime. This ensures that the user is further immersed in the environment. Given that the environment is unique, this minimises any chances of boredom or distraction, drastically decreasing the chances of lesser engagement due to the user’s previous knowledge of the system’s environment.

To accommodate this, the solution uses different algorithms and software development techniques to bring the above ideas to life. The following sections introduce the processes and algorithms that form a significant part of the basis of the solution.

2.6 Introduction to Procedural Content Generation

Numerous methodologies exist that one can use to develop a unique game. The standard practice in game development mainly consists of manually building the environment and assets. Although cumbersome, this process produces an environment that accurately captures the desired requirements. This method promotes several other advantages within the concepts behind software development. Principles like modularity, configurability, transparency and understandability promote an excellent grade of quality in the product created [38]. Having most of the solution's assets, methods and behaviours easily understood makes it much easier to maintain and work on, reducing costs in the long run. Although this method seems to be the traditional way of developing games, it presents several limitations which cannot be ignored. Large-scale games require tremendous development time, which is not feasible through conventional game development approaches. The use of PCG algorithms plays a significant role in such scenarios and allows the game to 'build itself', independent of designers and artists, significantly reducing costs and development time [39]. The concept of PCG, as outlined in [39], assumes various formulations. In the aforementioned work, it is defined as:

"...the algorithmic generation of game content with minimal user input or indirect intervention." [39]

Several popular games make use of such technologies and employ these algorithms to provide a sense of freshness and uniqueness every time the user opens the solution or game. The popular title 'Super Mario Bros' uses PCG to generate in-game content such as game assets, weapons, and map layouts [39].

These algorithms present numerous advantages which facilitate game creation, especially for games without a predetermined ending. Games can also be created to adapt to the player, shaping the user experience based on individual preference, user modelling, choices made and other attributes. This personalised environment can further foster a sense of pleasure and enjoyment in the player, promoting user engagement. Such methodologies also give rise to endless games, such as 'No Mans Sky', which, due to the algorithms' adaptive content generation, can never be fully explored [39]. Moreover, integrating of PCG can significantly impact games' creativity. This results in a unique creation that bears little resemblance to other games, enticing the players to give it a try [39].

Numerous PCG algorithms exist which can be used for various use cases. Through this research, the 'Perlin Noise' algorithm [39] is used to generate the solution's terrain. By integrating different customisable parameters, the algorithm can generate infinite environments through which the user can roam. The following section aims to give a good overview of the Perlin noise and the Diamond-Square Algorithm.

2.6.1 Procedural Content Generation Algorithms

As outlined, there exist numerous PCG algorithms one can use. Their use case, however, generally depends on what needs to be generated. These algorithms can be used for various scenarios, including trees, terrain, level layouts, dungeons, and text, among many other uses [39].

Perlin Noise: Explained

Perlin noise (or gradient noise) is a well-known tool commonly employed for terrain generation, which generates terrain based on a gradient [39]. This method uses random gradients representing slopes' steepness and direction instead of the traditional method of directly producing height values and interpolating the slopes [39]. This method has several advantages, including smoother transitions between terrain chunks and avoiding any artefacts interrupting the seamless terrain [39]. By using lattice-based generation, the algorithm is more efficient in terms of both computation and memory. Random gradients are generated at lattice points as Two-Dimensional (2D) vectors, from which the height values are then derived [39]. The dot products between the aforementioned gradient vectors and those at neighbouring lattice points are then calculated. These calculations result in the height values at the non-lattice points, which are then interpolated, creating an organic and natural landscape [39].

Other algorithms, such as the Fractal Brownian Motion, Random Walk, Context-Free Grammar, and Cellular Automata, cover various use cases beyond that of terrain generation [39]. The extensive range of applications highlights the versatility of PCG algorithms, allowing for utilisation across various contexts and domains. When amalgamating these algorithms with AI, a unique user experience can be created, fostering further user engagement. The solution built in this research uses various machine learning algorithms which help predict the environment the user would most likely enjoy using. This personalisation aims to deepen user engagement and immersion, ensuring the user is well-distracted and, therefore, perceiving lower pain levels.

The following section introduces the concept of machine learning algorithms.

2.7 Machine Learning Paradigms

AI has brought forth numerous developments in many domains, including digital health. An example is using sensors, the physiological data they collect, and machine learning algorithms to predict an individual's stress levels. Such a solution utilises machine learning algorithms, which, by processing the sensor data collected from bodily worn sensors, can predict whether an individual is stressed with a certain degree of accuracy. Such machine learning algorithms fall under supervised learning.

2.7.1 Supervised Learning

Supervised learning is classified by algorithms that must first be trained on labelled data to be used for accurate label predictions. This labelled information consists of the input data and their corresponding labels. When training is completed, the models can predict and classify new information based on the data processed during the training phase [40]. Some popular classification algorithms include SVM, Decision Trees, and Naive Bayes. If labelled data is unavailable, one can utilise unsupervised algorithms that do not require any labels to be used [40].

2.7.2 Unsupervised Learning

As outlined, algorithms categorised under the unsupervised learning term do not require any labelled data beforehand. Instead, they employ a different strategy to recognise relationships, patterns and underlying structures within the data. This approach uncovers information that would otherwise be hidden, and a deeper understanding and value are extracted from the data used. Popular unsupervised algorithms commonly employed are K-means clustering, Hierarchical clustering and autoencoders, amongst many others [40].

2.8 User Modelling

In software engineering, user modelling is a strategy that captures or maps various user characteristics, demographics, preferences and behaviours, amongst other aspects, to create personalised environments or solutions specifically tailored or adjusted programmatically based on the user's data [41]. Personalised solutions are more enjoyable and can help simplify an individual's life. Numerous techniques, such as machine learning, statistical analysis and data mining, can deliver such personalised experiences [41]. User Modelling provides a way through which a system can adapt based on the users' needs and behaviours [42]. Through information such as the users'

preferences and previous usage, the system attempts to infer the best environment for that specific user [42]. There exist several methodologies one can use to create user models. Two common approaches are implicit and explicit methods [42]. Implicit methods harness the information generated through the users' interaction with the system, such as clicks, and time spent in specific areas or pages depending on the use case. Explicit methods on the other hand gather information through the use of questionnaires or other tools which can be used to fetch information directly from the users [42]. User modelling techniques can significantly enhance user engagement and personalisation, but their effectiveness heavily relies on the quality of the data being used. If the data is ambiguous, incomplete, or false, the system's adaptations may be less effective and could potentially yield adverse results. When handling personal user data, it is crucial to ensure that it is stored and processed with great care [42]. This is particularly true for systems that utilise physiological data or any other information pertaining to an individual's health.

2.9 Overview

As seen in the concepts mentioned above, familiarising oneself with the nature of pain, its physiology, and other elements mentioned throughout this research is paramount to fully grasp the methodology behind VR pain mitigating solutions. This chapter, therefore, aimed to encapsulate an understanding of pain and its physiology, pain assessment methodologies, VR, PCG, machine learning algorithms, and user modelling. The next chapter presents the literature review, which discusses and evaluates research pertaining to the use of VR pain mitigation methodologies.

3 Literature Review

As outlined, numerous methodologies can be utilised for pain analgesia [6]. When an individual experiences pain, the body undergoes physiological changes similar to those noticed during a stress response [43]. Pain impacts numerous individuals, significantly affecting their well-being and overall quality of life. According to the Institute of Medicine, pain is deemed to be a prominent public health issue that can potentially lead to multiple disorders [44]. It also presents a nationwide economic burden estimated at a minimum of \$560 billion annually [44]. Given the adverse consequences caused by pain, there exists an evident demand for alternative pain mitigation methodologies [44], which reduce the need for traditional pain analgesics. Studies have established that practising mindfulness and meditation techniques can reduce perceived levels of pain while simultaneously alleviating stress and other depressive symptoms [30].

Exploring alternative approaches that reduce our reliance on conventional pain mitigation methodologies is a flourishing research topic. This is especially true due to the exponential technological advances, expanding the development possibilities in areas such as digital health. Research findings demonstrate that incorporating known physiological and psychological knowledge of pain with technology is exceptionally beneficial and can lead to significant outcomes. An example of this is shown in [11], where VR distraction therapy is shown to reduce perceived pain by up to 60%. Numerous avenues exist through which one can be distracted. With distractions being so central in our daily lives, many explore strategies to help them focus and concentrate. Technology, although beneficial in many ways, has provided many ways through which one can be distracted. With social media constantly at our fingertips, we are presented with endless 'entertainment', hooking us to our devices, many times at the cost of other responsibilities. For a distractor to be effective, it must be exciting and cognitively compelling, effectively preoccupying the individual from current tasks. Games are prominent examples of good distractions, diverting attention and instilling a sense of escape. In addition, VR technologies introduce an added layer of immersion, further engaging individuals within this virtual environment on a cognitive and possibly sensory level [45]. The introduction of VR within the domain of pain mitigation illustrates a logical progression in the expansion of research pertaining to the efficacy of distraction therapy for pain management. This section aims to provide a deep understanding of the studies available in this domain, serving as a solid foundation for the work built in this research.

3.1 Virtual Reality to Mitigate Pain

Virtual reality introduces numerous benefits to the domain of digital health. In pain mitigation, VR is employed in a variety of settings, not only to manage pain but also the emotional distress such conditions present. A commonly used application is during medical procedures, which are well-known for being painful [46]. The existing body of research concerning the application of VR-based therapy for pain mitigation is notably limited [47]. With the field of research being in its exploratory stages, the work done throughout this research aims to further the knowledge available in this domain. This work aims to introduce a novel approach to further immerse participants within the VR environment through AI-driven personalisation and content generation.

As outlined, pain can be categorised through its numerous dimensions. Throughout this review, pain is classified as being either chronic or acute. Given that the qualities of pain vary depending on its type, the applications and efficacy of VR mitigation techniques may also produce varying results depending on the setting. Therefore, these must be studied independently depending on the pain category, explicitly noting the solutions' characteristics, results, and limitations.

3.2 Virtual Reality and Acute Pain Mitigation

Being the most common type of pain [48], the development of non-analgesic pain mitigation techniques for acute pain presents numerous advantages. Several notable methodologies use VR to manage acute pain [47]. Chuan et al. [47] highlight the prevailing presence of inconsistencies and biases within numerous studies of this nature, emphasising the importance of an in-depth literature review [47]. There are many causes from which an individual can experience acute pain. One commonly addressed in studies is pain induced by burns or dressing [49–53].

3.2.1 Virtual Reality Pain Mitigation for Patients Experiencing Intense Pain

In [50], Hoffman et al. study the use of VR analgesia for patients suffering from extensive, severe burn wounds. The research consisted of 11 male patients in total, starting from the young age of 9 up to 41, all having severe burns which required hospitalisation. The research's participant pool was unfortunately quite limited and, therefore, might have introduced several limitations and biases within the study, which might ultimately lead to inconclusive outcomes. Before the experiment, the participants were administered standard opioid analgesics along with benzodiazepines

[50]. This study was only available for individuals who were still experiencing excessive pain despite the use of analgesics [50]. This, consequently, highlights a clear limitation in the effectiveness of conventional analgesics and stresses the importance of the availability of other non-analgesics pain-mitigating methodologies such as VR. This is further emphasised in a recent study by Hoffman et al. [53], where problematic issues such as analgesic dosage restrictions are mentioned. The authors outline that these restrictions mainly stemmed from opioid side effects, medicine tolerance and addiction [53].

To circumvent any potential procedure deviations from one day to another, the patients underwent wound debridement, which is known to be a painful medical procedure. This was carried out in two different treatment conditions: one with VR distraction and the other without, the order of which was randomised, minimising any likely bias [50]. The experiment consisted of having the participants in a hydro tank, which is typically used when treating burn wounds of such nature. A custom VR headset was placed on the individual's head, ensuring that no evidence of the natural world was visible [50], highlighting the importance of immersion and presence in such methodologies. The solution used in this research was 'SnowWorld', shown in Figure 3.1. SnowWorld is a VR snowy environment specifically designed to help burn patients



Figure 3.1 SnowWorld VR application, reproduced from [50]

during medical procedures [50]. It delivers an immersive, icy world through which they float via a predetermined path and interact with elements by shooting snowballs at snowmen, penguins and igloos. The study highlights the promising outcomes of immersive VR solutions, such as SnowWorld, in reducing pain. The results demonstrate a significant reduction in pain intensity, unpleasantness caused by pain, and time spent thinking about it. These findings, therefore, suggest that VR has the potential to be a

practical approach for managing pain in various clinical settings. Furthermore, the authors report a 41% reduction in the participants' perceived pain levels. Hence, it can be concluded that VR can also effectively relieve intense, excruciating pain [50]. A potential limitation that Hoffman et al. [50] note is the absence of head tracking and tactile cues within their solution. Instead of using head-tracked movement, users can look around the game using a joystick, making the experience less engaging. This lack of realism and added complexity plays a significant role in the participants' immersion and might produce less compelling results [50, 54].

3.2.2 Cutting-Edge versus Entry-Level Virtual Reality Technology for Pain Mitigation

In a separate study by Hoffman et al. [54], the authors explored the impact of high-tech versus low-tech VRs setups on pain mitigation during brief thermal pain stimuli. During the study, the high-tech setup utilised a superior headset and more user-engaging elements, while the low-tech setup was cheaper and had fewer engaging features. While the SnowWorld solution was used for both configurations, a restricted version of the world was used in the lower-grade setup. These restrictions removed engaging factors that allowed user interaction with the environment, a feature well known to increase immersion. These included interacting with snowmen through snowballs, head motion tracking, and action-based sound effects, lowering the participants' overall immersion [54]. In the high-tech VR group, the participants wore a Kaiser XL-50 high-resolution helmet¹ that provided full field-of-view coverage. Entirely blocking the view of the natural world minimises external distractions and better maintains user engagement. In the control group, non-immersive, see-through Virtual Vision glasses were used. These offered a smaller field of view and lower image resolution when compared to the headset used in the high-tech VR group [54]. The glasses' see-through element would be helpful in an Augmented Reality (AR) based solution but might not be as effective when complete immersion is required.

The results achieved throughout this study show that immersion plays a significant role when employing VR for non-traditional pain analgesia. [54] outline that the group using the high-tech equipment demonstrated significantly greater pain reduction when compared to the ones utilising low-tech VR [54]. Additionally, the high-tech group reported a remarkably higher increase in enjoyment and felt a greater sense of presence during their VR experiences [54]. Furthermore, a significant positive correlation was noted between the reduction of pain and the individuals' level of presence within the VR environment [54]. This study demonstrates that a person's

¹https://www.researchgate.net/figure/the-kaiser-xl-50-vr-800-and-ce-500-hmds_fig1_321844896, Last accessed: 11/11/2023

immersion and engagement in the virtual environment are crucial for effective pain relief. As expected, the participants' level of enjoyment, or 'fun' as expressed within the study, positively correlated with the solution's level of immersion. The authors [54] suggest that in distraction-based pain mitigating methodologies, pain and VR compete for attention. Hence, immersing systems benefit from more significant pain mitigation. This statement also suggests, however, that such solutions only work in cases where pain is of a mild to moderate nature, as intense pain is much harder to be distracted from, as outlined in [54, 55]. Conversely, in a study published in 2020, Hoffman et al. [53] show that VR can also be effectively used to mitigate intense noxious stimuli, indicating that the multi-dimensional relationship between VR solutions and pain mitigation requires much more research. Additionally, these papers display excellent progression in the field of VR pain analgesia, with Hoffman's work spanning from 2004 [54] to 2020 [53] in the papers reviewed. As with most studies in this domain, several limitations were present, which would have aided the area of research [54]. The experiment's exposure time was one of these issues. Since the experiment only lasted two minutes and consisted of a short 30-second pain stimulation window, many factors might have affected the results, such as the anticipation of the pain ending and non-intense pain stimuli. Therefore, the effectiveness of such solutions for more extended periods of pain requires further examination [54]. Furthermore, as outlined in the study, patients may respond differently to diverse virtual worlds. While VR was found to reduce pain in this context, it is unclear whether the results can be generalised to all possible VR environments.

As outlined, a more recent study by Hoffman et al. [53] studies the use of VR analgesia for adolescents aged 6 to 17 suffering from extensive, severe burn wounds. The authors compare the effectiveness of VR treatment against standard traditional pain medication while the burn wound is being tended to and debrided [53] as shown in Figure 3.2.

3.2.3 Accessibility in Virtual Reality Pain Mitigation Solutions

The experiment utilised a more refined version of the SnowWorld environment described in [50, 54]. The updated version was improved by introducing woolly mammoths, flying fish, and additional interactable features and audio cues to enrich the users' immersive experience further [53]. This study tackles an interesting concern which might often go unaddressed: the accessibility and comfort such pain-mitigating techniques must provide. Patients who have been extensively burnt require a solution which can be used with minimal activity and no contact. Having burns on the face adds further complexity to such VR solutions, which generally require a Head-mounted Device (HMD) to be worn. To accommodate patients suffering from extensive burns to



Figure 3.2 Patient undergoing VR therapy during wound debridement, reproduced from [53]

the face, the VR goggles were held right in front of the patient's head through the use of a mechanical arm, as can be seen in Figure 3.2. This relieves any pain and discomfort the VR device might have otherwise produced [53].

Similarly, since headphones could not be worn due to the extensive burns, a speaker was used to keep the VR environment's immersive capabilities as unrestrained as possible. In contrast to the aforementioned studies, the experiment in [53] took place over ten days, with every treatment lasting approximately 20 minutes. This provides further insight into the strength, effectiveness and engagement such treatments maintain over an extended period. The results show that the worst-pain scores for VR therapy were significantly lower than those of the control experiment. As seen in Figure 3.3, the pain ratings continued decreasing slowly as the days went by, with some inconsistencies on days four and five. The least pain experienced in the VR therapy was also significantly lower than the non-VR therapy. For other secondary measures, such as the enjoyment felt during the VR experience, time spent thinking about pain, and the unpleasantness of pain, however, no significant results were noted [53]. Despite the lack of significance, the time spent thinking about pain was 24% lower in the VR group. Pain unpleasantness was 8% lower, and fun was 44% higher, all displaying promising results.

The patients' comfort should greatly be prioritised when it comes to digital health solutions, as it can significantly affect the efficacy of the therapy being administered. Pain hinders an individual's well-being. This is not only through the discomfort pain induces but also through the physical limitations it introduces. To reduce the pain experienced, organisms tend to avoid the activity that commonly

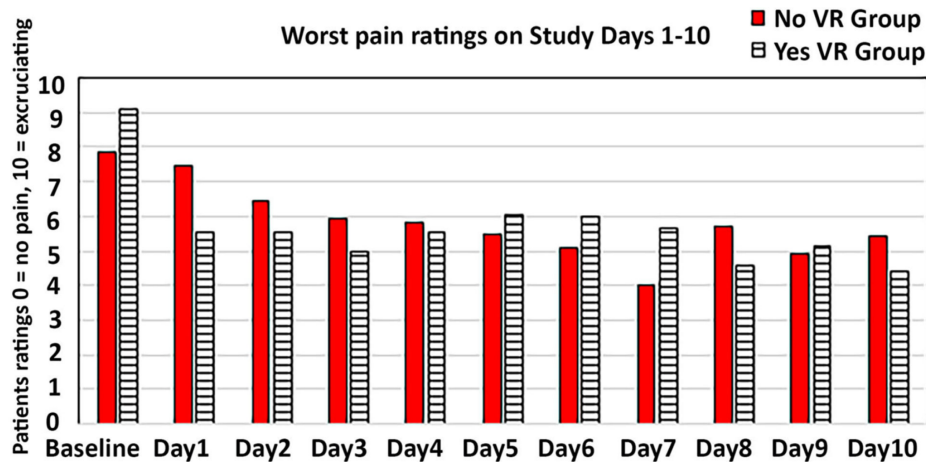


Figure 3.3 Worst Pain ratings in the VR vs No-VR experiment, as seen in [53]

exposes them to it. This often leads to a loss of basic physical abilities, such as a decreased range of motion in activities that were once possible [56]. Physical therapy is a typical approach which helps individuals maintain their body's range of motion and accelerate the pace at which it recovers [56].

Carrougner et al. [56] studied the efficacy of VR for pain mitigation and investigated its possible contributions to improved range of motion for several body joints during physical therapy. This was achieved by evaluating pain scores and maximal range of motion before and after treatment over two consecutive days [56]. Similar to the results achieved by other studies utilising SnowWorld VR, Carrougner et al. [56] report that the SnowWorld VR environment significantly reduced individuals' levels of pain during physical therapy. The time these patients spent thinking of pain was also reduced, emphasising the efficacy of such interventions on an individual's perception of pain [56]. The average increase in the patient's range of motion across all studied joints was reportedly 10.2 degrees, showing no significant improvement [56]. Although the results show no significant effect on individuals' range of motion, the perceived levels of pain show promise in efficiently using VR based solutions for pain mitigation. Some limitations were noted, however, which might hinder the results achieved. The main limitation introduced was the lack of control within the treatment conditions. Not limiting the subjects' visibility between the VR and non-VR treatment conditions might have influenced their pain reports, potentially leading to biased results in favour of the VR treatment [56]. Such limitations could affect the validity and reliability of research findings and emphasise the importance of proper management during a study's testing and experimentation phase. Although all the studies reviewed up till now have detailed impressive results and findings, not all studies report a significant reduction in perceived pain.

3.2.4 Distraction's Pivotal Role in Virtual Reality Based Pain Therapy

In [57], Walker et al. report that during a painful male medical intervention known as a medical cystoscopy, the difference noted in patients' pain and anxiety was not medically encouraging. In comparison with the findings by Hoffman et al. [50], no noticeable differences were identified in patients experiencing severe to excruciating pain even though the same VR environment, SnowWorld, was used across these studies. These findings emphasize the impact various factors have on the outcomes obtained. Even when well-performing VR applications are used, factors like immersion levels, personal tastes and the type of pain experienced play an influential role in non-traditional pain analgesia. These factors are seen in this study's results, where the participants outlined that the environment was not as immersive. This lack of immersion could, therefore, explain the undesirable results achieved in the participants' levels of pain. Walker et al. emphasize that the control group underwent a procedure created to closely imitate a standard cystoscopy procedure. This included using lidocaine jelly lubrication, the display of the cystoscopy on a monitor, and frequent interactions with the urologist [57]. These factors promote a sense of control, peace of mind, and distraction among the participants. The authors, therefore, argue that these measures might have reduced the control group's perception of pain, resulting in skewed results compared to the results achieved using VR [57]. It is worth noting that the VR group could not communicate with the urologist or look at the monitor displaying the procedure, both of which are factors that could have played a role in the pain mitigated in the control group. The authors also mentioned that the variables introduced by the VR technology and novel questionnaires might also have played a part in the results achieved [57]. As seen in [54] and as outlined in this literature review, the solution utilised for VR distraction plays a pivotal role in the results achieved. Walker et al. [57] therefore specify that since the distractor was not as effective, the results achieved in the study are possibly inconclusive and further investigation is required in the domain of VR analgesia.

3.2.5 Consumer Grade Virtual Reality Pain Mitigation For Labouring Women

Another application of VR pain mitigation is seen within a pilot study for labouring women [58]. In [58], Frey et al. outline the pain women often experience throughout the memorable and extraordinary childbirth experience. Because of this, numerous women are administered strong neuraxial analgesics (administered close to the spinal cord [59]), which help mitigate the intensity of the pain felt. The most commonly employed and effective analgesic utilised to alleviate some of the pain experienced



Figure 3.4 An image captured from the Ocean Rift VR application, reproduced from Steam [60]

during labour is epidural. However, like any other medication, this can induce several undesirable side-effects [58]. Considering that just 17% of women in the United States report having an unmedicated birth [58], non-analgesic pain mitigation techniques such as VR can be incredibly beneficial. Such benefits include reducing potential medicine-induced side effects, personal satisfaction and increased breastfeeding rates. When compared to other studies, this research only employs consumer-grade components for VR, such as the SamsungGearVR² and a Samsung Galaxy Phone. These commercially available devices make accessing and using such solutions more accessible for the everyday user, which is a factor that needs to be taken into consideration when addressing such a global issue. The cost of VR equipment varies greatly depending on quality and features. As seen in [53], VR equipment can cost as high as \$40,000, which, although providing the best technology available, is too expensive for the average consumer. Nowadays, however, good quality, reasonably priced VR technologies such as the 'SamsungGearVR'² and the 'Meta Quest 2'³ are available. Throughout this study, the Meta Quest 2 headset and controllers are used, ensuring that the solution built is accessible by the majority of the people.

Refreshingly, Frey et al. [58] do not use SnowWorld VR distraction but opted to make use of the 'Ocean Rift'⁴ scuba diving simulator. In Ocean Rift, one goes through a simulated dive with several animals from which the user can choose, an example of which can be seen in Figure 3.4.

Relaxing music is also played to further immerse and calm the participants. In terms of user engagement, the participants' head movements were tracked along with a hand controller, which captured user input, allowing users to take pictures throughout their underwater simulation [58]. In the updated version of Ocean Rift, the user can dive to wherever they desire and choose which creature they wish to dive

²<https://www.samsung.com/us/support/mobile/virtual-reality/gear-vr/gear-vr-with-controller/>, Last Accessed: 29/10/2023

³<https://www.meta.com/quest/products/quest-2>, Last Accessed: 29/10/2023

⁴<https://www.meta.com/experiences/2134272053250863/>, Last Accessed: 29/10/2023

with. In the study, perhaps for consistency, Frey et al. do not mention the participants' freedom to move and only mention manatees within the diving environment [58]. To reduce bias, the participants were all giving birth for the first time and were not using any pharmacologic analgesia. Aligning with most of the results of other studies exploring the use of VR in acute pain mitigation, Frey et al.[58] found that the VR experience significantly decreased the worst pain intensity, time spent thinking about pain, and pain unpleasantness scores, as can be seen in Figure 3.5. As seen in [53], VR analgesia was medically effective in easing distress in severe pain scenarios. Although the results achieved are encouraging, the potential of under-reporting pain scores after the VR intervention is present. This issue however exists within most self-reporting questionnaires, where the results rely entirely on the participants' honesty and ability to set aside any emotions or personal beliefs that might interfere with the answers given. The novelty of the technology might also play a role in its immersion and presents an excellent opportunity for such solutions to be used in acute pain scenarios, as individuals would still be intrigued during their first few sessions. Finally, the study only consisted of 28 patients, which produced significantly good results but cannot be generalized to all women going through labour [58]. These limitations present the need for further investigation in the application of VR methodologies for labour pain mitigation, especially if the optimal configuration for such a scenario is to be found.

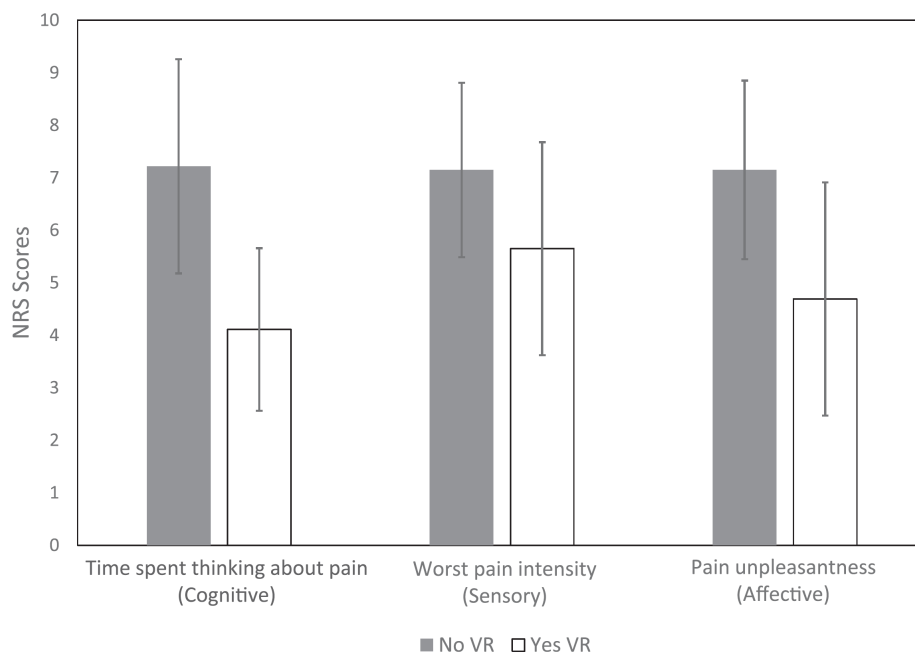


Figure 3.5 Results achieved in [58], comparing both VR and non-vr groups

As seen throughout the aforementioned studies, VR can effectively reduce perceived pain in acute pain scenarios. The biology and treatment to relieve chronic pain can vary quite a bit and are not as direct as dealing with pain of an acute nature.

The following section aims to shed light on the changes and effectiveness, if any, that VR therapies have on chronic pain.

3.3 Virtual Reality and Chronic Pain Mitigation

Several prominent studies have addressed the problem of chronic pain through the use of non-pharmacological analgesia. A study recently conducted by Darnall et al. [61] looked into the feasibility and efficacy of a home-based VR program for individuals suffering from fibromyalgia and chronic lower back pain.

3.3.1 Virtual Reality versus Audio-Based Meditation For Pain Mitigation

An interesting comparison was made in this research between a VR methodology and an audio-based treatment, which was not seen in other studies reviewed. Similar to other consumer-grade equipment used in other studies, an Oculus GO headset was utilised for the VR group, ensuring that participants could obtain a similar headset once the experiment is concluded. In contrast to studies addressing acute pain, which typically consist of one or a few sessions, this study took place over 21 days [61]. This illustrates the importance of the efficacy VR solutions must maintain over a more extended period. Since immersion plays a crucial role in distraction therapy, the environment must be enticing enough to keep the user engaged over several uses. This ensures that VR solutions can be effectively employed for individuals suffering from chronic pain, which is persistent throughout an individual's life. Darnall et al. [61] note that the perceived pain results peaked on the study's 15th day. This delay in the solution's efficacy shows that factors such as getting acquainted with the VR technology and the virtual environment, content delivery and patient engagement, amongst other factors, all play a crucial role in a study's results. Rather than solely relying on immersion, a different course is taken in the VR therapy used in [61]. The program aimed to immerse and relax the user and improve the participants' self-help skills. The treatment consisted of three main content categories, which sought to provide brief CBT lessons, relaxation techniques, and mindfulness [61] to the participants. These well-known teachings and exercises are semi-independent of the immersion provided within the solution and can, therefore, be employed regardless of the setting. Both the VR and audio-based therapies included identical exercises, with the audio-group closely resembling the VR group's exercises, excluding any visual references the VR variation might have provided [61].

Darnall et al. employ numerous methodologies throughout their home-based



Figure 3.6 VR Environment visualising users breath, reproduced from [61]

therapy, both in the VR and audio-based groups. However, further information about these methods is left to be desired, as the provided details are not explained in depth. Given that good studies in this field are not abundant, all the research within the domain should aim to further the knowledge available. This includes providing all essential information that might be beneficial to replicate or improve upon the study's results. However, this might have been purposefully omitted due to its intricacy and left for the researcher to investigate. The exercises are outlined in Table C.1.

An interesting approach that one of the therapies utilised is the employment of a breath detection algorithm [61]. Using the HMD's microphone, the algorithm accurately detected the participants' breathing, enhancing immersion without needing physiological sensors. This was used to visualise the users' breathing within the scene [61], helping them regulate their breath throughout the breathing exercises. Figure 3.6 shows an example of these visualisations, where the rays of light are emitted from the tree based on the users' breathing. Such therapy also helps with mindfulness practices, where focus is regularly drawn toward the individual's breath.

The results achieved show great promise in the utilisation of VR distraction therapy for chronic pain mitigation. The self-administered techniques, such as breathing exercises and CBT, provided significantly effective pain mitigation, lowering pain intensity scores in both the audio and VR groups. As can be seen in Figure 3.7, however, although the VR group started with an average higher pain intensity, this decreased significantly lower than the audio-based group as the days went by, with the

gap being especially evident from the 15th day onward [61]. The same was noted for pain-activity interference, which was notably lower in the VR group [61]. Overall, the study's findings indicate that the VR therapy had significantly improved pain intensity and interference results, surpassing the audio-only based treatment. Darnal et al. emphasise that the dynamic interaction between the user's breath and the VR environment was a vital aspect of the environment's contributions to the effectiveness of the VR treatment [61].

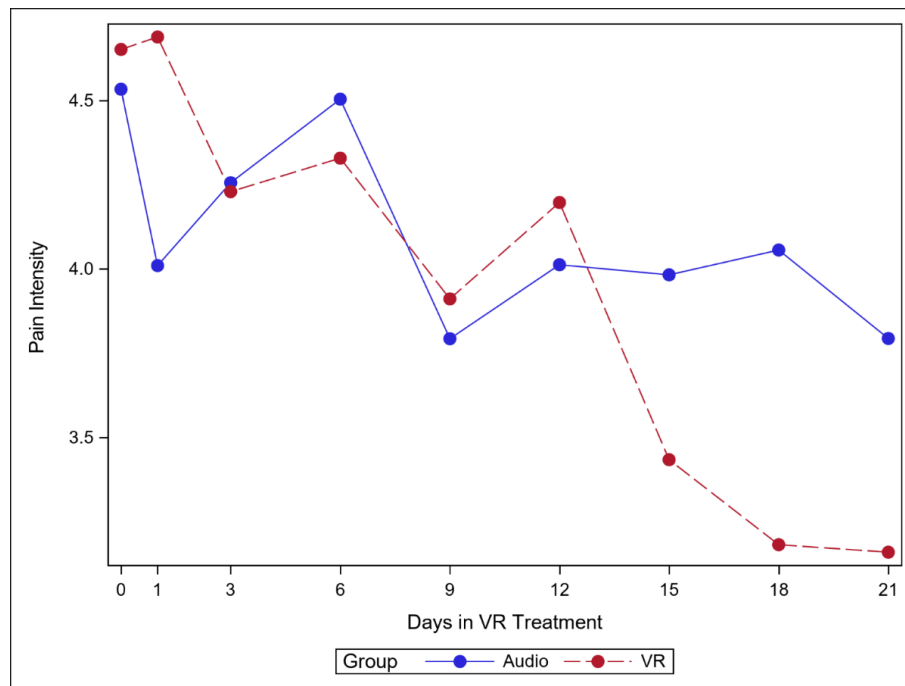


Figure 3.7 Pain Intensity Scores in VR and Audio-based Treatment. Reproduced from [61]

3.3.2 The Efficacy of Virtual Reality Based Therapy Over Time

As briefly outlined, the efficacy such treatment maintains over a longer period is a concern that studies must address. This is addressed in two recent studies by Garcia et al. [62, 63]. Throughout [63], the authors explore the efficacy of VR solutions versus a placebo VR setup they refer to as 'ShamVR', as displayed in Figure 3.8.

The study involved 179 adults suffering from chronic lower back pain. The participants' pool's average pain was 5/10, with a 1.2 standard deviation. The number of participants that partook in this study was also significantly larger than the quantities noted in the other studies reviewed. These numbers ensure that bias or personal factors do not affect the results as much. A critical factor ensuring that pain can be categorised as chronic is the duration for which it is felt. The participants in this study had all been experiencing pain for five years or more, making it a very healthy group for



Figure 3.8 Experiment setup used in [63]

a study of this nature [63]. Garcia et al. [63] followed a similar approach to that found in [61], where an at-home based self-administered VR treatment was utilised to promote pain mitigation. The authors state that this work aims to build on their group's earlier findings [61] by increasing the treatment longevity to 56 days from the previously used 21. The authors state that since CBT and mindfulness-based therapies tend to be eight weeks or longer, the VR therapy implemented aligns more with these timelines [63]. The program was also improved by employing interoceptive techniques (techniques which help one understand what is going on in their body) and expanded upon the solution's previous iteration's self-coping, healing and neuroscience-based teachings [63]. An exciting approach not outlined in other studies was the comparison Garcia et al. make between standard VR and sham VR throughout their experiments. According to the authors, this was done to shed light on any possible pain mitigation due to placebo effects and the novelty of the technology being used [63].

The Sham VR consisted of a 2D environment without any immersive attributes or educational content, as displayed in Figure 3.8. The commercially available Pico G2 4K all-in-one HMD ⁵ was used for both the therapeutic and the sham groups. This device provides minimal latency and is outlined to be easier to use than other devices [63]. Both of these are required elements within any technology-based therapeutic solution. The therapeutic VR program utilised is referred to as 'EaseVR' by AppliedVR. This aims to support pain mitigation by harnessing research-based techniques that are well known to help in pain mitigation, stress relief, relaxation, and distraction. Every session lasts approximately 2 to 16 minutes and incorporates a range of treatment

⁵<https://www.picoxr.com/global>, Last Accessed: 31/10/2023

modalities. These include mindfulness videos with guided breathing, therapeutic voice-overs and music, distraction games, breathing exercises, relaxation scenes instructing participants about the benefits of progressive relaxation techniques, and pain-educating visuals and voice-guided teachings [63]. As for the Sham VR, 2D videos of nature were used along with neutral music. Similar to the previous study in [61], the pain location, duration and intensity were recorded. Apart from these, the participant's demographics were also noted, including age, gender, and ethnicity [63]. As seen in most studies, an 11-point scale from 0 to 10 was used to take note of the pain intensity before and after treatment sessions. Many variations of these scales exist, with multiple utilised through the outlined research. In this study, the Defense and Veterans Pain Rating Scale was used [63]. Apart from pain intensity, Garcia et al. also assess pain interference, physical function and sleep disturbance, patient's global impression of change, pain catastrophising, pain self-efficacy, and chronic acceptance amongst other benchmarks [63]. Looking at the results, both groups reported a significant decrease in the average pain intensity. With a reduction of 42.8% and 25.1% for the therapeutic and Sham VR groups accordingly. The results achieved exhibit great confidence in the benefits such solutions generate for individuals suffering from pain. Similarly to the trends seen in [61], a gradual reduction in average pain intensity was observed in both groups as the days went by, as depicted in Figure 3.9.

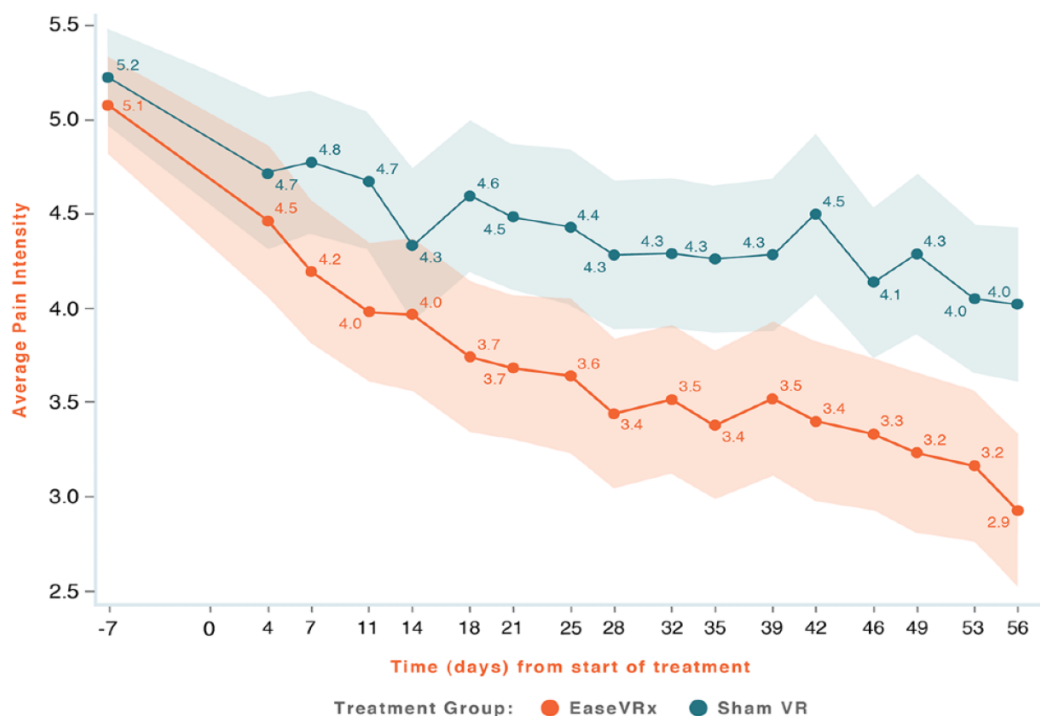


Figure 3.9 Average pain intensity score results as seen in [63]

This being said, however, the EaseVR group's reduction was much more

prominent. Although the sham group's treatment effect wasn't reportedly significant, the therapeutic VR group demonstrated a significant treatment effect with a p-value of 0.004, showing that the EaseVR treatment was medically effective. Looking at other primary outcomes, the pain's interference with mood, activity, sleep and stress all reported reductions in both groups, with the EaseVR group performing significantly better when it comes to the pain interference with stress and activity [61]. Interestingly, participant engagement did not vary considerably between the two groups. This result might, therefore, shed light on the role of immersion within these environments. Since the therapeutic environment should have been much more immersive, the pain mitigated might be tied more to the CBT and meditative exercises rather than immersion. Another factor contributing to this argument is that, as seen in both [61] and [63], the benefits significantly improved as the days passed. Overall, the EaseVR group reported a significantly better experience, with a notable reduction in the number of over-the-counter analgesics used.

Regarding treatment satisfaction, the EaseVR group was reportedly more satisfied and likely to continue using such treatment [63]. As can be seen, VR therapy solutions can effectively be used for pain mitigation, even over a longer period of time. Due to the nature of chronic pain, treatment must remain effective for extended periods, not just a few weeks. A particular strength noted in the pool of participants used in this study is the well-distributed geographical coverage, including participants from both rural and urban settings [63]. As outlined in Chapter 2, user demographics can significantly impact how individuals process and experience pain. With this in mind, a limitation might be evident in this work [63], where the participants are predominantly women. The findings here might, therefore, not translate well in terms of generalisation, and further research might be required on this front. Garcia et al. outline that the findings within this research align well with previous work, showing that highly educated females are more inclined to use self-care mindfulness-based digital health technologies. The fact that the participants all suffered from the same type of chronic pain might also pose limits for the results achieved, with further research being necessary to see how these results translate for other chronic pain conditions such as migraines.

In [64], Garcia et al. continue building on their previous findings, revealing further knowledge on the effects of VR solutions on pain mitigation. In this research, the authors shed light on the longevity aspects of the VR treatment, outlining the treatment's efficacy over six months post-treatment [64]. Although one would expect such treatment not to sustain substantial effects once stopped, the results found in [64] might shed new light on the psychological effects such a treatment boasts. Looking at the average pain intensity for the EaseVR group, a significant decrease was noted, with the average rating going from 5.1/10 to 3.0/10 from the initial to the

end-of-treatment results. Following these encouraging outcomes, as shown in Figure 3.10, the post-treatment results never exceeded the average pain intensity of 3.8.

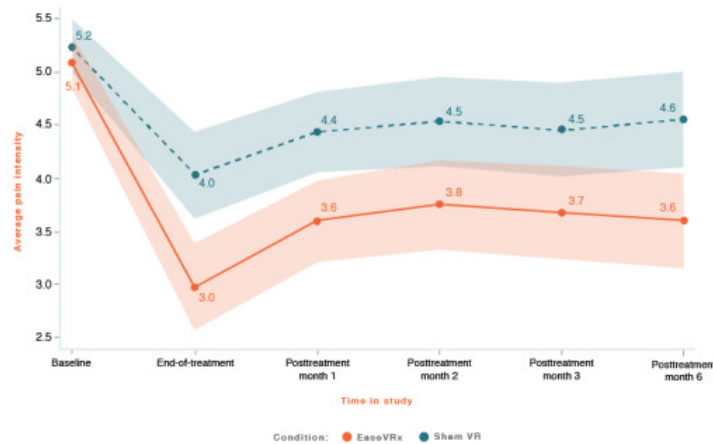


Figure 3.10 Garcia et al. average pain intensity results - 6 months post study

Six months after the participants' last therapy, the average pain intensity was still sitting at a remarkable 3.6/10, showing that some effects persisted for an extended period [64]. The same results were noted for pain interference with activity, mood, sleep, and stress metrics [64]. The results in the Sham VR group displayed similar trends, although these were less significant. Lastly, an interesting finding which [64] aimed to answer was the difference, if any, the socioeconomic status bears on the VR treatment's use and engagement. According to the authors, the examined socioeconomic status benchmarks, education level, and household annual income had no significant impact on treatment engagement, showing that such solutions can be helpful within many settings.

3.3.3 Virtual Reality Pain Therapy for Young Individuals

Looking at studies that apply VR therapy for other chronic pain conditions, Shiri et al. studied the pain mitigation efficacy of a VR system for young individuals suffering from chronic headaches [65]. Headaches are a common stressor in an adolescent's life [65]. The use of medication in young individuals should always be exercised with caution. As with any medication, medicinal side effects and overuse of analgesics might have severe consequences on an individual's quality of life [65]. This study consisted of 10 individuals aged 10 to 17, three of which were females. These young participants were all diagnosed with either chronic tension headaches or chronic migraines and had been experiencing these symptoms for six months or longer. An exciting approach outlined in this research is the implementation of biofeedback sensors, which record the users' galvanic skin response. This physiological signal was preferred due to its sensitivity to headaches, efficiently capturing the participants' discomfort. According to Shiri et al.,

such systems help users understand the complex relationship between their state of relaxation and headache progression [65].

The solution consisted of galvanic skin response sensors, the ProComp Infiniti system, and a desktop computer. Several images were captured for every participant, each representing a different emotional state. These included neutral, agony, and happiness. An algorithm then processed the sensor data in real-time and displayed the patient's image, which best corresponded with their emotional state. The participant's headache was also depicted by utilising a shape on the image, varying in colour and size depending on the headache's strength [65]. According to Shiri et al., these visualisations allow participants to track their progress in achieving a relaxed mental state, helping them better understand their ability and potential to control their headaches [65]. The more relaxed one becomes, the less noticeable visualisations become, allowing one's virtual self to guide them towards relaxation and away from pain. This study consisted of 10 sessions in total, each lasting approximately 30 minutes, depending on the patient's performance. The results are based on nine participants, as the tenth withdrew due to the perceived ineffectiveness of the therapy administered. However, the results show that the exercises and teachings produced good results. After treatment, participants reported significantly lower daily life intrusiveness related to their headaches ($P < 0.05$). Headache intensity was also compellingly lower post-treatment ($P = 0.068$ significance using the Wilcoxon paired sample test) [65]. The therapeutic techniques demonstrated promising results in reducing pain, with lasting effects post-therapy. Improvements were also noted in the participants' quality of life benchmarks, achieving a statistically significant reduction of 8.89 post-treatment, which persisted even during follow-up examinations [65]. As can be seen in both [64, 65], pain relief benefits last months after treatment [64, 65] and can therefore be effectively utilised for individuals suffering from chronic pain. A notable limitation seen in the study conducted by Shiri et al. was the technology used. Although the authors refer to the system as a VR solution, the technology used was not immersive and didn't use any well-known commercially available VR technologies. The limitations caused by inadequate VR technologies are further outlined in Chapter 3.2 where Hoffman et al. [54] compare the difference in results different technologies yield.

3.3.4 Pain Mitigation through Google's CardboardVR

Looking further within the domain of chronic pain and different VR technologies, Amin et al. [66] study and compare the efficacy of using a cardboard-based mobile VR tool versus the well-known Oculus Rift ⁶. The study consisted of 17 males and 15 females, all suffering from chronic pain. Throughout the experiment, the patients were not divided into different groups. Instead, all the participants tested both experiment variations. The solution utilised the 'InMind' application as a form of distraction, an application commonly used with the Google Cardboard VR. This allows the user to travel through the human brain following a predetermined path, shooting at enemy neurons within the environment. The authors mention that the environment is similar to SnowWorld, which was utilised by numerous researchers, including [50, 53, 54], and delivered outstanding results. In their study, Amin et al. accentuate the importance of providing an accessible solution that can be utilised by everyone, particularly since a majority of individuals suffering from chronic pain are unable to sit or stand still for extended periods [66]. To ensure that physical limitations are mitigated as much as possible, a swivel chair was utilised, which allows patients suffering from chronic neck pain to turn through the chair's rotation rather than having to twist their necks when using the VR headset [66]. Notably, the authors did not attempt to find a way to negate the game's head-tracking feature. Instead, they found a way to facilitate the user's experience while not impinging on immersion, greatly signifying the importance of immersion in these solutions. Similarly to the work carried out in this study, the complete experiment took 30 minutes on average and consisted of approximately two 10-minute simulations. Several questionnaires were provided before and after every session, capturing the participants' experience and their present and retroactive pain intensity [66].

The results conform well with the previously discussed literature, where the solution running on the traditional HMD achieved significantly less pain intensity scores than the pre-VR and cardboard VR experiences. The cardboard VR solution still performed well, however, and achieved significant pain-analgesic benefits when compared to pre-VR scores [66]. Even though the technology used impacts the results achieved, the cardboard solution is relatively inexpensive and can, therefore, reach a broader audience, especially given the prices certain VR headsets can reach. Given that the cardboard VR only requires a smartphone to run, the solution can be utilised as a home-based, cost-effective analgesic, which requires little effort and funds. This affordability and user-friendliness open doors for future research, which should delve further into the efficacy of such a solution, especially through minor adjustments, such as different software and increased comfort.

⁶https://en.wikipedia.org/wiki/Oculus_Rift, Last Accessed: 01/11/2023

3.3.5 The Efficacy of Virtual Reality Pain Mitigation Across Different Medical Conditions

In [11], Jones et al. investigate the use of VR pain mitigation on 30 participants suffering from various chronic pain conditions. The study employed the use of a VR application called 'Cool!' through the use of the Oculus Rift DK2 HMD. If the patient suffered from conditions that might impede or intrude on the VR experience, a stereoscopic 3D display 'DeepStream 3D Viewer' was employed instead of the traditional HMD. The authors state that research found no difference between the two VR technologies in terms of pain reduction and immersion efficacy [11]. Such technology can, therefore, be employed in situations where the user is suffering from injuries or chronic pain above the chest, which might be uncomfortable and hinder the benefits that can be achieved from such a system. As mentioned, Cool! was used throughout this study as a means of distraction. This consists of a fully immersive virtual fantasy landscape full of caves, trees, hills, snow and even otters, through which participants travel along a predetermined path. Jones et al. emphasise that throughout the environment, the participants travel at a slow and constant pace [11], which might minimise any nauseating effects the VR setting might produce. Calming ambient music is also played at a moderate volume, calming the user while not hindering communication with the researcher. Immersive attributes, such as the users' ability to interact with the environment, are also available in Cool!. Through an optical mouse, individuals can throw orbs and fish at flames and otters, both reacting through playful mannerisms, colour changes and sounds when hit [11]. An example of Cool! can be seen in Figure 3.11, where a snowy lake is presented together with several otters.



Figure 3.11 The cool! VR application as used in [11], reproduced from [67]

Notably, since the experience lasted for only five minutes, the authors state that numerous participants asked if they could use the application for a longer period of

time once the experience finished. Such a reaction motivates further research in this domain, where additional work can be done to enhance the users' experience, comfort, and immersion. This study satisfies multiple criteria desired from studies tackling VR and chronic pain mitigation. The most important of which is the assessment of the VR solution on multiple chronic pain-inducing conditions. Comprehensive coverage of various chronic conditions ensures that the results cover a wider audience and wouldn't solely pertain to a specific set of people. The list of conditions covered includes abdominal pain, chest wall pain, lumbar spine pain, thoracic spinal pain, cervical spine pain, hip pain, neuropathy, shoulder pain, interstitial cystitis, and myalgia (muscle pain) [11]. According to Jones et al., participants experienced chronic pain for an average of 16 years, ranging from 1 to 43 years. The inclusion of participants who have suffered from chronic pain for 43 years can provide further insight into the strength such solutions have. The results are particularly promising, with all participants reporting a degree of pain reduction throughout the experience. The group started with an average pain rating of 5.7 out of 10 and reported an outstanding 2.6 average pain rating during the experience [11]. After the experiment, the average results increased to a 4.1 pain rating, which is still a very optimistic outcome. Both results were statistically significant.

Interestingly, three participants noted no difference in pain intensity levels before and after the experience. However, all participants registered a decrease in pain as the experiment was carried out, with 33% of participants reporting an impressive 100% decrease in pain [11]. The participants' level of immersion within the environment might have played an essential role in the results achieved. The average virtual world engagement levels were 8.4 out of 10, demonstrating immersion that ensured the participants were thoroughly distracted from pain, with little room for improvement [11]. Participants' comments throughout the experience are outlined, with many requesting a longer version due to their great enjoyment. Jones et al. highlighted that despite using the standard Oculus headset, none of the participants suffering from neck pain reported any discomfort, even though head and neck movements were required throughout the experience [11]. Furthermore, the analgesic effects achieved over only 5-minute sessions were comparable to that of morphine, which reduces pain intensity by 30% according to research mentioned in [11]. It is a common misconception that technology-based solutions only appeal to younger individuals and that older people would not be interested in trying such therapy. However, it is essential to note that the median age of the participants in this study was 50 years old. This demonstrates that virtual reality-based pain management can also benefit older individuals who, according to the study, have no issue utilising and benefiting from such solutions [11].

As previously outlined, pain and stress relief have long been observed through

mindfulness and meditative practices. Garcia et al. [62] provided an example of this, where breathing exercises and mindfulness were integrated within their VR treatment. The following section aims to introduce VR based solutions that specifically employ meditation and mindfulness techniques to ease pain.

3.4 The Integration of Virtual Reality Mindfulness and Meditation for Pain Mitigation

Mindfulness and meditation are both well-known practices which date back thousands of years. Enriched through different cultures and religions, such as Hinduism and Buddhism, numerous meditative practices have been tailored for various uses [68]. Given the period from which they originate, meditative practices have been studied extensively. While some benefits might be up for debate, research shows that these methodologies can offer significant improvements when incorporated into our daily lives. Meditation and mindfulness practices, in particular, have gained recognition for their potential to enhance physical, mental, and emotional well-being [69], all of which are factors which can significantly reduce an individual's perception of pain. Many who practice meditation learn to embrace nature and surround themselves with scenes and elements that harness a sense of tranquillity during their practice. This is a prevalent theme in solutions integrating meditative practices with VR, with most environments depicting beautiful landscapes and calming music or sounds of nature. All of these are known factors that play a role in reducing perceived pain.

3.4.1 Virtual Reality Meditation and Opioid Use Disorder

An example of the described setting is seen in a recent study by Hargett et al. [70], where meditative exercises are integrated within a VR environment to study the efficacy of such methodologies for pain mitigation. In [70], the 'Calm' application was utilised with an Oculus Go HMD. As the authors outline, the Calm application offered ten different 10-minute guided meditations at the time of writing. These included guidance through popular philosophical practices, perseverance, choice, and gratitude, amongst other choices [70]. The application offers users a choice of meditation environments: a redwood forest, a white sandy beach, or a mountain lake, all known to induce a sense of serenity.

A significant advantage this study presents is that it is based on patients suffering from opioid use disorders, which incentivizes the development of non-analgesic pain management techniques due to these individuals' desperate need for non-analgesic pain relieving methodologies [70]. The study included 11 patients

suffering from acute pain and a form of opioid tolerance, abuse, or dependence. A notable precaution not mentioned in most of the studies reviewed is that due to the analgesic effects of some medications, the experiment was executed at least one hour after any medication was consumed. This ensured that the individuals' baseline scores captured the patients' pain ratings accurately [70]. A numeric 11-point scale from 0 to 10 was used to measure pain intensity before and immediately after the experiment. The experiment spanned ten minutes, during which the participants were guided through one of the ten-minute meditation sessions offered by the aforementioned 'Calm' application while utilising an Oculus headset [70]. A gender distribution of 54.5% female and 45.5% male was observed among the participants, eliminating any gender bias in the study's results. Prior to the experiment, the participants reported an average pain rating of 6.68 out of 10. With the average post-experiment pain rating score marked at 3.36, a statistically significant average pain score reduction of 3.5 was noted [70]. All patients reported reduced pain after the VR experience. Three participants reported an impressive 100% reduction in pain once the experience was over, with one of the participant's perceived pain levels dropping from 7 to 0 [70].

Given the encouraging results achieved, Hargett et al. highlight that patients suffering from opioid use disorders are more susceptible to reporting higher pain scores and have a more challenging experience when trying to mitigate pain, shedding light on the solution's validity. VR meditation, therefore, proved to be an effective pain mitigation methodology which most individuals can employ, even those who struggle with pain relief. It is also worth noting that the mean age in this study was reportedly 53.5. This shows that, as seen in [11], VR solutions can be effectively used by an older audience without any issues, even though they might not be as technologically inclined. Finally, the authors note that the medical professionals readily accepted the VR intervention, and there were no participant complaints. Overall, Hargett et al. report that their work proved that a statistically significant pain reduction can be achieved using low-cost VR technologies [70]. The results are conveniently condensed and displayed in Table 3.1.

3.4.2 The Amalgamation of Physiological Sensors and Virtual Reality Meditation for Pain Mitigation

In [71], Gromala et al. amalgamate numerous methodologies to produce the 'Virtual Meditative Walk': a virtual meditative experience tailored for pain mitigation. This proof-of-concept solution consisted of an immersive virtual environment, which, through biofeedback sensors and guided meditation, presents an immersive pain relieving environment [71]. The authors highlight that due to the nature of chronic pain, such studies cannot rely solely on distraction. In contrast, [11] had no meditative

Participant number	Pre-session pain rating	Post-session pain rating
1	8	3
2	8	6
3	8.5	8
4	4.5	0
5	7	4
6	7	6
7	2	0
8	7	0
9	10	5
10	7	2
11	4.5	3
Mean	6.68	3.36
Range	2 - 10	0 - 8
Standard Deviation	2.228	2.730

Table 3.1 Pain ratings per participant as seen in [70], reproduced from [70]

exercises or pain-coping mechanisms within their research and still obtained remarkable results. Providing users with mindfulness, meditation, and other pain-relieving methods ensures that they retain control over their feelings and emotions rather than relying solely on the immersiveness VR provides. Such solutions also pave an easier path for individuals to step into these well-established pain-relieving methods [11], which might appear daunting and complex without proper knowledge and instruction. An example of this is seen in the aforementioned research by Garcia et al. [63], where pain relief reaches its peak performance only after 15 sessions had passed, indicating that the meditative and CBT exercises had a significant impact on the results achieved. If the solution described in [63] relied solely on immersion, the highest pain relief scores would have been immediately visible. This progressive improvement highlights that such meditative methodologies take time and effort to learn. Gromala et al. utilise Mindfulness-Based Stress Reduction (MBSR), which they describe as a practice requiring sustained effort and time to master [71].

The Virtual Meditative Walk was specifically tailored for individuals to feel safe, focused and at peace within an environment that promotes an immersive and stable meditative experience. Such environments support individuals as they learn and master the physiological aspects required to benefit from MBSR [71]. The virtual environment takes the user through a virtual walk in a mountainous forest abounded with vegetation and greenery. As the user is taken along the predetermined path, the environment's weather changes based on the participant's cognitive arousal levels,

which are captured through galvanic skin response sensors. These visualisations help users understand their state of mind and allow them to work against something visible while witnessing the progress being made. An example is given which outlines how the environment's fog dissipates as the user achieves a relaxed state. Sounds are also mentioned, which become more apparent and spatial with decreased levels of arousal [71]. The study consisted of 13 individuals aged 35 to 55, all suffering from chronic pain. These were split into two groups: the VR group that experienced the entire solution consisting of the virtual environment and the audio-based MBSR, and the control group, which was only required to listen to the MBSR exercises. The 'DeepStream' stereoscopic viewer was used instead of commercially available headsets like the Oculus headset. The reason behind this decision was primarily due to the comfort and flexibility it offers. As opposed to conventional VR HMD that are generally worn on the head, the stereoscopic viewer sits in front of the users' eyes, as discussed in [11]. However, it is worth mentioning that in [11], none of the participants utilised the DeepStream technology when presented with the choice and preferred using a commercially available HMD. As outlined, the results achieved within Jones et al.'s study [11] displayed no issues with the HMD for patients suffering from chronic pain, even when the pain was located within the neck [11]. As a precaution, Gromala et al. [71] devised multiple design sessions, which clarified any limitations that might hinder the study's experiment. Notably, these focus groups outlined that some patients struggle to sit for 20 minutes straight and cannot bear the weight and pressure HMDs might induce. To simulate the effect of a walk, the authors lead us to believe that a treadmill was planned to be used. However, due to the complexity this introduced, this technology was omitted from the main study [71].

The main experiment consisted of 12-minute MBSR training sessions, where the technology used was dependent on the participants' group. The results show that the average pain levels decreased by 2.6 for the VR group. The control group, on the other hand, experienced no average pain reduction, with the readings being identical to before the session started. A statistically significant drop was noted in the VR group as time elapsed within the experiment, while the control group, on the other hand, harboured a very weak reduction [71]. These findings are incredibly encouraging and show that technology can significantly improve and amplify the benefits generated from practices that have been moulded for thousands of years. Such solutions can also significantly reduce the time individuals need to benefit from meditative techniques. This is mainly due to the immersive and distraction-less environment that VR introduces. As individuals become accustomed to the solution and the novelty aspect decreases, the pain relief is mainly derived from the environment's meditative benefits. In future studies, longer session times should be utilised to provide further insight into these solutions' relationship with pain relief and time, as seen in [62–64]. Gromala et al.

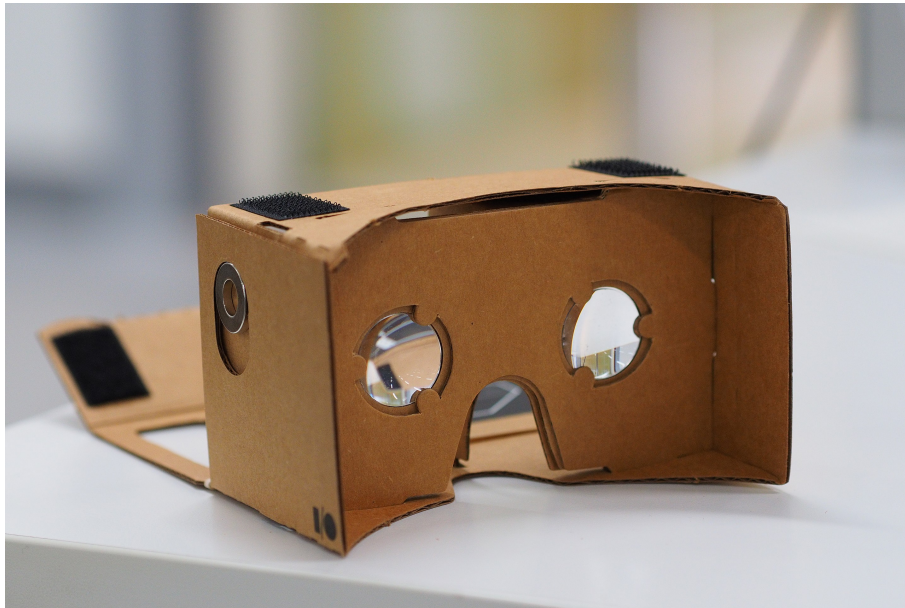


Figure 3.12 Google's cardboard VR as used in [66], reproduced from [72]

also highlight that the solution was built using a cross-platform game engine. This detail is vital for such studies as it introduces the importance of having solutions such as the virtual meditative walk, which runs on multiple devices. This ensures that individuals can utilise this technology without requiring a specific device. Comprehensive coverage is essential in such methodologies, whose reach is paramount. A similar approach is employed in our study, and the Unity game engine is utilised as the primary foundation for the solution built. This ensures that the application can run on multiple devices such as computers, HMDs like the Oculus, and even smartphones, which, when used in conjunction with portable stereoscopic viewers as seen in [66] and Figure 3.12, can effectively be used as a low-budget VR headset.

3.4.3 Virtual Reality Meditation for the Elderly

In [73], Baños et al. designed two virtual environments tasked to induce a sense of joy and relaxation in older people. As previously outlined in Chapter 2, stress and anxiety can potentially induce or amplify an individual's levels of perceived pain. This study, therefore, serves as a promising approach which indirectly affects the participants' pain levels through anxiety and stress mitigation. The study consisted of 18 participants aged 58 to 79, 14 of whom were women [73]. It is worth noting that most participants were not as technically inclined; most used computers for emails only, and 7 had no prior experience with computers. The experiment consisted of two 20 to 30-minute sessions in which the participants were asked to select one of the provided virtual environments: relaxation or joy. The study reigns prominence when describing the environmental aspects, providing an in-depth understanding of the solution's flow. The

virtual environment consists of well-known factors that induce positive emotions. These include greenery, vegetation, trees and blue skies. A path is provided that leads the users to a stone bridge where flowing water can be seen and heard, further instilling a sense of comfort. The path then leads to the main attraction, where a choice needs to be made between three other paths. Each path directs the user to a different emotional exercise, selecting from a lake, a stream, or a tree. As outlined, two variations of this environment were available for the users. It is worth noting that the elements used were selected through research, with colours, brightness and sounds all based on the emotions they elicit [73].

In the 'relaxed' environment seen in Figure 3.13, one can choose a path that includes a tree providing a slow rhythm breathing exercise, birds chirping, and subtle melodies, most of which are elements commonly employed amongst many of the previously outlined studies. A simpler approach is taken in the lake option, where the participants can observe and immerse themselves in its beautiful scenery. Finally, in the stream option, a mindfulness element is presented, through which the user is asked to focus on ongoing sounds, including music and flowing waters. As in most mindfulness practices, the user is encouraged to let go of any thoughts and focus on the sounds, redirecting their mind should it go astray throughout the exercise. Individuals are also asked to acknowledge thoughts during the experience and accept them for what they are, only thoughts [73]. The practices mentioned in this study conform closely to well-known mindfulness practices that guide the mind to the present moment by focusing on sensory elements [18].



Figure 3.13 VR Relaxation environment used in [73], reproduced from [73]

If, on the other hand, the user selects the 'joy' environment, they are presented with a brighter, colourful field. The user is offered three options, each providing a different joy-inducing exercise. The tree option tasked the user with reminiscing any pleasant memories they have had throughout their lives. Reviving these happy experiences, they are asked to describe the memory in detail, highlighting factors such as temperature, location, wear and scenery [73]. The stream option was similar to the lake option presented in the relaxation experience, where mindfulness practices are employed, tasking the user to focus on the things they see, such as colours, the sky's beauty and luscious greenery. Finally, the lake option presents a place of nature, including a beautiful sunrise. The participants are asked to absorb nature's beauty and bask in its magnificence, which is often taken for granted [73]. Once the initial sessions were completed, the participants were also allowed to try the other environment for two additional sessions, 10 of whom accepted the invitation [73]. Throughout this study, one cannot help but appreciate the options and care taken in devising an ideal environment for elderly patients. The results obtained indicate that both virtual environments were effective in reducing anxiety levels among elderly patients. The reduction in anxiety was statistically significant, suggesting that the virtual environments positively impacted the participants' emotional state. Moreover, the elderly patients reported high satisfaction levels with the virtual environment and felt greatly immersed and present within it [73]. Baños et al. identified several limitations in their experiment. The study's small sample size lacked diversity, possibly leading to inconclusive results. Additionally, it lacked a control group that experienced a neutral environment. Such a setup would aid in further understanding the benefits of the environmental elements specifically tailored to reduce anxiety. In contrast, our study addressed this limitation by first exposing the participants to a default version of our virtual environment before proceeding to the main proposed solution, highlighting whether the personalisation factors produce better results.

3.4.4 Virtual Reality Meditation and Cognitive Function

In [74], Kosunen et al. present 'RelaWorld', a VR environment specifically tailored to facilitate meditation and derive further value from the practice. Given that such practices tend to be quite challenging for beginners to grasp and engage in, the authors aimed to produce a neuroadaptive VR solution that combines numerous technologies, resulting in a beneficial tool for both beginners and experts. An interesting approach is taken in this study, in which the users' brain activity levels are recorded in real-time using an electroencephalogram sensor. After processing the sensor's data, these readings are used to estimate the users' levels of concentration and relaxation [74]. Although this study does not focus on pain specifically, systems which have been

previously outlined within this literature review, such as [71], are also mentioned, highlighting the therapeutic effects such solutions can have on individuals suffering from chronic pain amongst an array of other conditions. Perhaps lending to the definition of immersion provided in the research, in *RelaWorld*, users find themselves immersed in a virtual tropical island. The definition provided highlights the metaphorical origin of the term 'immersion', stating that it mainly derived from the physical experience of being submerged in water [74]. Instead of water, in the VR environment, users find themselves surrounded by a bubble of energy whose clarity varies depending on the users' state of relaxation. As seen in most studies, the Oculus Rift DK2 HMD was utilised to immerse individuals in this alternate reality. In contrast with most of the papers reviewed, the authors outline that Unity3D⁷ was the game engine utilised to develop their solution. Given that Unity is a multi-platform game engine, *RelaWorld* could, therefore, be enjoyed on a plethora of other devices, ensuring that the solution is accessible by many individuals. Seeing the unity engine deliver such well-performing outcomes, this study served as an excellent motivation to select the game engine to be used as the basis of this research.

Kosunen et al.'s [74] solution was created specifically for meditation and offers two different practices: focused attention and body scan. Both of which are tailored to help individuals with their meditation practice. In the focused attention option, a number of floating spheres are displayed, as depicted in Figure 3.14. By highlighting a

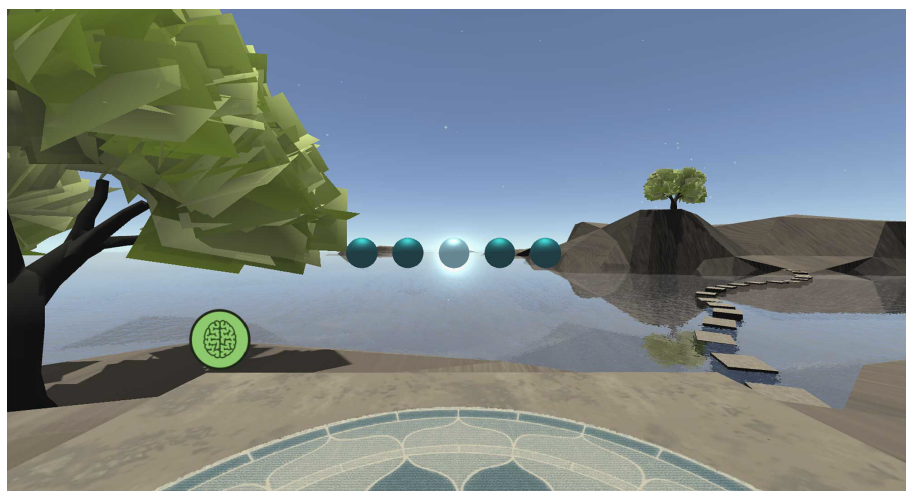


Figure 3.14 Focused attention exercise as shown in [74], reproduced from [74]

specific sphere, the user is instructed to focus on one particular object for several seconds until the selection is shifted. An earlier iteration of the solution didn't employ a shifting methodology, which resulted in numerous individuals complaining that the procedure was too monotonous. Having to stare at the same ball for 10 minutes or so, the participants also complained of eye strain, with some even outlining that they even

⁷<https://unity.com/>, Last accessed: 05/11/2023

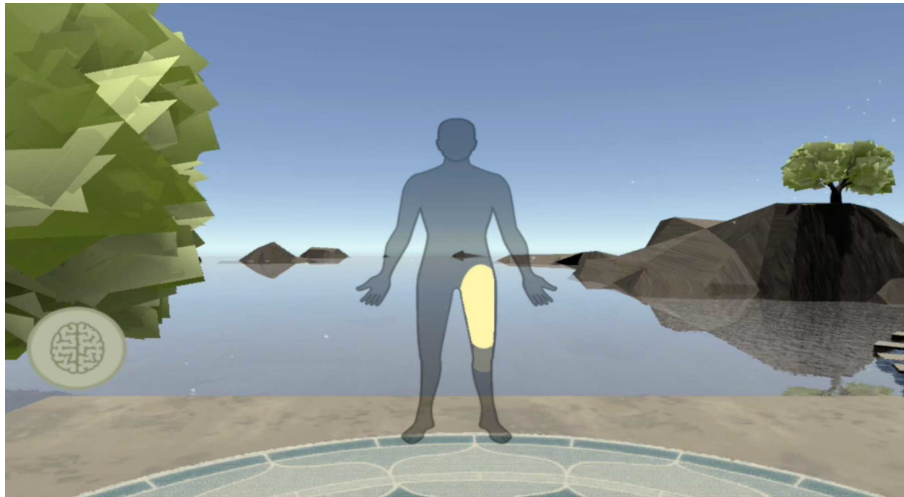


Figure 3.15 Body focus exercise as shown in [74], reproduced from [74]

started to shift focus to the LED screen's grid instead of the spheres at particular times, further highlighting the monotonous nature of the exercise. During the body scan exercise, a greyed-out representation of the body is displayed, indicating which body part to focus on and relax [74] as shown in Figure 3.15.

This exercise guides individuals by highlighting specific body parts the user must focus on until full body coverage is achieved. An interesting approach is employed through the study's experiment, where 43 university students aged 20 to 48, 26 of whom were female, were assigned to complete a set of tasks throughout the procedure. Initially, a baseline 5-minute reading was taken prior to the actual experiment, serving as a control reading. The individuals were then tasked to complete six 10-minute relaxation exercises using Relaworld. To nullify the effects of previous meditations and induce stress within the participant, 3-minute memory tasks were employed between sessions. Overall, the whole procedure lasted approximately 2.5 hours [74]. In the domain of pain mitigation, none of the studies digested throughout this literature review experiment with sessions of that length. Conversely, many authors emphasise the importance of short procedures due to the discomfort lengthy sessions might induce in patients suffering from pain. The study compares the results achieved through three different settings: a control condition where the solution is running on a standard monitor without any biofeedback adaptation, the solution running on a HMD without any biofeedback, and finally, the complete solution with all the implemented features and biofeedback, running on a HMD [74]. This comparison is incredibly beneficial in furthering our understanding of how different aspects and adaptations affect the solution's efficacy in reducing anxiety. This knowledge can also be utilised in this work to reduce an individual's pain level, mainly due to the strong relationship such psychological factors have on the perception of pain, as outlined in Chapter 2.

The results show no statistical difference between the focused attention and

body scan meditation types. The participants reported finding the focused attention exercise more boring compared to body scan when used without the HMD and neurofeedback, as highlighted by a meditation depth questionnaire [74]. Regarding meditative immersion, the HMD with biofeedback performed the best. When the HMD approach was compared to the control group, a statistically significant drop in score was noted. It is worth noting, however, that with regard to meditation depth, no statistical significance was present in the difference between the neurofeedback solution and the HMD-only solution [74]. Examining the negative factors which individuals might associate with meditation, such as anxiety and boredom, the results show that individuals experienced significantly more negative emotions through the screen-only experience (control group). Although the neurofeedback condition performed best in this regard, no significant difference was noted compared to the 'HMD only' condition. Relaxation, self-reflection and happiness, on the other hand, were significantly lower in the control condition. Interestingly, no notable difference was noticed between the other two conditions. Finally, the neurofeedback condition reported the highest perceived levels of presence, while the control condition, as expected, exhibited the lowest levels of presence [74]. The authors, therefore, outline that even though VR provides a significant increase in meditative benefits, neurofeedback technologies have the potential of further immersing individuals in meditative practices [74].

3.4.5 Virtual Reality, Cognitive Behavioural Therapy and Fibromyalgia

Botella et al. [75] discuss the efficacy of CBT in conjunction with a meditative VR environment to treat patients suffering from fibromyalgia. The study consisted of six women aged 47 to 65 years old in total, all of whom were diagnosed with fibromyalgia by a rheumatologist [75]. On average, the sample was suffering from the condition for 11 years, clearly indicating that the pain felt can be classified as chronic [75]. In terms of medication, all participants were taking some form of analgesics. Three of them were taking steady doses of pregabalin [75], which is an analgesic commonly employed to relieve neuropathic pain and is also prescribed for conditions such as fibromyalgia [76]. The rest of the patients, on the other hand, were taking over-the-counter painkillers. It is important to note that the authors informed the participants to maintain their medication regime and not make any changes because of the study. Multiple measures and questionnaires were used to capture the study's results accurately. These included the FM Impact Questionnaire, Chronic Pain Coping Inventory, VR Satisfaction Scale, Positive and Negative Affect Schedule and the Beck Depression Inventory-II [75]. An interesting approach was taken in the treatment used by Botella et al., where the exercises involved a group CBT program for individuals

suffering from fibromyalgia. The program utilised VR depending on the exercise being carried out, which ensured that individuals were relaxed and focused on the task at hand, as will be further explained in the following section.

Given the different nature of therapy utilised in this study, it can be noted that the sessions were much longer than in other studies. Botella et al. delivered 10 group sessions in total, all of which were approximately two hours long [75]. The length of these interventions is quite surprising, especially given that multiple studies, as mentioned earlier, stress the importance of shorter sessions when dealing with individuals suffering from chronic pain. The authors also highlight that the sessions were delivered with varied frequencies; the first six weeks aimed to provide as much information as possible, acclimating the participants to the teachings and methodology utilised. The last four sessions were then delivered on a weekly basis, minimising aid and support to promote user practice [75]. As outlined, the treatment consisted of multiple parts that encapsulated vital teachings and methodologies that helped individuals understand their condition and unwind. The sessions notably consisted of in-depth explanations of the nature of chronic pain and fibromyalgia, how CBT can help with these conditions, teachings of relaxation and how such practices can significantly affect their quality of life, activity pacing, cognitive restructuring, mindfulness, and relapse prevention [75].

Given the nature of the study, integrating VR within all aspects of the aforementioned segments would prove quite difficult and might even nullify the technology's benefits. Botella et al., therefore, employ VR to assist in a number of these segments, particularly in the relaxation and mindfulness components [75], which are the ideal disciplines where the technology is seen providing excellent results. This being said, VR could have been implemented in additional segments, such as the CBT teachings and exercises, as successfully demonstrated in previous studies [61–64]. Although slight limitations in using VR existed within this study, the technology was still successfully employed, yielding good results. In the relaxation component, VR was used to deliver slow breathing training and exercise for 10 minutes accordingly [75]. Once the 10-minute training was completed, the participants were instructed to maintain their slow breathing rhythm for another 10 minutes. To enhance user experience, a peaceful virtual environment with calming visuals and sounds of the sea or meadow was provided [75]. VR was also used in the mindfulness segment, where the same environment was used to immerse and teach the participants how to observe different elements, which often go unnoticed or unappreciated. This included observing the waves at the beach, listening to the flow of water, and the seagull's calls. Such teachings are commonly employed in mindfulness practices and help individuals live and appreciate the current moment. As for the pain the participants might have been experiencing, they were asked to observe their feelings and redirect their

attention back to the stimuli presented in the virtual environment. After both exercises, the participants were asked to continue these practices outside the experiment without using VR. This ensured that the participants honed the skills they would have just learned and applied these teachings to real-world scenarios [75]. A limitation noted in this study is the technology used for the virtual environments. Instead of utilising the standard HMDs, a large display and speakers were employed to immerse the group of individuals within the environment. Since HMDs offer a greater success rate in pain mitigation, using this technology could have improved participant immersion and the results achieved.

It is worth noting that the solution used, 'Engaging Media for Mental Health Applications', contained more than the two environments outlined, including a forest, a desert and a snowy landscape, which are meant to invoke different emotions in the users. Our solution's algorithms can generate environments similar to these descriptions, specifically tailored based on the user's predicted liking. The results show that the participants were very satisfied and accepted the use of VR to support the CBT therapy provided. Looking into the participants' abilities and daily life function, the 'Fibromyalgia Impact Questionnaire' showed that the functional status improved significantly throughout the six months post-treatment follow-ups. Although the levels of depression were not significant throughout the study, a drop was noted when the pre and post-experiment levels were compared. However, no notable difference was seen in the follow-up results [75]. Botella et al. demonstrate that the segments integrated within their therapy can significantly improve participants' well-being, with a notable increase in positive affect from post-experiment to follow-up sessions. Improvements in the participants' coping strategies were also noted [75]. Interestingly, the authors outline that such a solution is relatively cost-effective. Allowing the participants to be grouped while undergoing the experience significantly reduced the time taken and resources required. Overall, the participants were delighted with the solution, stating that the VR aspects helped them immerse themselves further into the treatment. Additionally, participants reported that the benefits of using VR extended beyond the sessions, as they could recall the calming visuals provided and effectively practised the therapeutic techniques at home [75].

3.4.6 Improving Meditation through Gamification

Choo and May [77] utilise well-known gamification techniques to promote meditation within the proposed solution. Known to increase user engagement and solutions' efficacy within the digital health domain, the benefits gamification techniques deliver are well known [77]. In their solution, a point-based system, 'Serenity', was used to reward the player for successful meditations. The authors highlight that a successful

meditation is not based on the users' performance but on its completion [77]. This mitigated any performance anxiety that might be induced through users' attempts to get the highest score, which would nullify the concept behind meditation itself. This further reinforces the notion that mistakes and poor performance are not only tolerated but encouraged as a means to improve oneself. These points could then be used to unlock hidden content, such as new mindfulness scenes and meditations. Although this might seem like a limitation in terms of the availability of such practices within the solution, Choo and May highlight that unlocking these features over time, rather than having everything from the start, does not overwhelm the user with too many options and allows individuals to acclimate themselves into the process [77]. Regarding the chosen environments, well-known meditative locales such as Angkor Wat were utilised and implemented within the solution, as seen in Figure 3.16.



Figure 3.16 VR Meditative Locale: Angkor Wat, reproduced from [77]

Calming sounds, such as birds chirping, were also integrated, further immersing the user in a meditative state. As outlined, numerous meditations were included within the application. These were 20-minute-long sitting mindfulness sessions, which also included guided breathing exercises. As seen in previously mentioned studies, Choo and May utilise physiological sensors that measure the users' emotional state. In this solution, an 'Emotive electroencephalogram headset' was used to measure the electrical activity in the participants' brains [77]. This was employed to encourage participants to relax and help them visualise their progress by altering the environment through their emotional state. For example, in the aforementioned Angkor Wat environment, flowers bloomed all over the area as the participants relaxed. Although an experiment utilising this solution was proposed, the research the authors mention could not be found at the time of writing, making it a significant limitation within the work outlined by [77].

3.4.7 Cognitive Engagement and Mindfulness Approaches in Virtual Reality Pain Therapy

Garrett et al. [78] conducted a study to evaluate the perceived effectiveness of VR therapy for managing chronic pain in cancer patients. For this, the authors conducted a two-armed participant-blinded qualitative experiment coined 'immersive multimedia' through which 23 participants were randomly assigned to either a VR group which utilised an HTC Vive stereoscopic headset⁸ or a non-VR control group which used a laptop display. The study involved four interventions, two cognitive and two based on mindfulness therapy and meditation [78]. The 'Carpe Luceum' and 'Obduction' applications were used in the cognitive interventions to invoke the mind. In Carpe Luceum, the user is asked to complete a series of puzzles in a soothing environment, as seen in Figures 3.17, and 3.18.



Figure 3.17 Carpe Luceum calming VR environment, reproduced from [79]

In Obduction, the user engages in a beautifully detailed environment as visualised in Figure 3.19, partaking in a sci-fi adventure and completing puzzles as the story progresses. For the mindfulness interventions, on the other hand, the authors use the solution seen in [71], titled 'Virtual Meditative Walk', along with 'Wildflowers'. In WildFlowers, the participants fly through a calming virtual environment as a butterfly, completing meditations as they progress. The study spans a total of 4 weeks with six 30-minute sessions per week (30 minutes per day). Several scales and questionnaires were used to measure the results achieved, including the VAS and the McGill Pain Questionnaire [78]. It is important to note that different types of cancer can cause varying levels of pain for individuals. Since the efficacy of pain mitigation techniques might vary depending on the kind of pain, having studies experiment and test these

⁸<https://www.vive.com/us/>, Last accessed: 08/11/2023



Figure 3.18 One of the puzzles in the Carpe Luceum VR environment, reproduced from [79]



Figure 3.19 Obduction VR game, reproduced from [80]

solutions in different scenarios increases confidence in utilising them in medical settings. The participants' pool consisted of patients suffering from different types of cancer, including abdominal, breast, bone, colon, kidney, lung, non-Hodgkin's Lymphoma, and throat cancer [78]. Twelve participants took part in the focus group that was implemented. The median ages of the groups were 59 and 58, respectively, with ages ranging from 37 to a maximum of 73. This inclusive range of ages can further back up the notion that VR interventions can be enjoyed and utilised by anyone, regardless of age. Although the results of the main study are still to be published or made publicly available, this research focuses on the aforementioned focus groups, which invited participants from the main study to provide an in-depth review of their VR pain mitigation experience [78]. This was done through an interpretative description method to provide a deeper understanding of the participants' opinions

Table 3.2 VR Experience Survey Questions reproduced from [78]

	Category	Guide Questions
1	General Experience with VR	Tell me about your experience with using VR. Are there any other points you would like to discuss about your experience using VR?
2	Pain Control	How useful did you find the VR experiences in managing your pain? If yes, how so? Which of the VR environments did you find most useful/worked best for your pain? Which of the VR environments did you find the least useful/worked least for your pain?
3	Other Benefits	What sort of benefits did you get out of using VR? Did the VR help with your sleep in any way? Did the VR help with your mobility in any way?
4	Adverse Effects	Did you experience any physical problems from using the VR? (probe: headache, nausea)
5	Support Required	What would you put off using VR in the future? What would encourage you to use VR in the future? What sort of support did you need to use the VR environments effectively? Was there sufficient help for you to use the VR environments?

and personal experiences, expanding the knowledge available in this emergent domain.

Garrett et al. [78] also shed light on the focus groups' pain characteristics, experience with gaming, and experience with VR, all of which are factors which might impact an individual's VR pain mitigating experience. A list of questions was devised as summarised in Table 3.2.

The questions asked throughout our experiment were significantly influenced by the questions provided by Garrett et al. [78]. Looking at the participants' opinions for the cognitive and meditative VR interventions, the results achieved show that participants preferred the meditative exercises, with Wildflowers being the most popular [78]. Several participants emphasised that environments consisting of an open world without roaming restrictions were greatly valuable. The users also commented on personal preferences' impact on an environment, stating that since such tools offer an escape from the reality of pain, having different environments would greatly benefit individuals, allowing them to immerse themselves for as long as they desire [78]. These comments further promote the framework built throughout this research, where an endless environment is generated based on users by employing different algorithms and software engineering principles and techniques.

Looking back at the findings by Garrett et al. [78], although 7/12 participants enjoyed the cognitive exercises, some found the puzzles tedious and frustrating. One

participant in particular even mentioned that the frustrating, stringent environment worsened their perception of pain [78]. The authors discussed comfort and usability as significant factors in therapeutic VR. Many participants shared negative feedback about their experience, citing discomfort caused by the headset's weight, prolonged session duration, limitations due to prescription glasses, and seat discomfort as critical issues [78]. Even though the main consensus was that the technology was quite uncomfortable to use, one participant in particular commented on the availability of this solution. They stated that having such a solution in the comfort of your own home helps you disconnect whenever you need to. Not having to go to the hospital for pain-relieving interventions also reduces the effort required and ensures that the solution is accessible to many [78].

Another factor which was brought up was the cost of these technologies. Although cheap options like the cardboardVR seen in [66] are available, factors such as efficacy and usability are limitations one must consider. Participants were asked about their perception of the VR experiment's effects concerning pain mitigation and their daily lives [78]. The results show that most users found the solution beneficial, with some stating they would be looking forward to their daily session as they realised that they were not feeling pain throughout the experience. Four patients, however, reported no benefits and even specified that specific exercises amplified the pain they were experiencing. A participant mentioned that the meditation inviting the user to focus on the pain felt aggravated the discomfort. The consensus was that the environments were very calming, with the beautiful scenery and meditation instilling a sense of fascination. Some environments, however, were unbearable to some users. Obduction seemed to generate frustration among some individuals, and Wildflowers, which involved flying around as a butterfly, had nauseating effects, although this receded as the experiments progressed [78]. Numerous studies reported long-lasting decreased pain ratings after the VR therapy. Garrett et al. [78] outline that most participants did not notice any persistent benefits. Five participants described some extended benefits, including pain mitigation lasting for approximately an hour, better sleep, and increased mobility [78]. Relaxation and immersion were the most prominent factors which induced pain relief among participants. Some participants mentioned that elements such as influencing the environment increased immersion. One, in particular, emphasised that the solution helped them connect back to their past, where they would hike, travel, and be active, activities which they were physically unable to partake in due to their present condition [78].

Overall, this study conveyed that the results VR solutions induce are highly dependent on numerous variables. Factors such as environment, technology and personal preferences are all aspects that affect the solution's effectiveness [78]. Personalisation is essential, with the authors stating that generic solutions are unlikely

to be fruitful for all participants [78]. Environmental design aspects such as nature, soundscapes and other positive atmospheres might produce better results and must be considered for a beneficial solution. This study, therefore, provides good backing behind the solution built in this research, where a personalised VR environment is created at run time, depending on the user making use of it.

3.4.8 Virtual Reality Meditation for Pain Mitigation through Self Discipline

Finally, we take a look at the work by Faraj et al., which details the changes a VR meditative intervention delivers for pain mitigation in individuals suffering from opioid use disorder. Compared with other studies that use self-assessment questionnaires, Faraj et al. dive into the physiological changes the body goes through when experiencing pain. This is done through a deep understanding of the patient's pain neuromatrix (a collection of brain regions fired when individuals experience pain)[81], cortisol levels and C-reactive protein (inflammatory biomarker) [81]. Self-assessment questionnaires were also used to assess the patient's pain ratings and other crucial benchmarks. Interestingly, research shows that meditative interventions influence the pain neuromatrix and its connectivity [81]. The study took place over 12 weeks, through which participants engaged in VR meditative therapy. Several baseline measures were collected before the study, including chronic pain, distress, self-efficacy, and emotion regulation. Pain ratings were collected before and after every intervention. Four saliva sample collections and two Magnetic Resonance Imaging scans were also performed. Faraj et al. outline an exciting approach for the intervention they devised. Instead of solely focusing on the relaxing attributes generally assimilated with meditation, the authors present the notion of martial art practices within VR [81]. The reason behind this methodology follows the concept that martial artists are generally portrayed as powerful beings with a tremendous sense of self-discipline and control. As outlined in [81], such practices might intrigue individuals who seek to reclaim their lives and not let pain or substances control them.

The VR environment developed takes the participant through various coordinated movements alongside specific meditative and breathing techniques. Faraj et al. emphasise that the exercise was designed to instil the feeling of a mighty warrior who must courageously face his struggles and reclaim his life. These chained movements and breathing techniques are coined 'Breath Brake' [81]. This Tai-chi-like movement consists of inhaling, holding in the breath, and exhaling, each in three-second segments while performing several controlled movements [81]. A comprehensive explanation of the 'Breath Brake' technique can be found in the work by Faraj et al. [81]. Furthermore, the participants were introduced to the Kids Kicking

Cancer Foundation and had one-to-one time with a specialised therapist who assisted with the teachings of the Breath Brake exercise, movements, breathing, and meditative techniques. A 15-minute VR based meditation is introduced, consisting of a novel approach not seen in any other studies reviewed.

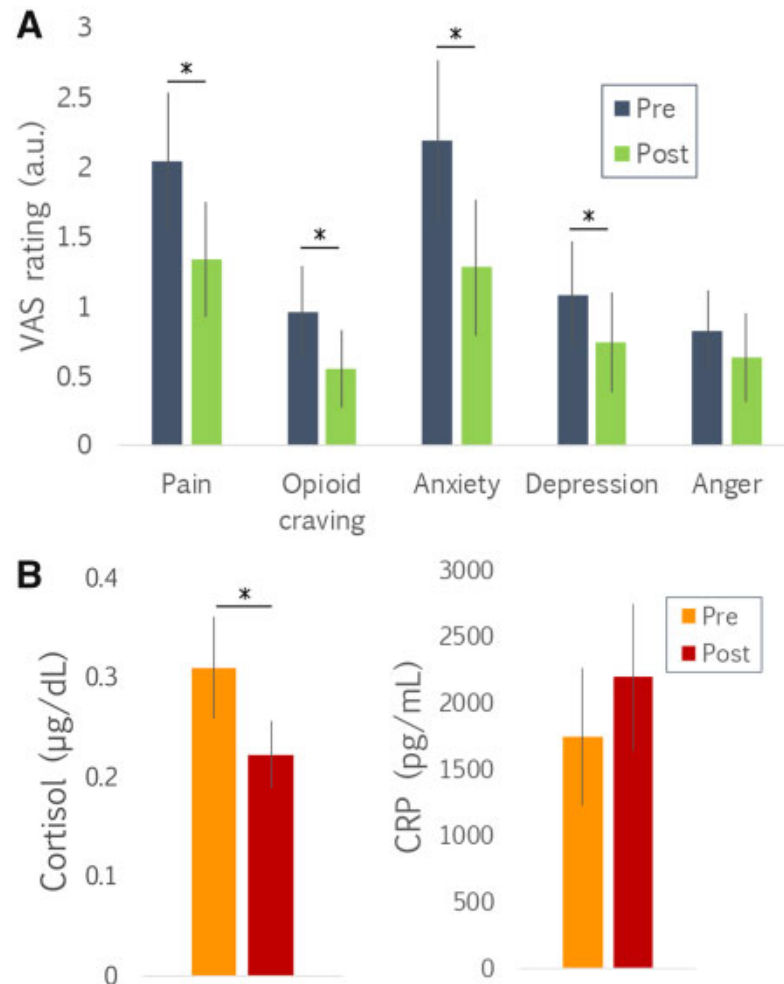


Figure 3.20 Results achieved in [81]

Initially, the VR intervention introduces eight children from the Kids Kicking Cancer program, stating that they experience less pain knowing that they are helping others learn. Perhaps a play at the users' emotions, the participants are asked to perform the Breath Brake exercise. They are also informed that the therapist managing the session will report their progression to the kids. The notion that our brain can be our downfall is then introduced as a monster, which can only be defeated through the participant's breathing, as explained by one of the children who appears next to the visualised monster. After the beast shrinks down, it washes away into a waterfall scene, initiating a waterfall meditation session. Although a HMD was used throughout the interventions, the participants were also given a smartphone-based application which they could use in the comfort of their own homes. Reminders using the children's voices were also implemented, encouraging participants to perform the Breath Brake

exercises [81]. The results outlined were based on fifteen participants who completed the study and were primarily females. It is worth mentioning that the participants were chronic opioid users taking an average of 95mg of methadone daily and reportedly suffered from lower back pain [81]. None of the baseline pain metrics were associated with demographic characteristics, anxiety, methadone dose, or depression. As displayed in Figure 3.20, the therapy sessions demonstrated significant effects on the VAS pain scores, depression, anxiety, and opioid cravings, with noticeably lower post-session levels. The opioid cravings displayed an interesting pattern, where they decreased for the first six weeks, increased again for two weeks and decreased for the remaining two weeks. A significant effect was also noticed in the cortisol levels, where the post-session levels were significantly lower. No changes in the C-reactive protein were noted [81].

3.5 Overview

As the literature reviewed shows, VR methodologies can effectively mitigate acute and chronic pain. Various factors play a significant role in relieving pain through such solutions. Elements such as gender, culture, race, and pain characteristics are all facets which need to be taken into consideration. Notably, the literature highlights the importance of well-performing technologies such as HMDs, immersive applications, and comfort within these solutions. To produce an immersive experience tailored to one's requirements, the environment must be personalised, capturing the user's characteristics, needs, and personality well. Significantly reduced pain ratings are noted through the reviewed research even though a non-personal solution is utilised. However, several aspects and constraints must be considered when examining these outcomes. These include small participant pools, lack of participant and pain type generalization, study longevity, and other VR methodologies implemented. Meditation, mindfulness, and CBT emerged as significant approaches that affected the efficacy of pain relief. Participants outline the importance of personalised environments that provide ways to disconnect from reality and relax. Due to the endless combinations of individual tastes and preferences, creating a personalised environment using conventional game development practices is not feasible. Therefore, the work done through this research aims to provide a solution that employs numerous algorithms and software engineering methodologies to produce an entirely personalised environment built at run-time. Using machine learning algorithms, PCG techniques, Unity, and an Oculus 2, an accessible VR environment is produced. The following Chapter describes the methodology used throughout this project, highlighting all the development work done to achieve this novel VR pain mitigation environment.

4 Methodology

The foundations of a project are arguably the most essential aspects of a solution. To build something which accurately captures and solves a problem, one must first research and understand the problem's domain. Through a careful background and literature review, this work aims to deliver an effective VR framework which produces personalised VR environments that relieve pain through mindfulness, distraction, and immersion, as can be seen in Figure 4.1. As briefly outlined, this work also presents a novel approach in this domain, where PCG methods and algorithms are used alongside user modelling strategies. This approach offers an environment which is generated at run-time and is unique for every individual using it.

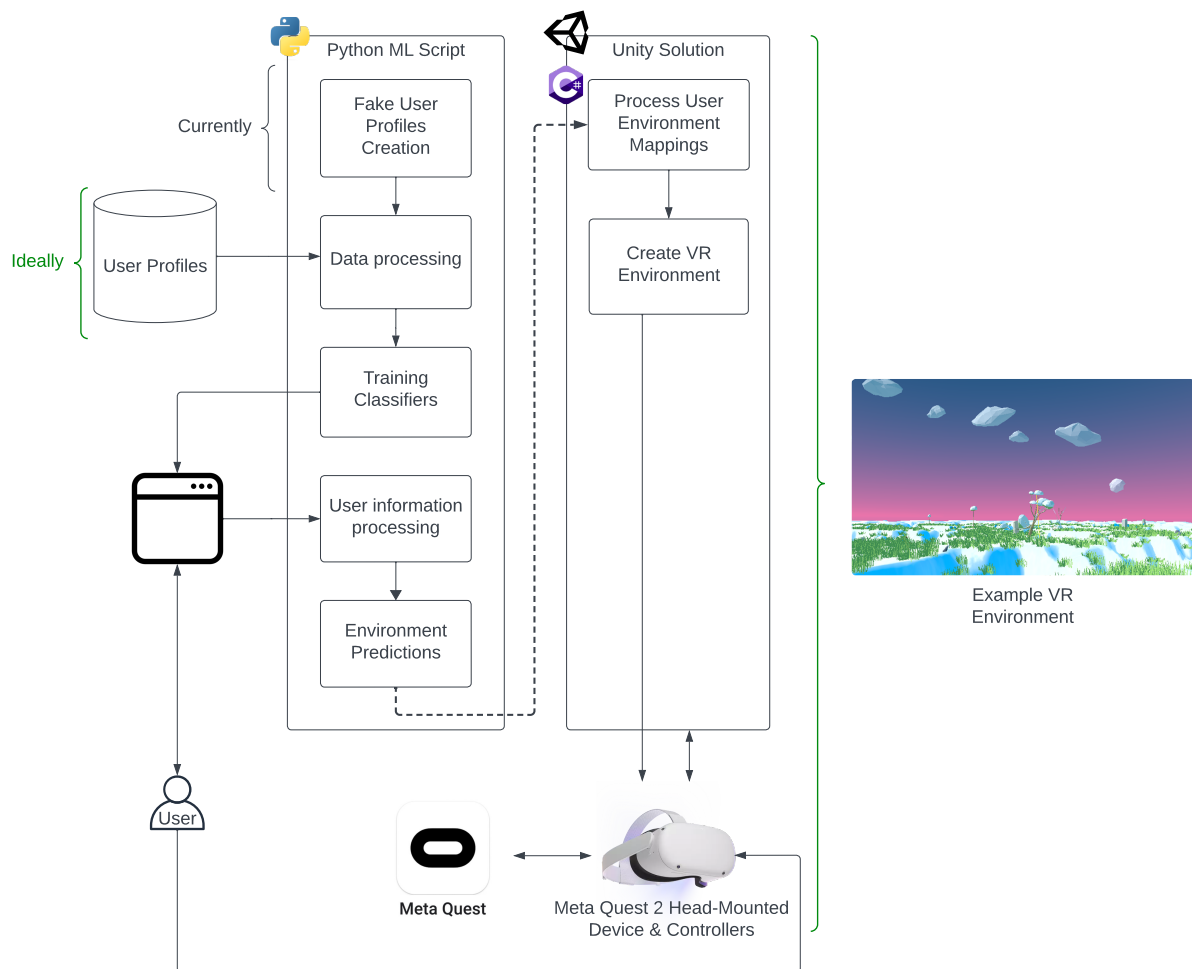


Figure 4.1 Framework Built

4.1 Design and Development of an Immersive Virtual Reality Environment

4.1.1 Project Design

The first part of the solution consisted of carefully devising a methodology that efficiently addresses the problem at hand. The project can be divided into two segments: developing and testing the solution built and the design and execution of an experiment. This chapter aims to thoroughly explain the artefact created, highlighting its development process, choices made, and issues faced, amongst other aspects.

Selecting an Appropriate Game Engine

Several game engines exist, serving as the main foundations of any game project; selecting the engine best tailored to a project's requirements is fundamental. Therefore, a careful understanding of the most popular game engines was necessary to decide which technology would best support the planned solution.

Unreal Engine¹ is a considerably popular game engine. Widely renowned for its visual capabilities, It provides various game development tools to develop beautiful and robust games. Capable of supporting the development of vivid games, Unreal Engine is notably an excellent option one can utilise to create immersive solutions that distract users from their pain and discomfort. However, a consideration which needs to be weighed in when developing VR solutions is the devices' capabilities. Realistic games require a lot of resources to run, especially when it comes to the device's Graphical Processing Unit (GPU), Central Processing Unit (CPU) and Random-Access Memory (RAM) capacities. Given that most commercially available HMDs are not as effective when running demanding games, a graphically intensive game would require another device, such as a gaming computer equipped with powerful components capable of bearing the solution's load.

Commercially available VR devices are quite expensive. Needing other devices strong enough to handle graphically intensive environments would significantly increase the monetary burden such solutions already introduce. Such factors must be considered when proposing solutions that must reach a broad audience. Pain doesn't discriminate; it can affect the rich and the poor. Individuals suffering from pain shouldn't have to suffer more due to not being able to afford therapy, which can improve their quality of life. With this in mind, further research was conducted, and Unity was chosen as the game engine for the solution built.

¹<https://www.unrealengine.com/en-US>, Last Accessed: 15/10/2023

Unity² is another popular game engine widely utilised for game development. Given that Unity was also employed in [74], selecting it as this project's foundation instilled much more confidence and ensured that a good solution could be built. Several factors made Unity an ideal tool, including its vast collection of assets and libraries, VR support, cross-platform development, C# scripting, ease of use, and detailed documentation. VR libraries are available in the Unity store, which allows developers to seamlessly integrate VR functionality within their application, depending on the hardware used. Another important factor is its multiplatform capabilities. As seen in the literature reviewed, entry-level VR technologies such as the Google Cardboard VR exist. These are capable of simulating a VR environment through the use of a smartphone, significantly increasing the use-ability and audience reached. It was of utmost importance then that the solution built could run on multiple devices and operating systems, including computers, HMDs, and smartphones.

Selecting the Best Virtual Reality Head-Mounted Device for a Pain Mitigation Solution

Numerous devices can be employed for VR. The Meta Quest 2 HMD was used in this project. This is composed of the HMD itself and two hand controllers. Having a refresh rate of up to 90Hz (or 120Hz using the experimental option) [82] creates a smoother experience, minimising the nauseating effects such devices suffer from. The display also boasts a high resolution that ensures the image is immersive and precise, an element exceptionally desirable in all displays [82, 83]. Most importantly, the headset sits comfortably and offers a fully immersive experience which covers the user's entire field of vision. Furthermore, the device's light nature (503 grams) [82] ensures that individuals suffering from pain are comfortable and immersed, which, as highlighted in the study by Garrett et al. [78], is a vital aspect in such solutions. The device also comes equipped with an integrated microphone and speakers, which offer spatial sound, ensuring that the user is fully immersed, and no external headphones are required. The Meta Quest 2 is also quite reasonably priced [82, 83] compared to other devices and is, therefore, accessible by many individuals. Lastly, the device can be used as a stand-alone solution. This allows users to freely use the device without being hindered and bothered by external factors such as cables, which patients outline to be bothersome [78]. With the benefits mentioned above and the included controllers, the Meta Quest 2 seemed to perfectly fulfil the criteria for affordable, well-performing VR devices that can be used for pain mitigation.

The device itself contains numerous applications which can be used. This project proposes a novel framework that can build entire environments at run-time based on the individual using it. The following writing aims to thoroughly explain the

²<https://unity.com/>, Last Accessed: 16/11/2023

work done throughout this research, delivering a comprehensive guide that other researchers can utilise.

4.2 Procedural Content Generation for Terrain Creation

The terrain was the first aspect that was looked into when building the solution. One can use numerous methodologies to create an environment's terrain manually and algorithmically. A central aspect proposed within the solution's core mechanics is its personalisation and endlessness. As outlined in Chapter 3, numerous participants comment on the importance of immersion within such applications. Furthermore, the availability of different environment options was also left to be desired. Given that participants suffering from chronic pain, in particular, would utilise such applications for a prolonged period, standard, non-changing environments tend to lose interest with time. Following these observations, PCG techniques are implemented within this work. As outlined in Chapter 2, PCG allows for entire environments to be built programmatically. In this research, such techniques were utilised to create a solution capable of generating an infinite number of VR environments at run time. Having the environment built programmatically also allows this work to produce an endless world through which users can roam freely as desired. The logic for the terrain is built following close reference to the tutorials provided by Sebastian Lague [84], which provide a deep understanding of the mathematics and inner workings required to generate landmass algorithmically.

4.2.1 Noise Generation

The terrain is the main element which needs to be catered for in a unique, endless world. The terrain in this work is built at run-time through PCG. The algorithm developed utilises Perlin noise, a gradient noise function commonly employed for procedural terrain generation. Noise functions can generate random, coherent patterns that can be used to simulate natural phenomena. Therefore, The first step was to create a function that generates the gradient noise for terrain creation. This generates a grid of randomly generated values ranging from 0 to 1, as depicted in Figure 4.2.

To generate a grid of noise, coined as a 'noise map', Unity's `Mathf.PerlinNoise` function was used. To introduce an element of customisability and control within the noise generated, the elements which affect the noise map's properties were all parameterised and made accessible through Unity's inspector interface. These elements included the width, height, seed, offset, scale, octaves, persistence, and lacunarity, all creating different results when changed. Looking at the non-trivial parameters, octaves refer to individual layers of noise; one octave is one layer of noise,

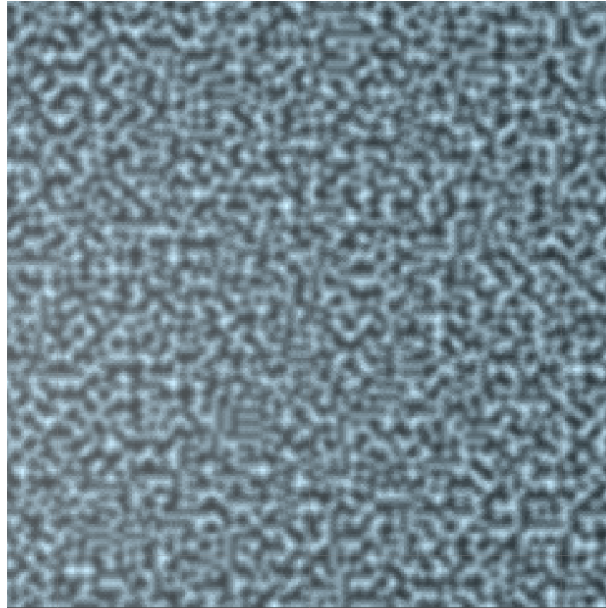


Figure 4.2 An example of a Perlin Noise grid generated through the solution

lacunarity manages the frequency growth between every octave, and persistence handles the amplitude reduction between octaves. Layering these together helps create a more natural-looking terrain, as can be seen in Figure 4.5. These are especially important when multiple noise maps are required. Therefore, The offset parameter allows for a seamless transition from one terrain piece to another, as seen in 4.3 (A). Numerous terrain chunks are required to create an endless world. To create the illusion of one seamless terrain, the terrain pieces are all placed next to one another, with one starting where the neighbouring one ends. Constantly using the same noise map, however, would result in the same terrain properties within every piece and would look repetitive, unnatural and unappealing. The previously mentioned elements help create a natural-looking landscape that flows coherently from one piece to another. The impact these elements have on the noise map generated is accurately outlined in Figure 4.3.

4.2.2 Generating a Mesh

Until this point, this research details the creation of 2D noise/height maps. For these to be effectively utilised in the VR environment, however, they must be represented in a 3D form. To do this, a mesh is created from every map and assigned to the object representing a terrain piece. This process is repeated for every piece of terrain required. The mesh is created by dividing the map into numerous vertices forming several triangles, as displayed in Figure 4.4.

The number of vertices in a map is taken to be the width multiplied by the height of the map being processed. A multiplier and Unity's 'AnimationCurve' are

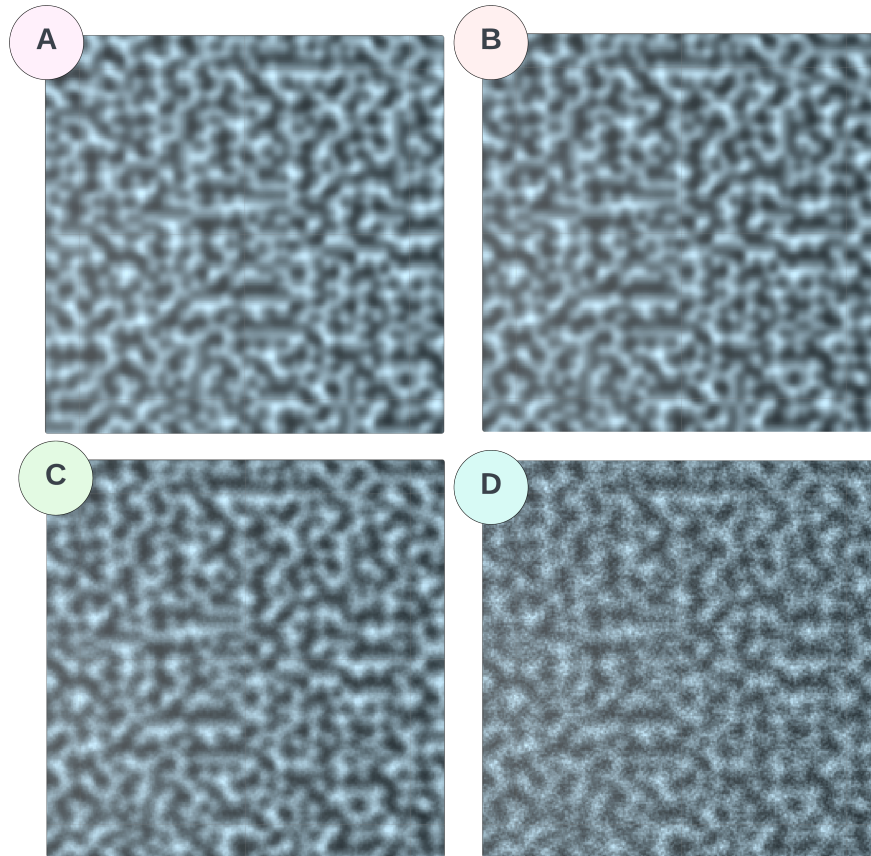


Figure 4.3 Different noise maps generated by altering the Offset (A), Lacunarity (B), Scale (C) - scaled by 10 from the starting grid in Figure 4.2, and Persistence (D)

utilised to control the meshes' elevations and make them more pronounced, creating mountains and slopes. While the multiplier helps make the mesh pop out, the curve ensures that only certain aspects of the mesh are multiplied, delivering an extra level of control on the generated terrain. It is worth noting that in Unity, a mesh cannot have more than 65,535 vertices. This further highlights the importance of splitting the environment into small chunks, ensuring that this limitation does not hinder the concept of an endless environment. Although the size of a terrain piece can be adjusted through the parameters set, the default size is set to generate squares with sides of 241 units and is the largest size possible per chunk. An example of a resultant mesh can be seen in Figure 4.5

4.2.3 Colourising and Texturing

When creating the noise maps, the grids are created using standard Perlin noise and colourised using a monochrome palette, showing the difference in heights with varying shades of black, as displayed in Figure 4.2. The noise map can be seen as a height map in itself, where 0 (white) is the lowest point in the map, and 1 (black) is the highest. A

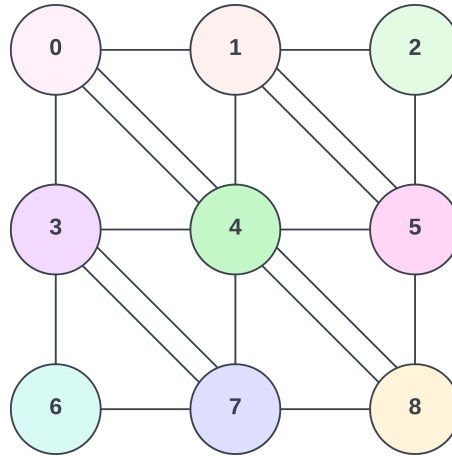


Figure 4.4 Diagram showing the logic used to transform a map into a mesh

step further towards creating an aesthetically pleasing environment which can be customised and altered programmatically was, therefore, to assign colours and textures to the mesh generated. To do this, an interface was built which allows for complete customisation of the map's colours. This is done by splitting the entire map into several regions as desired.

A region encapsulates a number of parameters, including the height at which the colour should be used and the colour to be used. This information is then used to create a texture from the colourised noise map, which is applied to the game object representing the terrain. A shader was also developed, enhancing the environment's aesthetic appeal. By introducing the ability to use 2D textures, colourising and blending between different layers, the solutions' potential to create an infinite number of different environments is further amplified. An example of the colourisation can be seen in Figure 4.6, where the mesh displayed in Figure 4.5 is colourised programmatically using the settings shown in Figure B.1.

4.2.4 Development with Performance in mind

As with all software solutions, quality engineering principles must be kept in mind to build a product that effectively satisfies requirements, performs well, and can easily be maintained. 3D environments can get quite cumbersome to run. Considering that the solution built needs to reach numerous devices with varying processing capabilities, innumerable precautions were taken to minimise the resources required to run this application effectively.

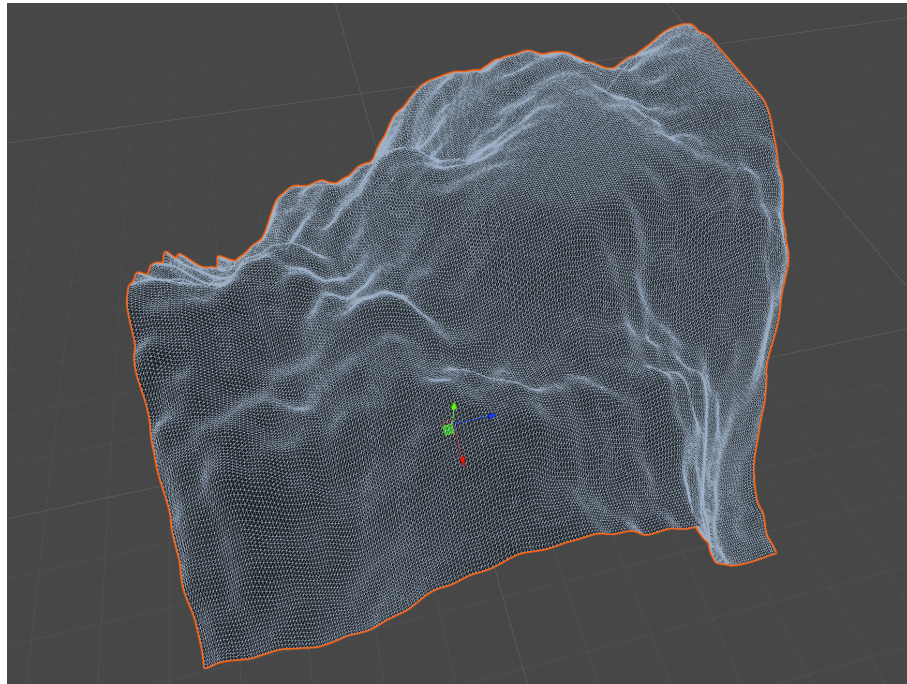


Figure 4.5 The mesh created from an example noise map

Dynamic Rendering, Level of Detail, and Terrain Generation

The first phase consisted of implementing dynamic environment generation based on the player's position. Through this methodology, the environmental aspects generated and rendered were only the parts within the player's zone. This is done by monitoring the player's position in the world and setting variables which measure the distance and area from the player to the very outskirts of the map. If the movement threshold is exceeded, the world and terrain are updated accordingly. If the terrain in the player's direction has already been generated, this is enabled back into the scene. However, the chunks that were not previously generated are generated and saved in memory. A simplified example of this generated through the solution can be seen in Figure 4.7, where elements are only rendered on the area visible to the user.

A similar optimisation which the Unity engine handles itself is frustum culling. Similar to the previously mentioned functionality, the Unity engine attempts to hide any game objects not within the user's field of vision. Since these elements are not visible within the user's view, rendering them would result in wasted resources. Furthermore, a level of detail controller was developed and introduced within the solution, which changes the level of detail within the terrain based on its distance from the player. This optimisation ensures that the player can still appreciate the environmental details and beauty of the elements that are close by. The level of detail is decreased for the elements that are a specific distance away, ensuring that they are still visible but consuming minimal resources to render, especially since most details would not be noticeable from a distance. This common approach in game optimisation

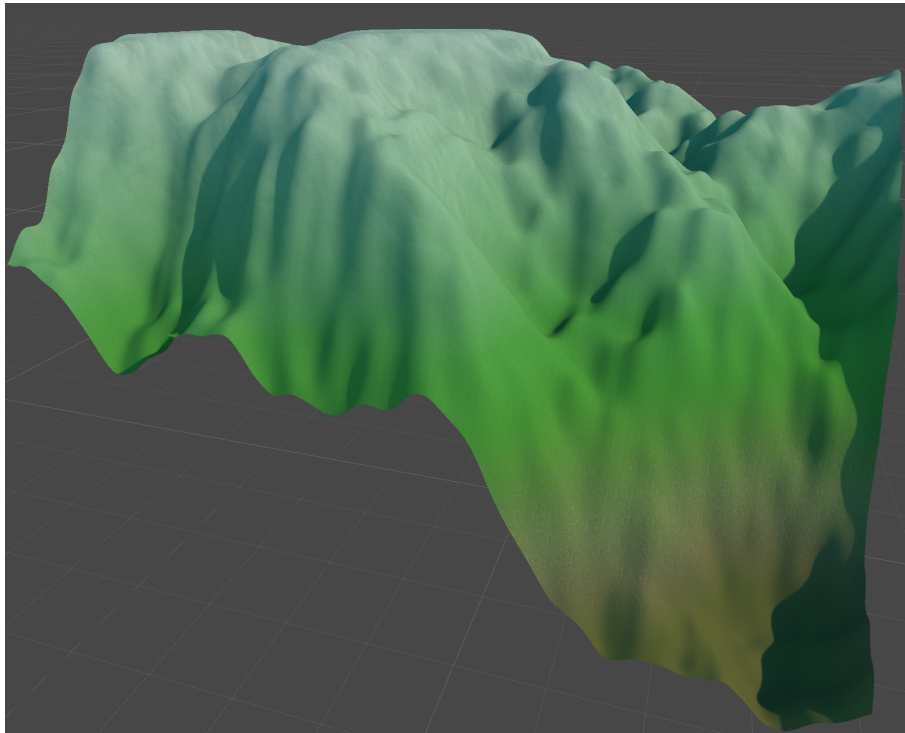


Figure 4.6 Colourised Mesh

ensures that the player's experience is not hindered while performance is optimal. It is worth noting that the level of detail and the distance away from the player are both elements that can be adjusted, allowing for great customisability and control before building the project.

The complexity behind spawning models

When a terrain mesh is generated, several models are selected and spawned based on a set of criteria. These mainly depend on the settings the user modelling script receives, which attempts to predict the ideal environment for that specific user. Numerous 3D models are placed in folders pertaining to one of the four available environment settings to discriminate between models and generate environments that conform to reality. Taking a cactus as an example, the model is placed in the desert directory, given that cacti are not typically found in forests and are frequently assimilated with deserts. Depending on the environment setting, these are then subdivided into the models' categories, such as grass, bushes, trees, and rocks. Given that the environment is created programmatically, special care must be taken to determine where to spawn the models. This solution uses the mesh vertices to check for valid points. Ray casts that collide with the models are used to ensure that the model is spawned on the terrain. If a collision, which is not a tree or any other non-terrain object, is detected, the model is spawned. The object's rotation also needs



Figure 4.7 Rendering elements on one single terrain chunk

to be considered since if the object spawns at a slope, it needs to be translated as per that slope to maintain realistic placement. This, however, also needs to be done with great care, as trees, for example, cannot be spawned based on the normal of the point selected since this would result in slanting trees. Additionally, the number of models created per terrain chunk is randomly determined by two numeric boundaries, which change based on the model type. For example, if trees are being generated, a number is randomly chosen between X and Y. This number represents the total number of trees that will be rendered for that specific terrain chunk. Finally, it is worth noting that all the models spawned are children of the terrain piece they pertain to, making it easier to hide and re-display objects when the player moves away.

Controlling the Level of Detail

As outlined, the environment chunks generated employ a 'level of detail' parameter, which, as the term denotes, controls the terrain detail. The levels of detail can be changed entirely based on the developer's requirements. A game object is made of numerous polygons, which detail the object's shape. The number of polygons in an object directly correlates to the level of detail that it exhibits. For the sake of performance, the solutions aim to present an endless low-poly environment. Environments that try to depict a realistic scene closely might suffer in terms of the

quality produced. This lack of quality, therefore, might reduce user engagement, especially in individuals who are used to enjoying modern graphically intensive games. As shown in Figure 4.13, a low-poly approach clarifies that realism is not the environment's goal but presents an alternate reality free from the perfection we trouble ourselves with daily. In itself, this environment can introduce a sense of relief within the users, especially those who constantly aim for perfection.

As explained in Chapter 4.2.4, the players' position was considered for terrain generation. The user's surrounding environment maintains a consistently high polygon density by constantly tracking the player's location. Numerous levels of detail can be specified within the solution and were developed to be easily altered through Unity's inspector. The default state contains three levels. The first of these is the closest to the user and has the highest number of polygons; given that this is what the user will be looking at, its clarity and appeal are greatly prioritised. The second layer has a medium level of polygons. The logic behind the second layer is that users might still be able to see the models quite closely and must, therefore, still be adequately presented. Lastly, the third level has the least amount of detail and represents objects that are too far away for the user to observe the details of. Figures 4.8 and 4.9 show an excellent example of this explanation, where wireframe views are used to show an example environment built using the developed solution. Given that the number of polygons cannot be reduced indefinitely, a finite selection of six levels of detail can be utilised.

These levels of detail introduce further complexity within the solution, where a terrain mesh needs to be generated for a specific terrain chunk with a particular level of detail. Given that when the player moves away from a terrain piece, the level of detail will decrease, this functionality demands that a new mesh is generated, consisting of fewer polygons. The mesh data per piece is kept in memory to ensure that this process does not loop on forever. Whenever a player reaches a specific movement threshold, conditionals are in place, which check if the terrain meshes at the user's position and the surrounding area already exists; if a chunk already exists, this is loaded; if not, the mesh at this position is created.

Multi-threading

Processing power is critical when dealing with progressively generated environments. Even though the environment is built at run-time, the user should still be able to play and roam as if it is a standard environment, and there should not be performance issues that hint that the environment is being built on the go. For such issues to be mitigated, multi-threading is implemented within the solution, which allows multiple threads to be utilised concurrently to process a task. Without such improvements, computationally intensive functions suffer from performance issues such as freezing,

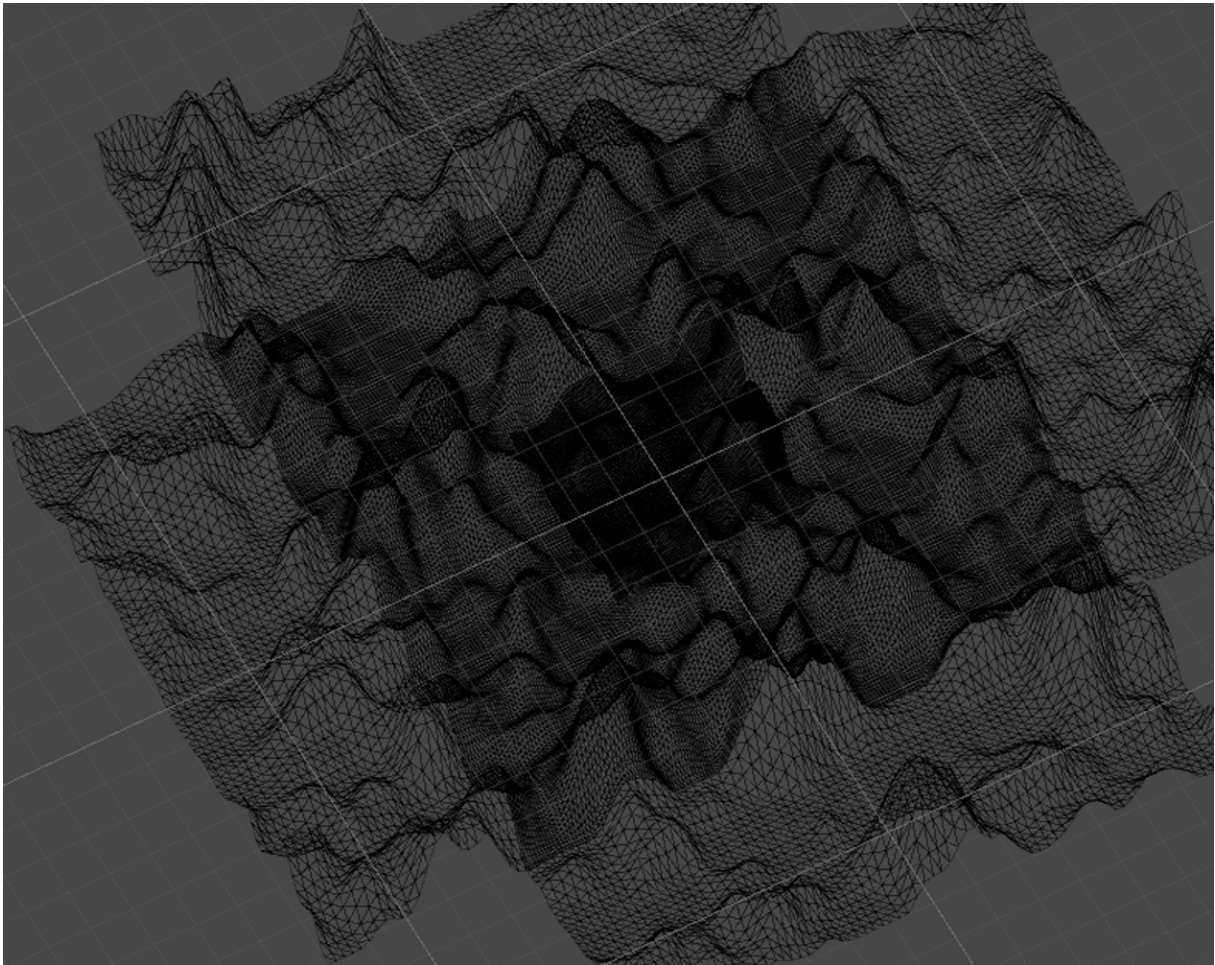


Figure 4.8 Terrain level of detail changing based on distance from the centre

system hang-ups, and other bottlenecks. The aforementioned factors may instil frustration and discomfort, potentially leading to heightened pain levels.

Graphics Processing Unit Instancing

GPU instancing is an integral part of the architecture implemented in graphically intensive games. As previously inferred, the CPU handles most computational tasks within software solutions. In graphically intensive environments and games, however, the CPU would be tasked with too many computations, the load of which can significantly decrease the game's performance. To mitigate this loss in performance, the load can be alleviated from the CPU through GPU instancing. In this work, GPU instancing is used to render several game objects repeated within the scene. Rendering prefabs can be taxing; using the GPU increases efficiency through its specialised architecture, specifically designed to handle complex graphics computations, resulting in faster rendering and higher frames per second. In this work, GPU instancing is primarily utilised to render grass and clouds within the environment. Multiple prefabs must be placed in close proximity to achieve realistic grass bedding, creating a dense

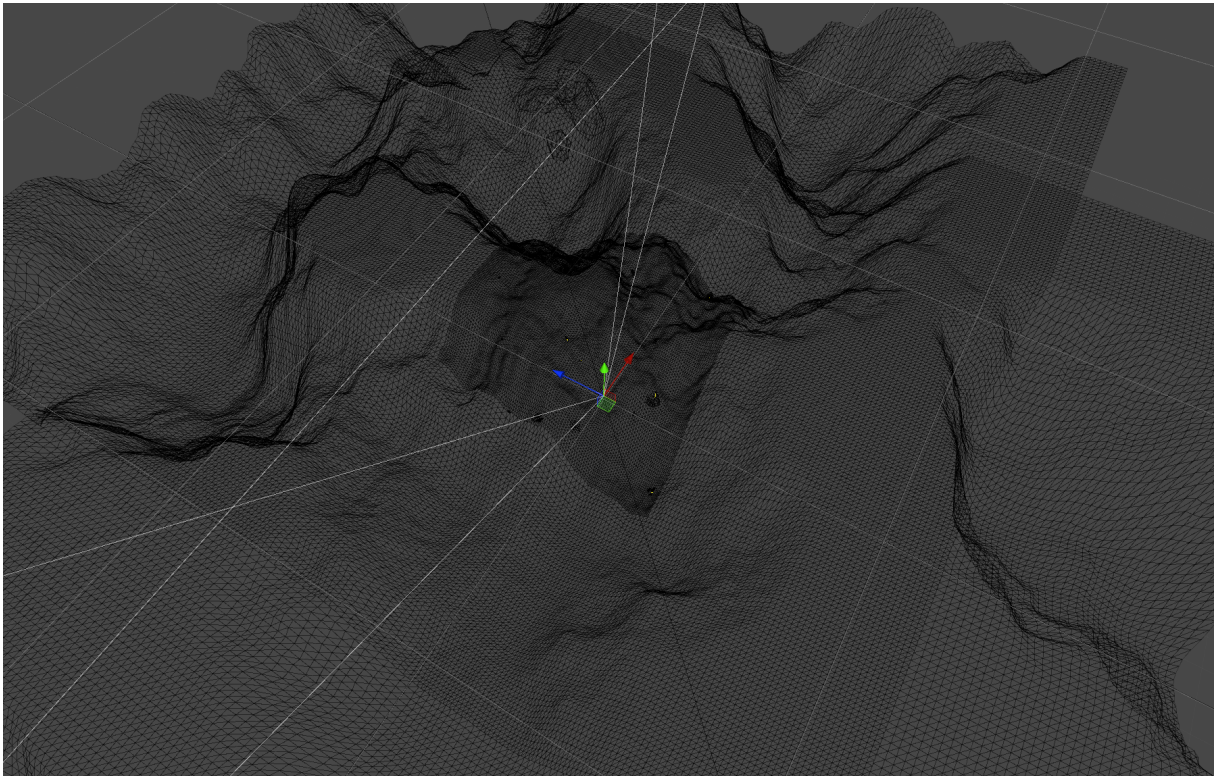


Figure 4.9 A closer look at a realistic terrain's polygons changing based on distance from the centre

chunk of grass. Multiple prefabs within a scene create numerous issues in terms of performance and cannot be rendered efficiently through the CPU only. GPU instancing can be utilised here, where the GPU draws multiple instances of an object through batching. An issue noted through this methodology is the limited instance interaction this method offers. Since the GPU does not contain information about the model's behaviours and physics within the environment, other elements cannot interact with the GPU-rendered models and, therefore, can only be used aesthetically. As outlined, given the importance of player interaction within the VR environment, most of the environment's rendering was handled through the CPU. GPU rendering, on the other hand, is used for factors that don't impact user interaction possibilities, such as grass blades and clouds.

Navigation Mesh

To introduce artificially intelligent characters such as animals in the solution, a navigation mesh must be integrated, instructing these models where they can roam and which areas are out of bounds. As can be inferred, baking navigation meshes at run-time over large quantities of terrain chunks stresses the CPU and introduces several performance issues, which, unless addressed, would greatly hinder the environment's performance. To mitigate this, the navmesh area is only generated on

the terrain chunk the user is presently on. Once the user moves to another chunk, the navigation area is regenerated. After several tests, this approach was deemed the best performing as areas including several chunks together significantly increased baking time. Research was also done in attempting to use nav mesh replacements, such as the well-known A* pathfinding implementation³ for Unity. However, further investigation indicated that Unity's inbuilt NavMesh library performs on par with this implementation and was therefore disregarded for this work. An example of the navmesh generated can be seen in Figure 4.10, where the navigation mesh (shown in blue) is only created for one specific terrain chunk.

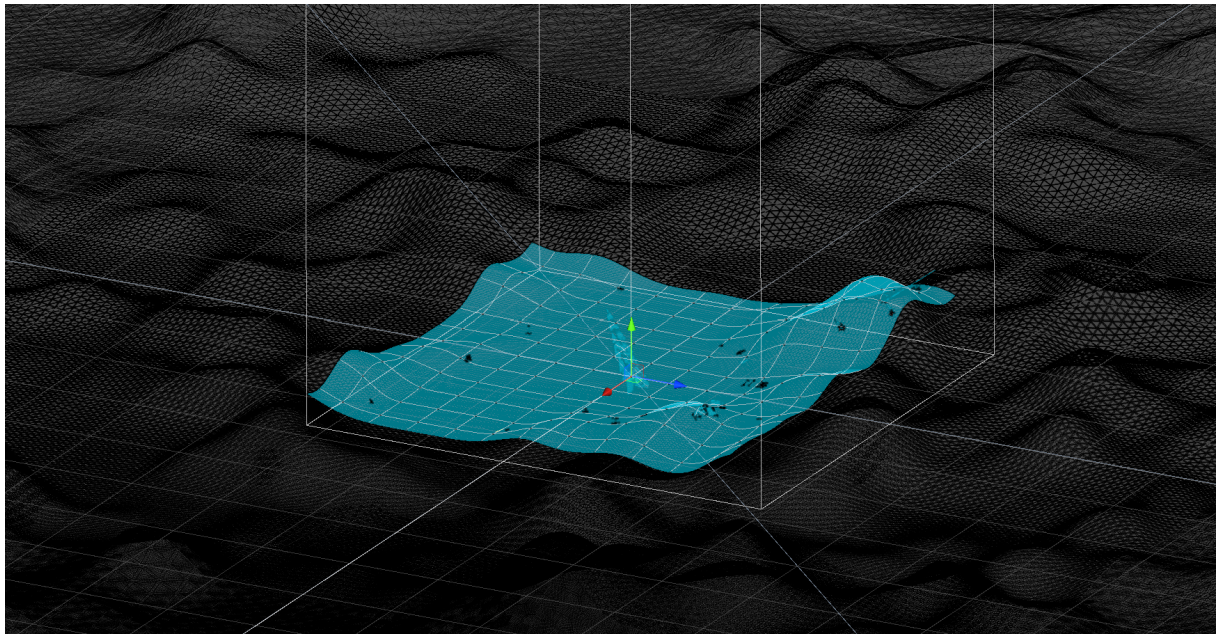


Figure 4.10 An example of the navigation mesh, rendering on one terrain chunk only (the one the player is on)

4.2.5 Creating a personalised environment

Algorithmically generating an environment introduces several possible benefits, one of which is personalisability and customisability. The development phase must account for such capabilities; parameters affecting how the environment is built must be included. This work aims to create a solution that, by amalgamating different software techniques, creates a novel pain-mitigating architecture. A Python script was created, which, using numerous machine learning algorithms, maps a user's profile to various elements within the environment. As previously discussed, an individual's identity, such as gender, age, ethnicity, and cultural beliefs, can affect how one processes and experiences pain. A multi-class SVM was used as the primary classifier, which predicts

³<https://arongranberg.com/astar/>, Last Accessed: 21/11/2023

the user's preferred environment based on their characteristics. Random user profiles were generated along with their preferred environments using the 'Faker'⁴ library. Custom algorithms which utilise Python's 'random' library were also created, which introduce a degree of control within the profile generation process. The profiles created were then used to train the aforementioned classifiers. These profiles followed the same schema and had the same requirements as the profile built at run time with the demographics and preferences selected by the user utilising the solution. Each generated profile had all the user characteristics randomly selected from the available options described in Table 4.1. Once the user profile is created, the environmental aspect labels are then randomly generated following the specifications in Table 4.2. This process is then repeated to generate other several random profiles. It is worth noting, however, that fake data was only used as a proof of concept. Ideally, meaningful data is used, ensuring that the created environment accurately encapsulates what the user desires.

The classifiers were built using the 'sklearn'⁵ library. The user profiles include factors that might affect the required environment — age, gender, race, pain type, pain location, intensity, and duration. Apart from an enriched immersive experience, the solution aims to cater for the different needs that various medical conditions might require. An example of which are individuals suffering from migraines, who prefer environments which are dark and noiseless, amongst other factors. The algorithm can cater to the individual's needs through these mappings and map out the environment accordingly. The following mappings are available: environment setting, level of vegetation, inclusion of ponds, sea or ice, volume level, lighting, weather, elevation, inclusion of animals, meditation, and the preference for a fantasy world, which renders elements that do not conform with reality, such as having sharks roam on land. To achieve the best possible classification, a model per environmental factor was created, each tasked with classifying a single aspect of the environment. Tables 4.1 and 4.2 present a deeper understanding of the data used. The information was normalised before being used to facilitate the classification process and help the algorithm. Using the 'Tkinter' python library, a GUI is built, which presents the user with a user-friendly interface through which users must enter the demographics mentioned above using predefined options and scales. Once the data is submitted through the submit button, the information is processed and sent to the trained classifiers, which attempt to predict the environment elements that best suit that user. The predictions are then sent through a socket to the Unity solution, which, through another script containing a socket listener, would be waiting to receive the information. The environment is only built if the information is obtained, although a default environment can be created if

⁴<https://faker.readthedocs.io/en/master/>, Last Accessed: 19/11/2023

⁵<https://scikit-learn.org/stable/>, Last Accessed: 19/11/2023

desired.

Feature	Details
Age	Number
Ethnicity	White, Black, Asian, Hispanic, Other
Gender	Male, Female, Other
Pain Type	None, Acute, Chronic
Pain Intensity	Number (0 to 10)
Pain Duration	Number (0 to 10)
Pain Location	Head, Neck, Shoulder, Chest, Back, Hips, Knees, Feet, Legs, Other

Table 4.1 Features used for User Profile Classification

Environment Aspect	Labels
Main setting	Forest, Desert, Snow, Exotic
Vegetation level	Low, Medium, High
Water preference	Yes, No
Lighting/Time of Day	Sunrise, Day, Sunset, Night
Animals	Yes, No
Elevation level	Flat, Hills, Mountains
Include Meditation	Yes, No
Weather	Sunny, Rainy, Snow
Sound level	Low, Medium, High
Fantasy World	Yes, No

Table 4.2 Environmental Aspects That Can be Changed Through a User's Profile

4.2.6 Developing a solution that promotes accessibility

Accessibility is an essential element that must be prioritised in any solution, especially those pertaining to digital health. The solution provides numerous elements which aim to facilitate the users' lives. The following sections introduce these aspects.

Voice Recognition

Numerous studies outlined in Chapter 3 show that individuals suffering from pain require specialised solutions which help them experience the VR environment with minimal limitations. Individuals suffering from pain in their hands or arms might not be capable of using the VR controllers. To further decrease the need for controllers, the

voice recognition library 'Undertone'⁶ was integrated through Unity's asset store. Undertone provided high-performance, offline voice recognition for 99 languages at the time of writing, making it an ideal package that aids in this project's accessibility. This library presents multiple possibilities; in this solution, the potential of such libraries is harnessed through the implementation of voice commands. In this case, a script was created that utilises Undertone's functions, allowing for programmatic modification and customisation. In this work, the script was made to listen to specific phrases that change the environment's functionality. Once the environment is built and the user starts roaming, the VR headset's microphone input starts being captured. This ability allows multiple commands to be integrated within the environment, allowing the user to control their player through vocalised commands rather than straining their body. In this work, to avoid complexity, only five commands are integrated. These are the 'start meditation', 'forest', 'snow', 'desert', and 'exotic' commands, which, when cited, start the integrated breathing exercise or change the environment's setting depending on the option voiced. Such technology is also used in [62] et al.'s work, where breath recognition alters the environment based on the users' breathing.

Movement speed and refresh rate

A notable factor outlined in the literature reviewed was the nausea that might be produced through the VR equipment, especially during its first few uses. Studies mention that the camera or player's movement speed should be kept slow and constant [11] to mitigate this. Following these considerations, the player's movement speed is kept slow in the environment. Although not advised, this speed can be increased and decreased as necessary through the Unity Editor. To further mitigate any nausea that might be caused through the VR equipment, a HMD that supports high refresh rates was chosen.

Environment Clarity

Unity's post-processing library ensures that the environment looks in its best shape, which introduces anti-aliasing and other visual enhancements that can be taken advantage of to make the scene look better, smoother, and less ragged.

⁶<https://assetstore.unity.com/packages/tools/ai-ml-integration/undertone-offline-whisper-ai-voice-recognition-246877>, Last Accessed: 20/11/2023

4.2.7 Mindfulness Integration

Mindful meditation exists in many variations. In this work, the meditation exercise guides the user through a few minutes of box breathing. This meditation was selected due to its simplicity and well-known effectiveness, especially given that not all individuals are proficient. As shown in Figure 4.11, a set of instructions is displayed in the application, which informs the user about the breathing exercise they will be guided through.



Figure 4.11 Box Breathing instructions as shown in the solution built

Visual countdowns are also integrated, which help guide the users and keep track of their breathing. Box breathing consists of repeating four breathing windows for a specific amount of time. The meditation involves four stages: inhaling deeply for 'x' seconds, holding the breath for 'x' seconds, exhaling slowly for 'x' seconds, and holding this state for 'x' more seconds. The environment also includes a therapeutic melody, gentle breathing sounds to guide the user's breathing and visual timers.

4.3 Implementing Natural Elements Promoting Pain Mitigation

To further promote pain mitigation, various elements are integrated, which are known to help individuals suffering from pain and emotional distress. Instead of solely relying on immersion and meditation, the solution promotes pain mitigation by including animals and vegetation.

Nature and Vegetation

Research shows that when exposed to scenes and sounds of nature, such as beautiful landscapes, forests, vegetation, and plants, amongst many others, individuals perceive reduced levels of pain and also exhibit a shorter recovery window [12, 85–87].

Numerous studies have looked into nature's positive effects through various methodologies. Most notably, some stress the importance of windows in patients' rooms [88] and assess the difference in comfort, anxiety, stress, and pain these have on individuals. Some studies use images and sounds of nature instead and still document favourable results. Sunlight exposure is also seen to be beneficial, especially in patients suffering from depression, where participants in sunlit rooms exhibit shorter stays and decreased use of analgesics than participants staying in dull hospital rooms [87]. To accommodate this, the solution generates environments entirely based on nature; the application also boasts numerous natural assets that can be spawned throughout the environment, ensuring that the user is never bored and always presented with a fresh, unique environment. An example of the different environments that can be generated can be seen in Figures 4.12 and 4.13.

Animals

Similar to the benefits of natural elements within an environment, animal exposure also displays beneficial results in the health domain. AAT is a well-known therapeutic approach that is significantly effective in improving patients' levels of pain [89–91] while also proving beneficial for well-being, mood, and anxiety [91], all of which are known factors affecting perceived levels of pain. Seeing the positive effects pets and animals produce, this work incorporates a plethora of low-poly animals that move around and interact with several elements, as well as each other, within the environment. Through Unity's navigation mesh, a navigation surface is built on the terrain where animals can roam freely. The 'Low Poly Animated Animals'⁷ assets

⁷<https://assetstore.unity.com/packages/3d/characters/animals/low-poly-animated-animals-93089>, Last Accessed: 21/11/2023

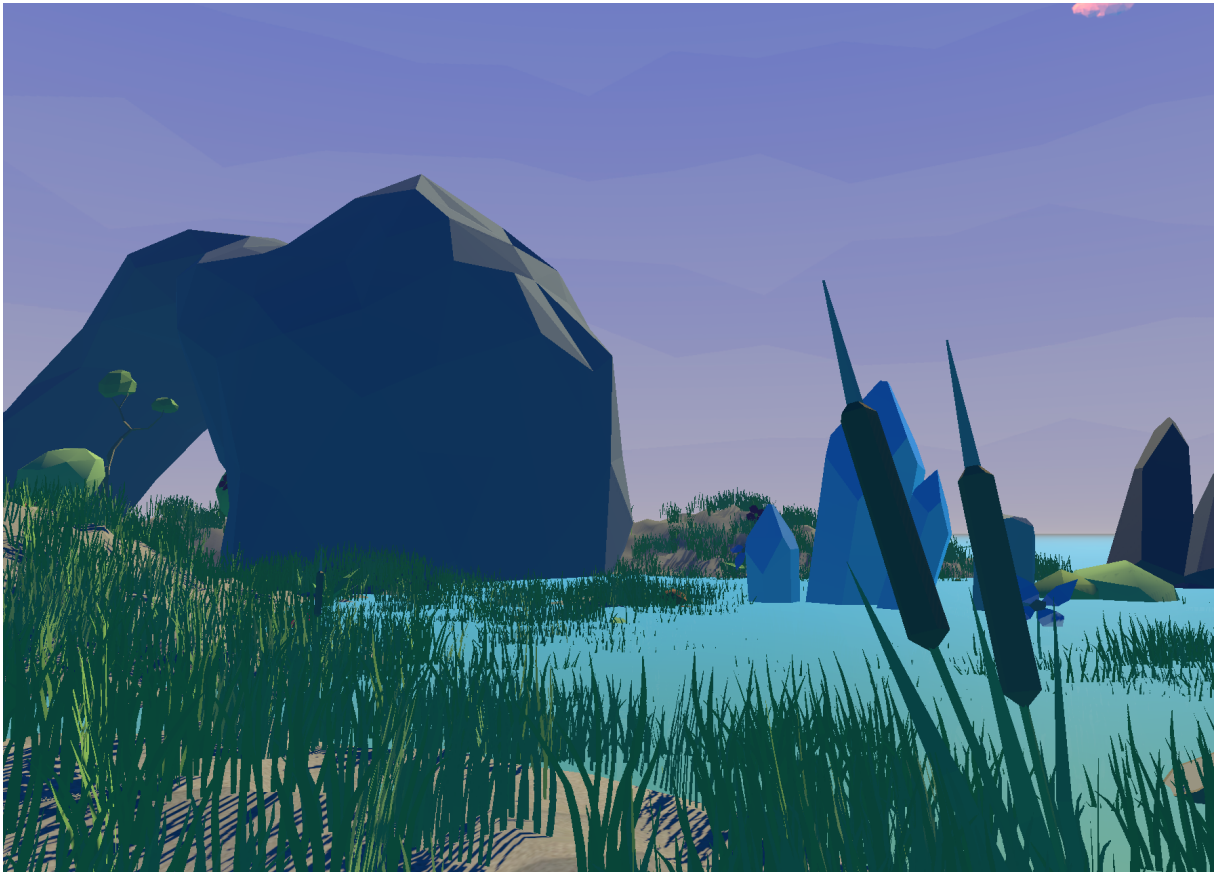


Figure 4.12 An example of an environment that can be generated through the solution

package is used, which provides not only various animal assets one can use in their solution but also animations and interactions between the animals that make the environment much more realistic and engaging. The integration of animals within the solution aims to further user engagement and introduce additional pain mitigation through the known benefits and positive emotions animals instil in medical therapies. An example of a sheep roaming through a generated environment can be seen in Figure 4.13. In this case, the use of low-poly animals helps to avoid overburdening the system's resources and ensures stable performance regardless of the system's specifications.

Even though low-poly animals and models are used, the generated environments are still spectacularly beautiful and have a very strong potential to grab the user's attention. A few other examples of random environments generated through the solution can be seen in Figures 4.13, 4.14, and 4.15.

4.3.1 Sounds and Music

To further immerse individuals within the VR environment, sounds of nature and handpan music are included in the solution. These are selected based on the users'

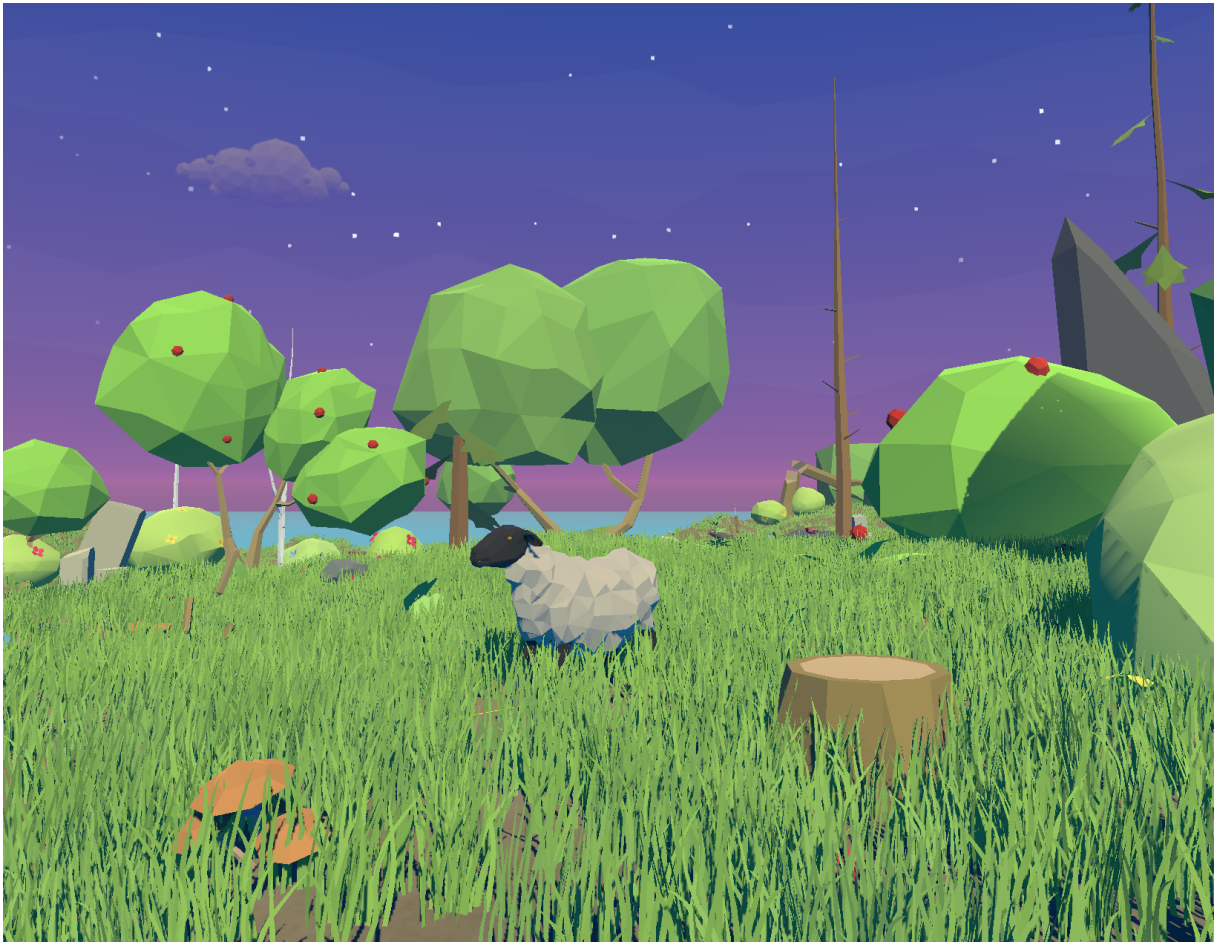


Figure 4.13 A sheep roaming around in an environment generated through this solution

profile and the generated environment. The selection of audio was carefully chosen based on its meditative effects and the positivity it instils. To further increase ambience and immersion, the animals included within the solution all have sounds embedded with them, and interact with each other.

4.3.2 Sky

The sky is one of the most important aspects of any scene. Making up for a large portion of any outdoor environment, ensuring that a clear, beautiful view is rendered above/behind the environment generated is crucial. Several skyboxes that depict different times of day are integrated to encapsulate a user's preferred time of day correctly. These include morning, day, evening and night. An issue which arose when making use of certain sky boxes with the VR HMD was that the skybox was only rendering in the left lens. This was due to the single-pass rendering settings within the Unity project; changing this to multi-pass solves this problem but creates numerous other performance issues since the environment would be rendered twice per lens. Different sky boxes were found to avoid this, whose shaders were developed with VR



Figure 4.14 A dog roaming around in an environment generated through this solution in mind.

4.4 The Player's Experience

When the solution is launched, it waits for the Python script to pass over the user's demographics and pain information. Once this data is submitted through the GUI, it is sent to the Unity solution so that it builds the personalised environment. Once the environment is created, the users find themselves in its clouds and descend slowly to land upon movement. The players can move around through the Meta Quest's controllers. The left controller allows them to move around the environment slowly, and the right controller allows them to rotate their player. The player's camera is controlled through the HMD itself, mapping the user's movement to the environment, further increasing immersion. Being infinite in nature, the user can roam for as long as desired without ever seeing the end of the virtual environment. Several commands are available which give the user a degree of control within the environment. These include 'Start meditation', and 'Snow', 'Forest', 'Desert', and 'Exotic'. Start meditation starts the box-breathing exercise, while the remaining commands change the setting of the environment to be rendered when the player reaches specific thresholds. These interactions are explained in further detail in their pertaining sections.



Figure 4.15 A sea lion meditating with the ambience provided through the environment

4.5 Virtual Reality Experiment

A VR experience was devised to evaluate the solution built, as seen in Figure 4.16.

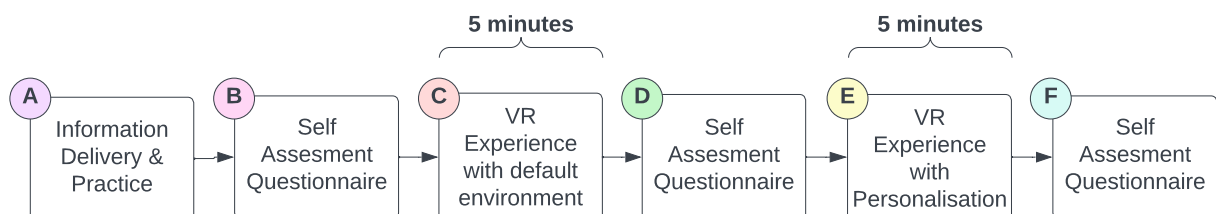


Figure 4.16 Virtual Reality Experience

4.5.1 Recruiting Participants and Ethical Considerations

Participants were enrolled in the study voluntarily. Prior to the experiment, they were provided with an information sheet, consent form and the first part of the developed questionnaire. Since personal characteristics are collected to generate a personalised environment, the participants are assured that their data will be anonymised and only processed for research purposes following their consent. Ethical considerations were highly prioritised, ensuring the participants were comfortable and safe. Even though comfortable and accessible environments should be prioritised regardless of setting, such studies dealing with vulnerable populations going through pain and discomfort should further prioritise these as much as possible, ensuring that the participant's

safety and well-being are prioritised. Given that VR equipment can have nausea and other undesirable side effects, proper care is taken to mitigate these as much as possible, such as instructing participants to remain seated throughout the experiment and slow in-game movement speed. To ensure that any conditions are not worsened through the technology used, proper care was taken in selecting a VR HMD which is comfortable, light, and non-intrusive, as explained in Chapter 4.1.1. Nevertheless, the participants were informed that such side effects might be encountered and that they could stop the experience whenever they desired. Participants suffering from chronic or acute pain were preferred, but this was not a requisite. Finally, the solution was built with inclusion in mind, ensuring that it can be used by multiple individuals regardless of socioeconomic status. This research endorses that effective pain mitigation should be accessible to everyone.

4.5.2 Developing a Survey Tool

A specialised survey tool was developed to appropriately capture the experiment's results, as seen in Appendix A. To capture the participants' perception of pain, multiple VASs are included due to the scale's simplicity and popularity in numerous other studies [9]. The developed self-assessment questionnaire allows for collecting a standardised set of results, which is paramount in such studies, and contains numerous elements participants could comment on. Keeping in mind that the tool is mainly devised for participants suffering from pain and discomfort, it was ensured that questions were straightforward to answer. As seen in Appendix A, the questionnaire consisted of many tickable options and prioritised simplicity as much as possible. Key terms were included through which the participants could note the environmental factors seen, preferences, and dislikes, amongst other elements. Since the same questions are issued after the standard and the personalised environments, the results could easily be compared, ensuring that all the information is extracted correctly from the experiments.

To ensure that the tool can effectively be employed for experimentation, it was tested for validation on a small sample group, ensuring that the responses were valid and non-ambiguous. This is especially important in such methodologies, where multiple elements can affect the results achieved and must be assessed.

4.5.3 Experiment Flow

The experience starts by informing the participants about the solution and the experience and obtaining their consent. The participants are informed that they can withdraw from the experience at any time. Once approved, the participants are given a few minutes to acclimate to the technology used. As previously outlined, the Meta

Quest 2 HMD and controllers are used throughout this experience. The participants are then asked to fill out a self-assessment questionnaire along with some details required for the environment to be generated. After this, the users are requested to use the default VR environment for five minutes, displayed in Figure 4.17.

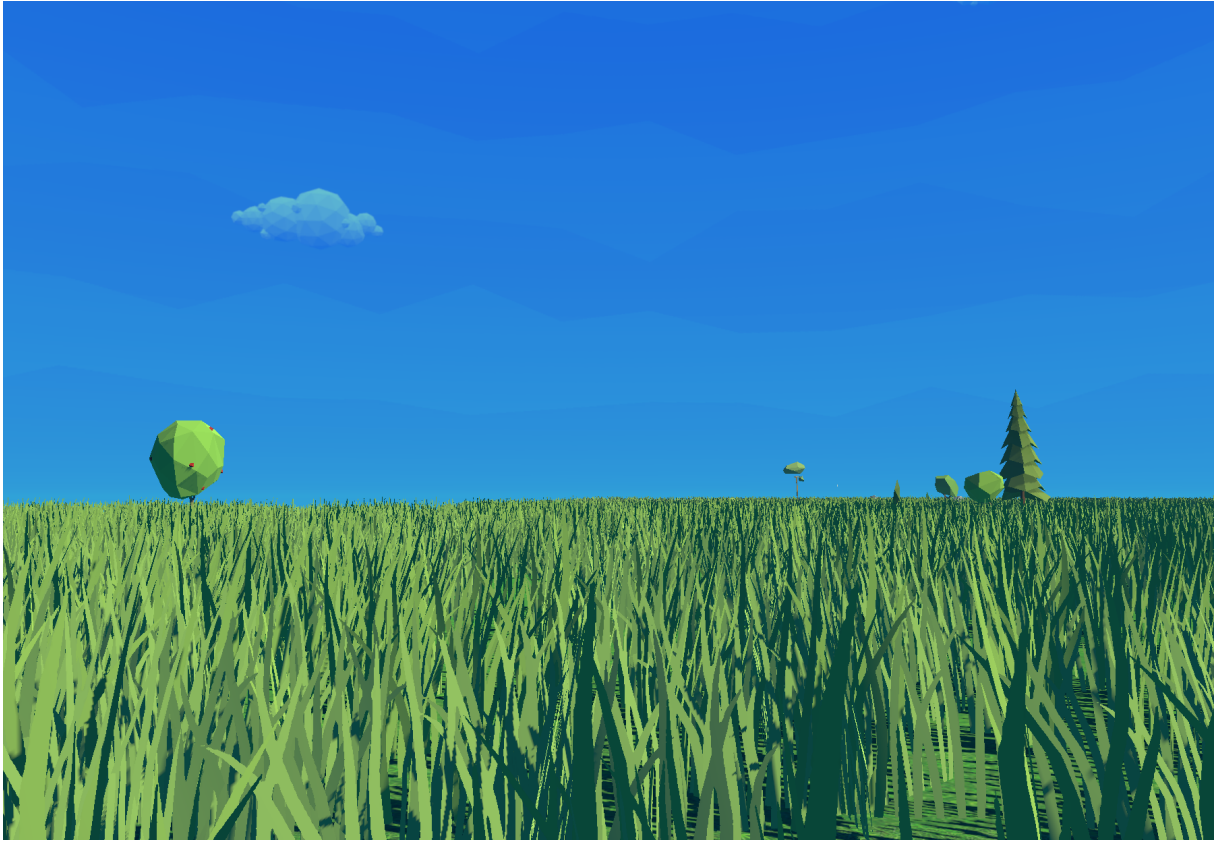


Figure 4.17 An example of the default/standard environment generated by the solution

Once concluded, the participants are asked to complete a self-assessment questionnaire detailing their experience. The same is repeated but with the personalised VR environment, which was generated and unique per participant. Another set of questions is then presented, which the participants must fill in. The details of the questionnaires used can be found in Appendix A.

4.6 Overview

This chapter thoroughly overviews the various elements developed throughout this work. Highlighting the project's decisions, design, and methodology, this chapter provides a comprehensive guide for researchers aiming to reproduce and improve upon the created work. Such an approach ensures that further work does not start from scratch and does not re-invent the wheel. Given that the results obtained throughout this research display great promise, as shown in Chapter 5, the elements documented in this section can serve as guidelines for other work, demonstrating the importance of certain elements which can significantly affect the solution's pain-mitigating efficacy.

5 Results and Evaluation

This section outlines the experience created throughout this work, the results achieved, and a thorough discussion of key factors that affected the results achieved.

5.1 Evaluation Methods

As seen in Chapter 3, numerous evaluation methodologies are employed throughout the literature reviewed. VAS and self-reporting questionnaires are predominantly utilised [9, 78] due to their simplicity and efficacy in capturing the participants' condition, comments, and experience before and after experimentation, depending on the nature of the study. In [78], both VAS and questionnaires were utilised to capture the participant's experience, and participants' comments were also analysed, which helped gather further information on the results achieved. The methodology used to evaluate the solution built throughout this project amalgamates VASs, self-reporting questionnaires, and participant comments, similar to the approach by [78]. The evaluation tool devised throughout the study was formulated with close reference to multiple research, most notably the work by Garrett et al. [78] and [92–94], who aim to capture the participants' experience with regards to pain and the solution's VR suitability accordingly.

5.2 Evaluating the Solutions Technical Performance

As per the principles of quality software engineering, testing was closely integrated as the solution was being developed. The metrics which were prioritised the most were Frames Per Second (FPS), which is a commonly known approach for high-level performance testing, CPU, GPU and RAM resource utilisation, as well as the total number of vertices, polygons, and draw calls within the scene. Unity's profiler was used for a deeper understanding of the solution's technical performance, which provides a thorough analysis of the build's ongoing operations and sheds light on the resources used on a process level. Overall, the solution performed great when tested on a machine equipped with an AMD Ryzen 3700x CPU, 32 GB of RAM, and an Nvidia RTX 4060ti GPU and a 42-inch display, and averaged at 120FPS, which was capped due to the display's refresh rate. A less modern GPU, an Nvidia 1060, was also used for testing, with the solution running similarly well. When using the Meta Quest 2 HMD, the frames averaged at around 80FPS, which still provided a smooth experience, especially since the HMD's refresh rate was set to 72 Hz. The RAM and GPU resources utilised by the solution were always far from reaching the system's limits due to the

care taken in managing resources. Further improvements would need to be implemented however, should the solution be required to run on a standalone VR headset due to the limited resources available on such devices. Looking at the CPU's utilisation on the other hand, it was very clear that it was doing most of the heavy lifting, with the utilisation percentage even reaching 100% at different points throughout the session, particularly when the NAV mesh is regenerated as the user walks on to different terrain meshes. Special care was taken to keep the number of vertices, polygons and draw calls within the scene reasonable. As previously outlined, the level of detail feature implemented within the terrain ensured that the terrain generated far from the player was always kept with a very low level of detail, greatly minimising the number of vertices and polygons within the scene. The loading and off-loading of models beyond the players' field of vision also played a crucial role in maintaining good performance as the player roams the world. Finally, to reduce draw calls, models which could be rendered by the GPU without affecting gameplay were handled through it.

5.3 The Virtual Reality Experiment

As outlined in Chapter 4, an experiment was designed and conducted to evaluate the developed solution. The experiment consisted of two five-minute VR sessions, each followed by a self-assessment questionnaire. The two phases were very similar and utilised the same equipment. The first phase consisted of the default version of the VR environment, which was relatively similar for all participants since no personalisation elements were included. On the other hand, the second phase employed the participants' information to generate a personalised VR environment, which the participants then used.

The participant pool consisted of six participants in total: three males and three females, all of whom were suffering from a form of chronic pain or anxiety. Given the strong correlation pain holds with one's psychology, anxiety was accepted as a form of chronic discomfort for Participant 4. Table 5.1 outlines a better understanding of the participants' profiles.

The participant pool encapsulated a wide range of chronic conditions, which, as expressed by some of the participants, severely limited their well-being. Including participants who suffer from different pain-inducing conditions is especially vital in evaluating the efficacy of the therapies such studies propose. Furthermore, this enriches our understanding of the complex relationship between pain and non-analgesic pain relief. It is important to note that because the experiment was conducted with a small number of participants, the results achieved cannot be

P No.	Age	Gender	Ethnicity	Pain Location/Condition
1	65	Male	White	Nose
2	65	Male	White	Chest, Legs, Hands
3	61	Female	White	Migraine, Lower-back
4	23	Female	White	Anxiety (Head, Chest)
5	30	Female	White	Head, Shoulder, Abdominal
6	29	Male	White	Head, Joints, Stomach

Table 5.1 VR experience participant profiles

generalised. Further investigation involving a larger and more diverse group of individuals with a variety of chronic conditions is essential. This will ensure that the solution developed can effectively reduce an individual's perceived level of pain and instil confidence in its effectiveness as an analgesic. Furthermore, the order in which the experiment was carried out could have played a role in the results achieved. Despite the efforts made to familiarise the participants with the equipment and solution used before starting the actual experiment, the possibility that they could have felt more confident by the time they were experiencing the personalised environments exists, potentially leading to better results. The participants may have also benefited from the standard environments' pain mitigation, enabling them to further engage and immerse themselves in the personalised session. All the participants were excited to try out the solution built, which is exceptionally encouraging for this research domain. This was primarily due to the VR aspect, especially since none of the participants had experienced VR before. It is worth noting that even though none of the participants had prior knowledge of such systems, no difficulty was pointed out throughout the experiment. This can be attributed to the highly intuitive VR device and the user-friendly solution built. Furthermore, the participants covered a broad age range, with the youngest being 23 years old and the oldest being 65 years old. Nevertheless, most participants shared the same excitement to participate in the experience and were not discouraged by their lack of familiarity with VR technology.

5.3.1 Participants' Perceived Levels of Pain

Prior to the experience, the participants were asked to outline their present levels of pain intensity. This was done to compare the participants' perceived pain intensity with those achieved after the two VR sessions. All pain levels were measured using an 11-point VAS ranging from 0 to 10, as seen in the questionnaire in Appendix A. The participants started with an average pain level of 4.83 and covered a range of 3 to 7 pain intensity before the experiment. As shown in Figure 5.1, the average pain

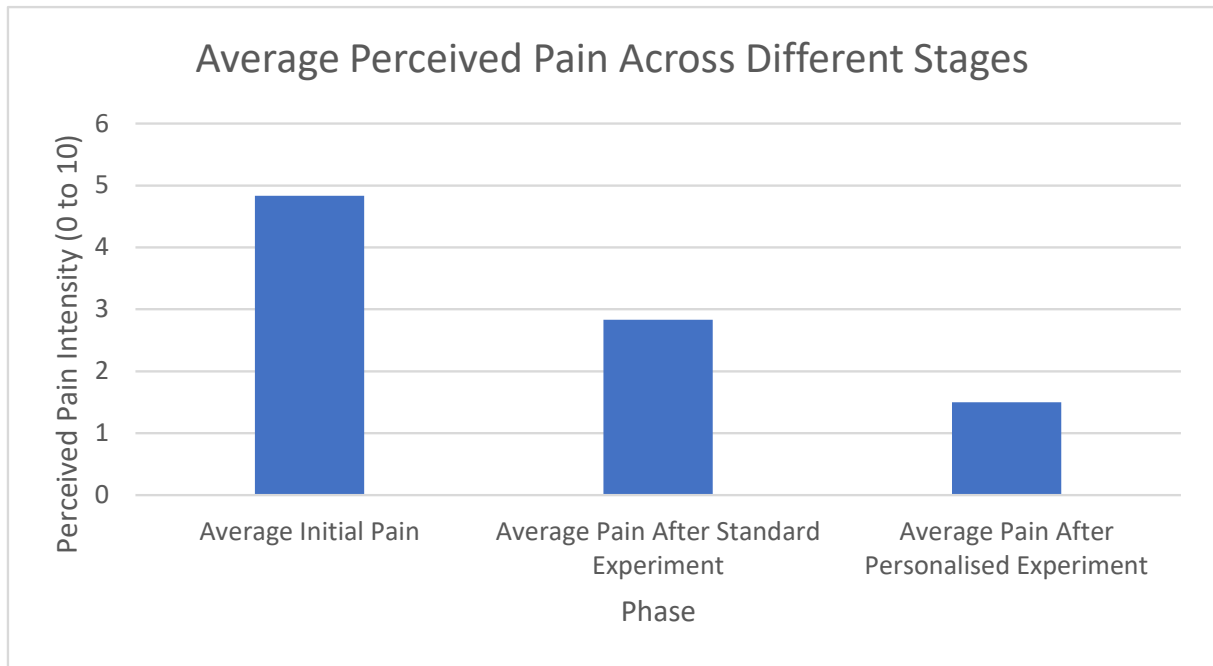


Figure 5.1 Average perceived pain across different stages

intensity after the first session displayed a notable reduction, with the score decreasing by 41.4% ($p = 0.136$) to 2.83. This shows that although the VR environment was not personalised, the participants were still immersed with a remarkable reduction noted after only five minutes, although this result was not statistically significant.

Furthermore, the average reported pain intensity after the personalised experience decreased to an encouraging 1.5, displaying a statistically significant reduction of 68.9% ($p = 0.0199$) in the participants' perceived levels of pain. Even though the standard environment proved to be significantly engaging, the personalisation aspect further reduced the participants' perception of pain by a significant 27.5% ($p = 0.025$), displaying the efficacy of user modelling within such solutions. The obtained p-values were all obtained from two-tailed paired Student's t-tests.

Since pain intensity is a rather complex subject, the experience aimed to deliver a deeper understanding of the factors that affected participants the most. Before looking into these elements, however, the pain intensity levels per participant are studied, as seen in Figure 5.2.

Starting from participant number 1, we notice a dramatic drop in the pain intensity and a further 1-point reduction between the standard and the personalised environments. This participant was very enthusiastic about the experience and commented several times about the fun and relaxing aspects of the solution. He also expressed that he wished for the experience to last longer as it was a genuinely engaging experience. This participant suffers from a condition resulting in a lack of mucus in the sinus membranes, which is very intrusive in his everyday life. He noted

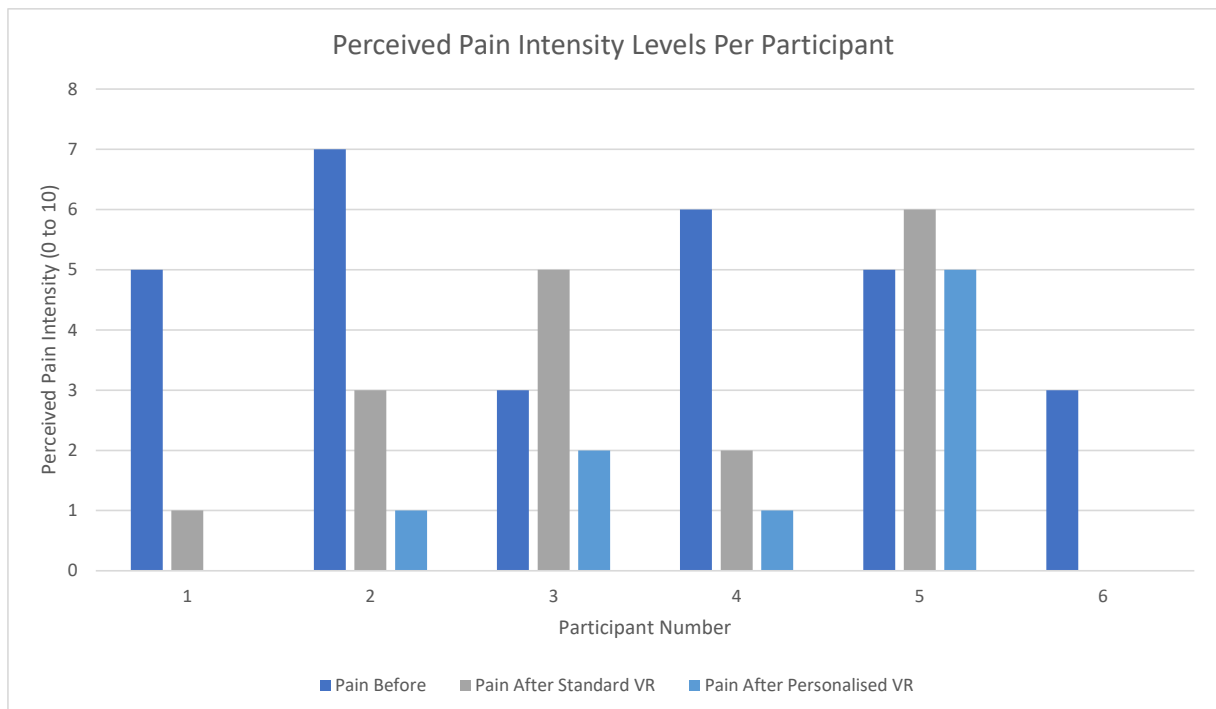


Figure 5.2 Pain intensity levels before and after each experience

that the condition worsens in the summer, when the temperatures are high, and it is an arid climate overall, especially in Malta. What could have helped in these reduced scores was the environment built. The standard environment, as outlined, consisted of a sunny forest setting, which does not instil an image of dryness. Most notably, the personalised environment, generated based on this participant's characteristics, consisted of a snowy setting, which, as the participant outlined, further helped stray away from the source of pain and discomfort. A comment which truly brings to life the efficacy such solutions generate is:

"If done during the summer, this first experience wouldn't have been as engaging. The last experience, the personalised version, would have been better in the summer than the first environment since it has a winter feeling."

Participant 2 recorded the highest initial pain level amongst all participants and had multiple conditions which affected his sense of well-being. A significant drop in perceived pain levels is also noted here, with the pain levels reducing by 5 points after the standard experience and by a further 2 points after the personalised experience. Interestingly, this participant was not particularly engaged throughout the experiment and commented on the solution's graphical and immersive elements, stressing that these could be improved. Even though both of these elements are remarkably important for such solutions, as outlined, this participant recorded a significant decrease in pain levels when comparing the pain levels encountered before the start of

the experience and the final pain level documented, dropping from a 7 to a 1 on the VAS. This sheds further light on the complex relationship our minds have with the perception of pain levels.

A notable increase can be seen in the pain ratings recorded after the standard experience for participants 3 and 5, where the perceived pain levels increased by 2 and 1 points accordingly. Both participants outlined that the default experience was nauseating, with Participant 5 immediately feeling dizzy at the start of the experience. This highlights the importance of implementing slow movement and other preventive measures within VR environments, as individuals who are not used to such experiences are susceptible to side effects, even when all necessary precautions are taken, as enforced in this experiment. Participant 5, however, suffers from vertigo, which might have amplified the discomfort felt. Overall, this participant did not enjoy the standard experience and reported not wanting to stay in that environment for a prolonged period. Participant 3 enjoyed the default environment but noted a feeling of nausea, which was amplified through the VR. Looking at the results achieved after the personalised environment, Participant 5's pain rating decreased by 1, reverting to the initial 5 she started the experiment with. Even though there was only a slight decrease in pain ratings, the participant found this experience much more enjoyable and far less nauseating, as discussed further in this evaluation. Notably, participant 3 outlined that the standard experience was more captivating, yet still achieved better pain-mitigating results during the personalised experience.

Participant 6 was very excited about the VR experience and started with a pain level of 3. Suffering from stomach acid issues, this participant started this experience feeling bloated and experiencing indigestion. For this participant, the pain ratings throughout both experiences decreased to 0, showing that the standard environment was sufficiently distracting. Although some limitations, such as user engagement and levels of graphics, were outlined as weak points in the solution, a substantial reduction in this participant's pain and discomfort was still achieved, highlighting the potential such solutions hold in distracting individuals from their pain.

Finally, Participant 4's pain was expressed in terms of anxiety and therefore presents an excellent opportunity to test the efficacy such solutions have on a wandering mind. Starting from a discomfort rating of 6, an immediate reduction of 4 points is noted after the experience in the standard environment. A further 1-point reduction is noted from the results achieved after the personalised environment. This participant was the youngest of the six and was notably the most enthusiastic throughout the experiences. Instead of relying solely on the calming factor the solution aimed to provide, this participant made the experience enjoyable by humouring herself through the various elements provided by the solution, finding glitches and interactions within the animal's movements funny, particularly during the personalised

environment. One of the participants reported an interesting incident where a bear was seen fighting with an unseen creature, eventually dying, and a vulture emerged from beneath it and walked away. This highlights the significance of avoiding a realistic environment in the progressively generated solutions, mainly when the elements within the environment can interact with each other.

Even though the perception of pain is highly subjective, certain elements, such as gender, ethnicity, and age, can play a role in how individuals perceive pain.

5.3.2 Gender and Virtual Reality Pain Mitigation

The group of participants consisted of an even gender split of males and females, with no participants selecting the 'other' option. As seen in Figure 5.3, both genders started off at approximately the same perceived pain levels. However, the results show that males benefitted much more from the overall experience, with an average reduction of 4.67. Conversely, females achieved a total reduction of 2 points, which is still encouraging. Looking into the difference between the pain ratings documented in the standard and the personalised experience, the female participants responded better to the personalisation aspect. Accordingly, they recorded a more significant reduction in perceived pain, with the average differences being 1 and 1.67 for males and females.

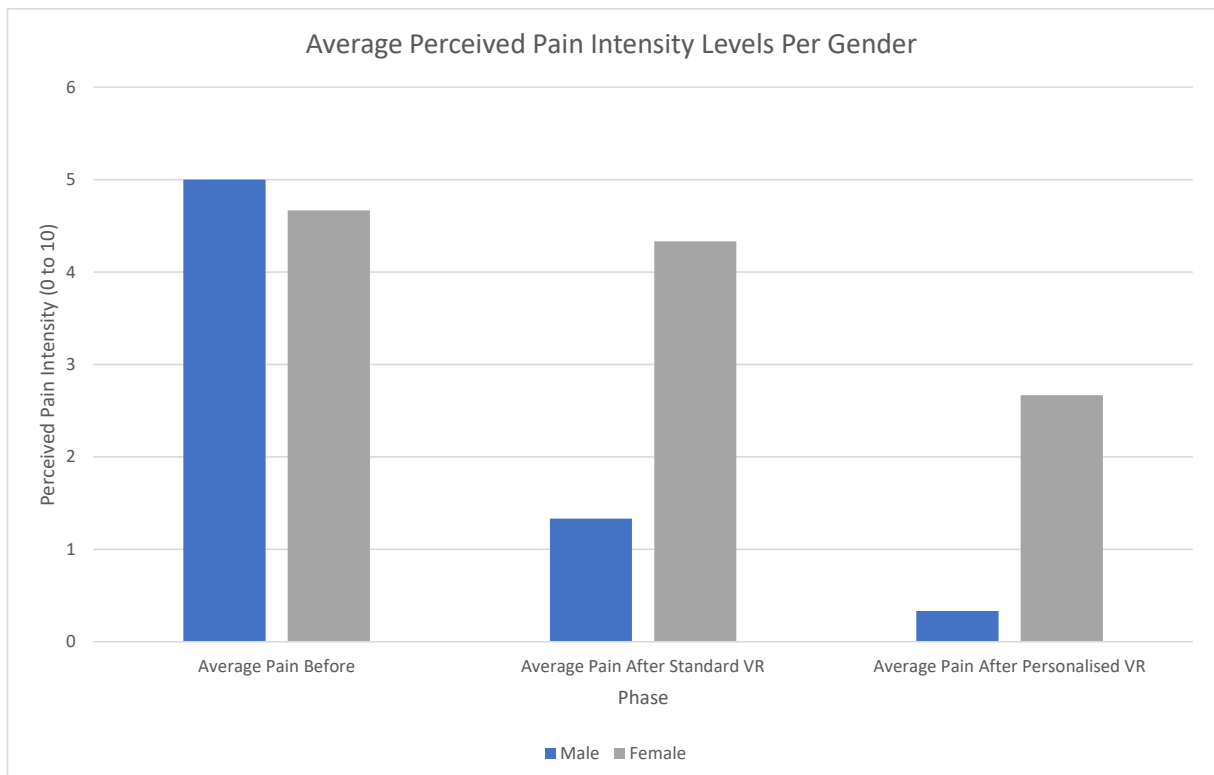


Figure 5.3 Average pain intensity levels per gender

5.3.3 Age and Virtual Reality pain mitigation

Concerning the different ages within the pool of participants, an even split can be noticed where the participants can be split into two groups of 3. The first represents relatively young individuals (below 31 years old), and the second consists of participants aged 60 and above.

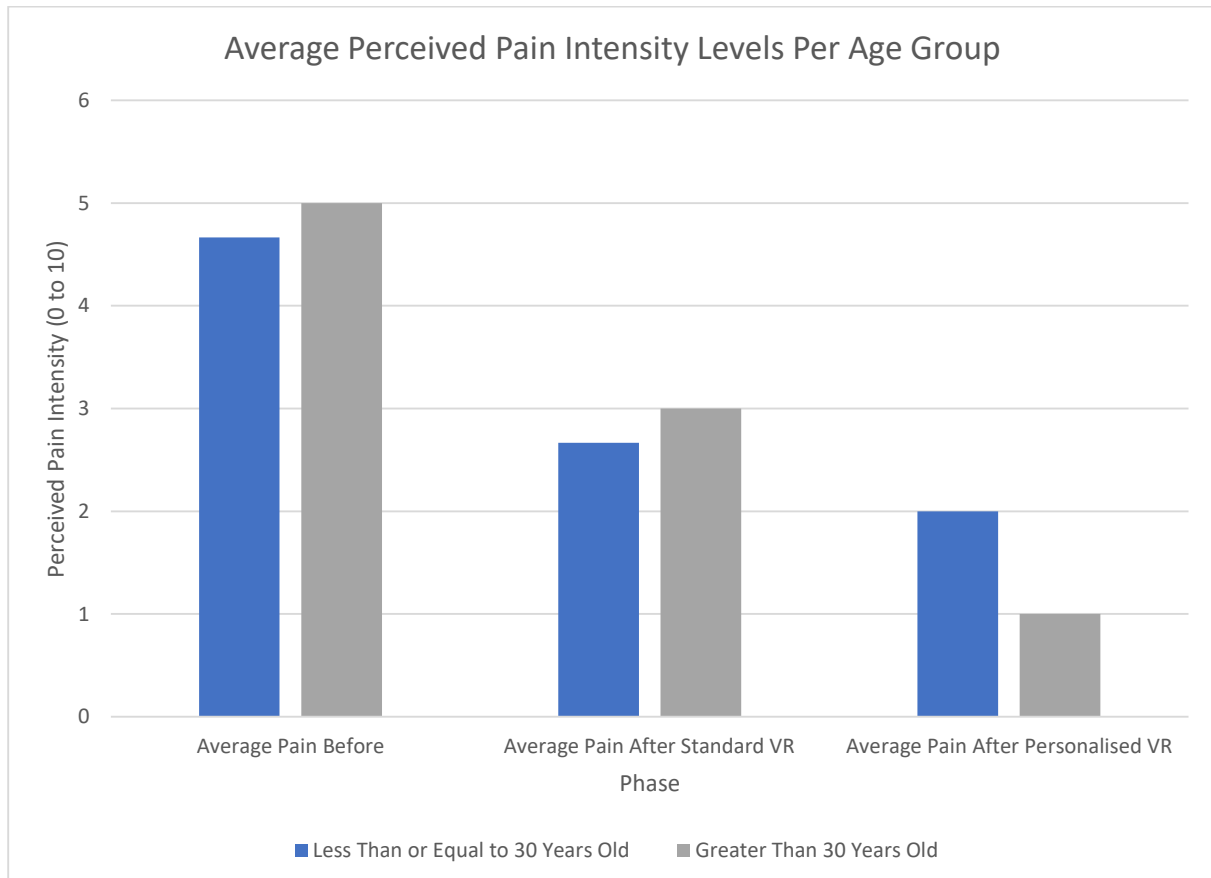


Figure 5.4 The Average perceived pain intensity levels per age group obtained in this work

Once again, as can be seen in Figure 5.4, both groups started at similar average pain levels. Looking at the average pain recorded after the standard experience, both groups display a similar decrease in intensity. The older group, however, displayed a more significant reduction in pain ratings after the personalised experience was over. This shows that the older audience better enjoyed personalisation. This being said, since this work serves as a proof of concept for the feasibility of the personalisation of a VR environment, the classifiers implemented were not trained on real data. As previously outlined, the 'Faker' Python library was used to generate fake user profiles, together with their preferred environments. Due to this limitation, these did not generate the personalised environments based on valid mappings but on fake information which does not necessarily capture the environments required by

individuals suffering from various conditions. This being said, the personalised environments still performed better than the standard environment. Although the training profiles contained fake information, some aspects within the personalised environments were notably more intriguing for several participants. This might be due to the safety aspect within the default environment. Given that the default environment is not personalised, the aspects generated within were all kept relatively basic, ensuring that it is an environment that can be enjoyed by everyone, as can be seen in Figure 4.17. The following section introduces the various environmental elements the participants noted throughout the two experiences.

5.4 Elements Affecting the Efficacy of VR Pain Mitigation Environments

As outlined, the participants were given the same questionnaire after both experiences. These aimed to capture what the participants liked and disliked in the environments, furthering our understanding of what individuals prefer from such experiences. This information is crucial for solutions such as the work built in this thesis, which tries to predict what an individual desires and generates it accordingly.

In question 4 in the questionnaire, the participants were asked to select or comment on their overall opinions about each experience, the results of which are outlined in Figure 5.5. The available options were:

- I found it extremely captivating
- I found the experience interesting but not as engaging
- I was comfortable
- The experience took too long
- I found the meditation helpful
- Other (please describe your thoughts)

Regarding the standard (default) environment, five participants found the experience comfortable, and only Participant 5 outlined a lack of comfort, mainly due to the nausea felt. In the personalised environment, however, all participants marked the comfortable option, showing that comfort does not solely stem from the technology used but also depends on other attributes such as the VR environment itself and sounds. Even though Participant 5 was feeling quite nauseous, it was noted that during the personalised experience, this was not a prevalent issue, which could be due to the

participant getting used to the technology (which notably might take some time to acclimate to), or due to the immersion achieved, especially since the participant marked that the personalised environment was highly captivating. Furthermore, after the standard experience, this participant noted that it was unpleasant. Both experiences received four votes regarding the meditation option, highlighting the mindfulness aspect such solutions can generate. Similarly, Participants 2 and 6 found both variations interesting but not engaging. As per the participants' answers and comments, this was primarily due to the lack of realism, low-poly graphics and lack of user engagement. Both participants desired elements they could interact with within the environment and felt bored simply roaming around. This, therefore, introduces the need for optional tasks within such environments, as simply asking the participants to be mindful and roam freely might not be effective for all individuals, especially those who are very competitive. Three participants found the standard environment to be extremely captivating. Comparatively, 5 participants found the personalised environment extremely captivating, once again showing that the personalised environment better captured the user's liking. Only one participant felt that the experience took too long; Participant 6 felt that the personalised experience took too long, perhaps due to the lack of engagement which was previously noted.

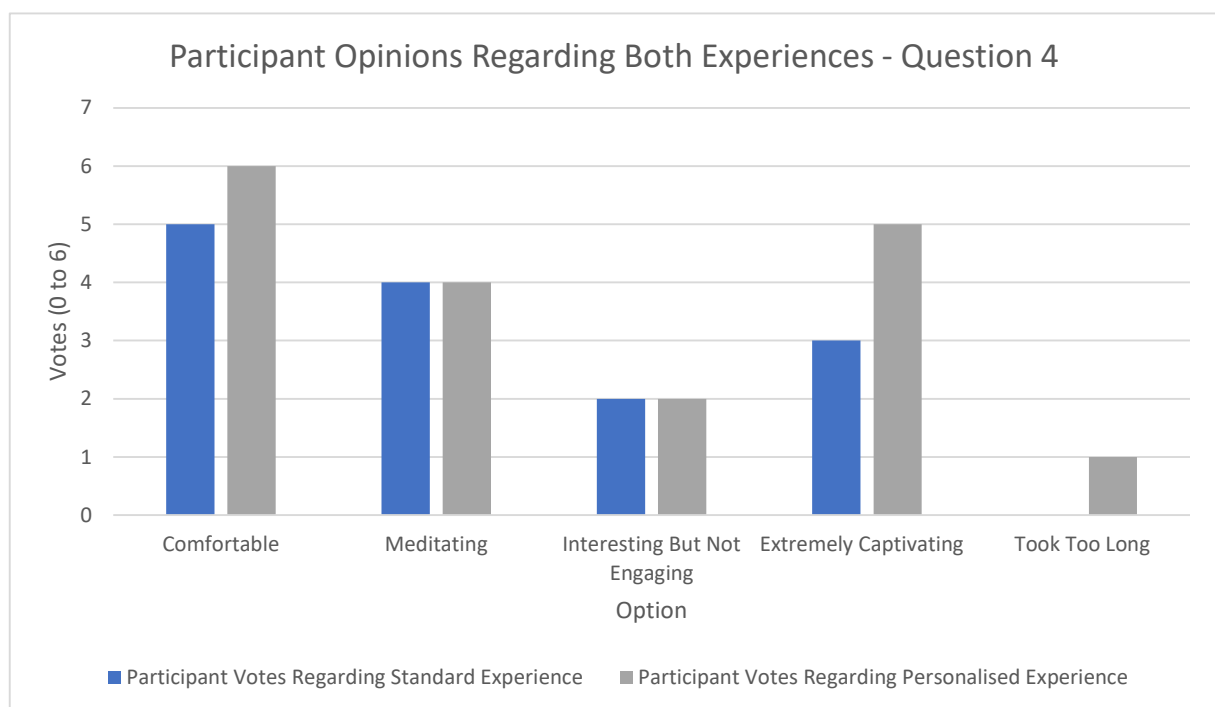


Figure 5.5 Participants' opinions on the standard and personalised experiments - Question 4

Furthermore, in question 5, the participants were asked to select which elements in the VR environment they enjoyed the most. As outlined in Figure 5.6, having six votes, the sound was the most appreciated feature in the standard

environment, which consisted of the ambient sound of a calm meadow and chirping birds. For the personalised environments, on the other hand, the ambience changed to calming handpan music for all participants.

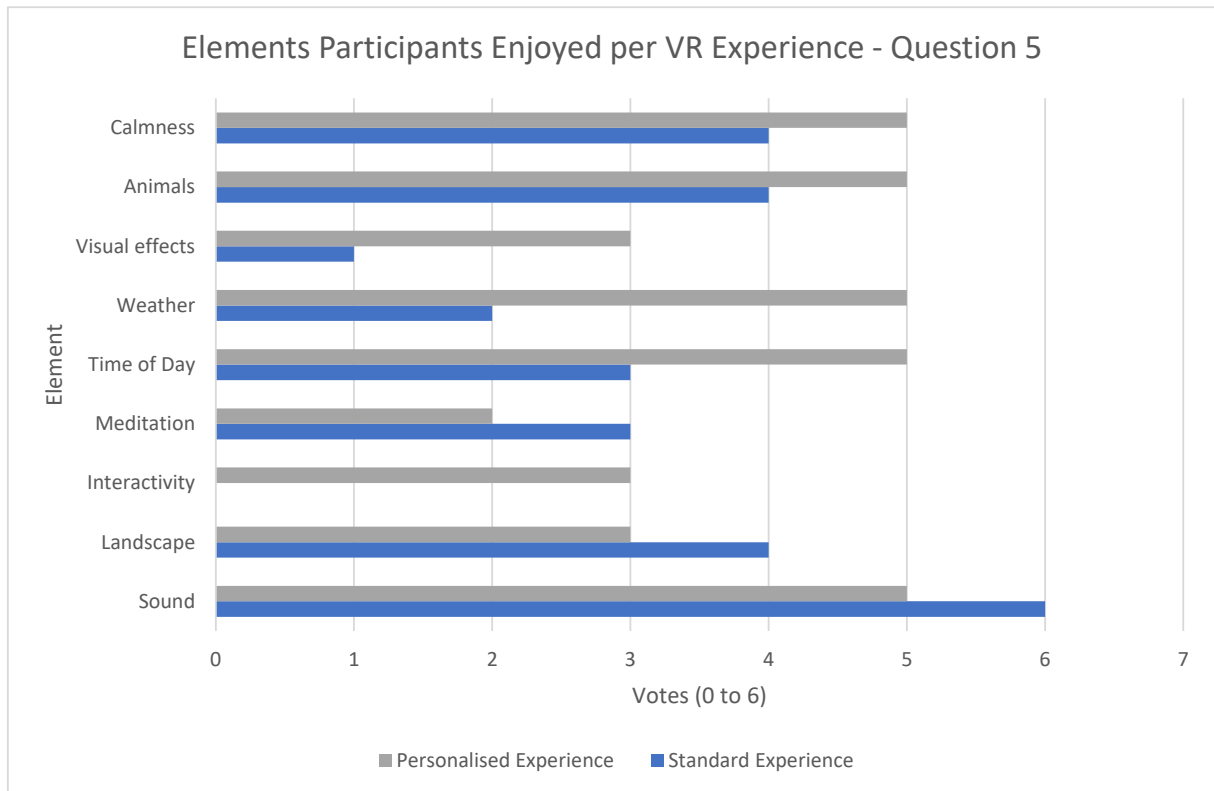


Figure 5.6 The elements participants enjoyed per VR Experience - Question 5

Participant 1 did not enjoy the sound in the personalised experience, particularly due to its high volume. The same was noted for the landscape; 4 participants enjoyed the landscape within the standard environment, which decreased to 3 for the personalised environment. Participant 4 outlined that the personalised landscape was set in the desert, which is not an environment she particularly enjoys. This shows the importance of varying environments. Developing a single environment is not feasible, especially when trying to reach multiple individuals with varying personalities and necessities. As for the interactivity, none of the participants found the standard environment interactive. Even though elements of the same nature were present in the personalised environment, 3 participants found the personalised environment interactive. This might have been due to the greater number of animals that could have been generated or varying animal sizes generated through the 'fantasy' option. The personalised environment does not conform to reality and attempts to bring the participant's childlike dreams to life, depending on the participant. As seen in Figure 5.6, the personalised environment performed better in most of the elements the participants were presented with, further highlighting the importance personalisation has in such solutions. A common idea shared between most participants was the desire

for more animals within the environments. As outlined, the meditative aspect implemented in these experiences consisted of being mindful of the sounds and environmental elements available. A breathing exercise was also available but was not made available during the experiments since some participants suffered from respiratory issues. Given that such exercises could draw the user's attention back to their condition, this exercise was entirely omitted for all participants so as not to introduce any variables between participants.

In question 6, on the other hand, the participants were asked about the elements they disliked the most. Most participants did not conform to the provided selection and inserted their own comments, which they felt better captured their thoughts. In the standard environment, the noted issues were the slow movement speed, dizziness, lack of animals and interactivity, and weather. As for the personalised environment, the interactivity and the landscape were the worst elements experienced, with one participant mentioning dizziness when going down a slope (such as a mountain).

To better understand what participants are drawn to in such environments and test how mindful the participants were of the visuals presented, question 7 requested the participants to mark the elements they noted throughout the environment. Figure 5.7 outlines the total number of different elements noted by the participants for both experiences. As one can see, the participants were mindful of numerous aspects in both experiences, demonstrating the importance of such elements for user engagement and immersion. Overall, the participants noticed six fewer elements in the standard environment, which could have hindered their distraction and, therefore, the results achieved. This being said, Participant 4 outlined that knowing about the question made her more attentive throughout the second experience. This, therefore, could have played a role in the results outlined, but also presents the potential of gamification within such environments, which, by simply having the users search and take note of certain elements, provides an immersive experience.

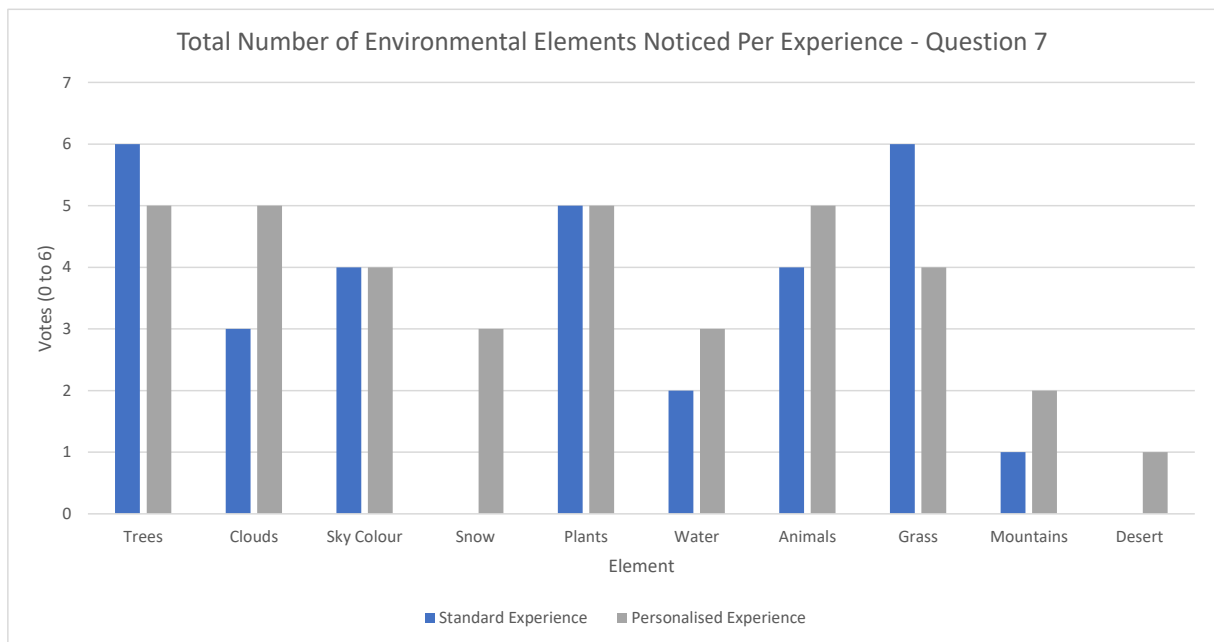


Figure 5.7 The total number of environmental elements noticed per experience - Question 7

5.5 Participants Experiences Overview

Most participants found the experiences exciting and enjoyable, although some outlined room for improvement. Several suggestions were made when asked for any improvements they would make to increase the solution's efficacy (question 9). Most notably, the player's movement speed was quite problematic, as the participants noted it was especially slow and made travelling tedious. Graphics quality is another element which was brought up, with two participants stating that low-poly graphics are not immersive and better visuals are required for such an environment to be engaging. Overall, the participants' lists of improvements were similar between the two sessions. These results outline the importance of vegetation, graphics, user interaction, and animals. Interestingly, all participants showed significant enjoyment with the inclusion of animals within the environments and should, therefore, be positively considered in any future work within this domain. The participants also notably appreciated the vegetation available, with numerous desiring more flowers, plants and trees. These results conform well with the research found, where animals and vegetation are well-known factors affecting individuals' perception of pain. Finally, participant 5 mentioned that using the VR technology was exceptionally problematic due to her nausea and suggested removing the VR aspect as an improvement. When asked (question 11) how accurately the environment captured their idea of a relaxing environment, the results achieved, as displayed in Figure 5.8, show that apart from participants 2 and 5, the standard environment was satisfactory, with the average

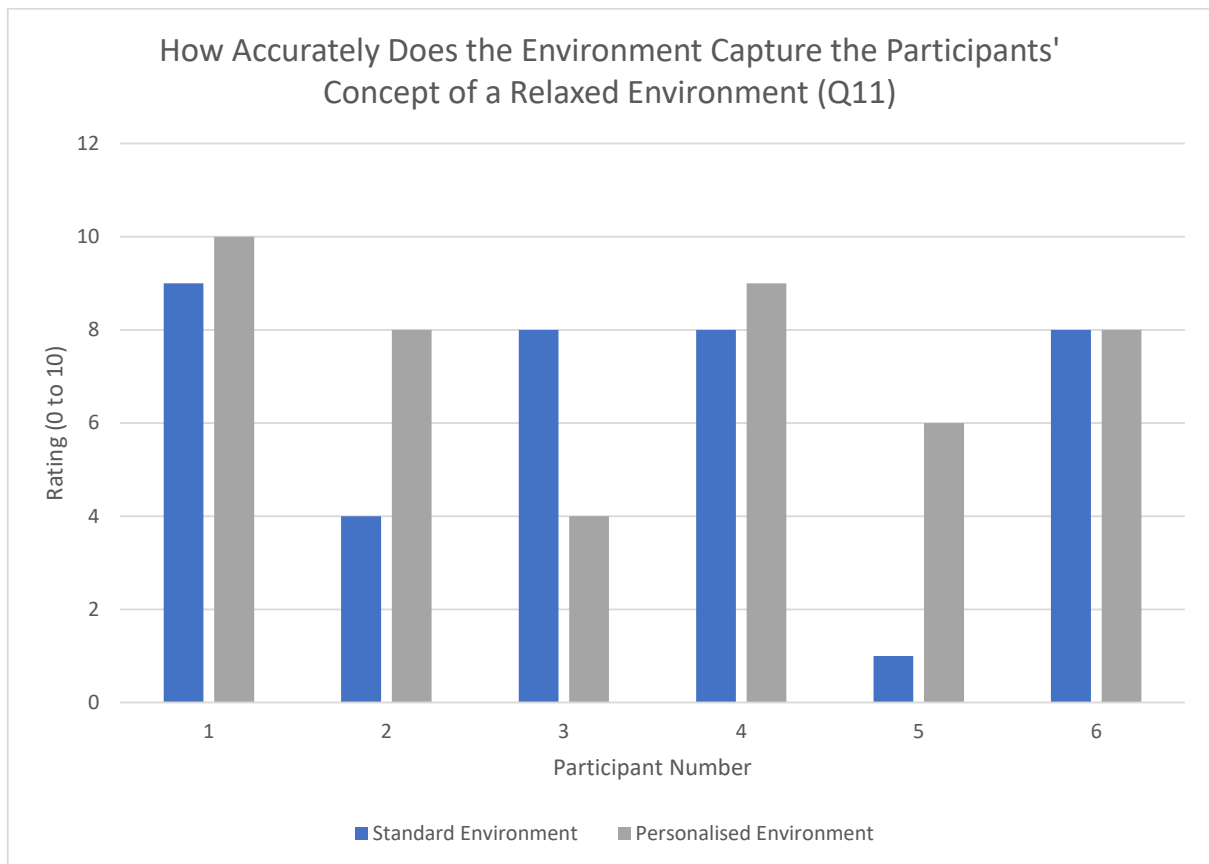


Figure 5.8 How accurately does the environment capture the participants' concept of a relaxed environment (Q11)

score sitting at 6.3 out of 10. Looking at the results achieved in the personalised environment, the average increased to 7.5, showing that participants felt it better captured their idea of a relaxation environment, as displayed in Figure 5.9.

This is especially true for participants 2 and 5, whose scores increase from 4 and 1 to 8 and 6 accordingly. These results are incredibly encouraging for personalised environments and show that a personalised approach can harness further potential for non-analgesic pain mitigation. Finally, 5 out of 6 participants felt that such solutions can be effective for pain mitigation, relaxation and meditation due to their engagement, fun, relaxation and escape from reality. Participant 5, on the other hand, felt that the solution was too game-like and, therefore, less relaxing.

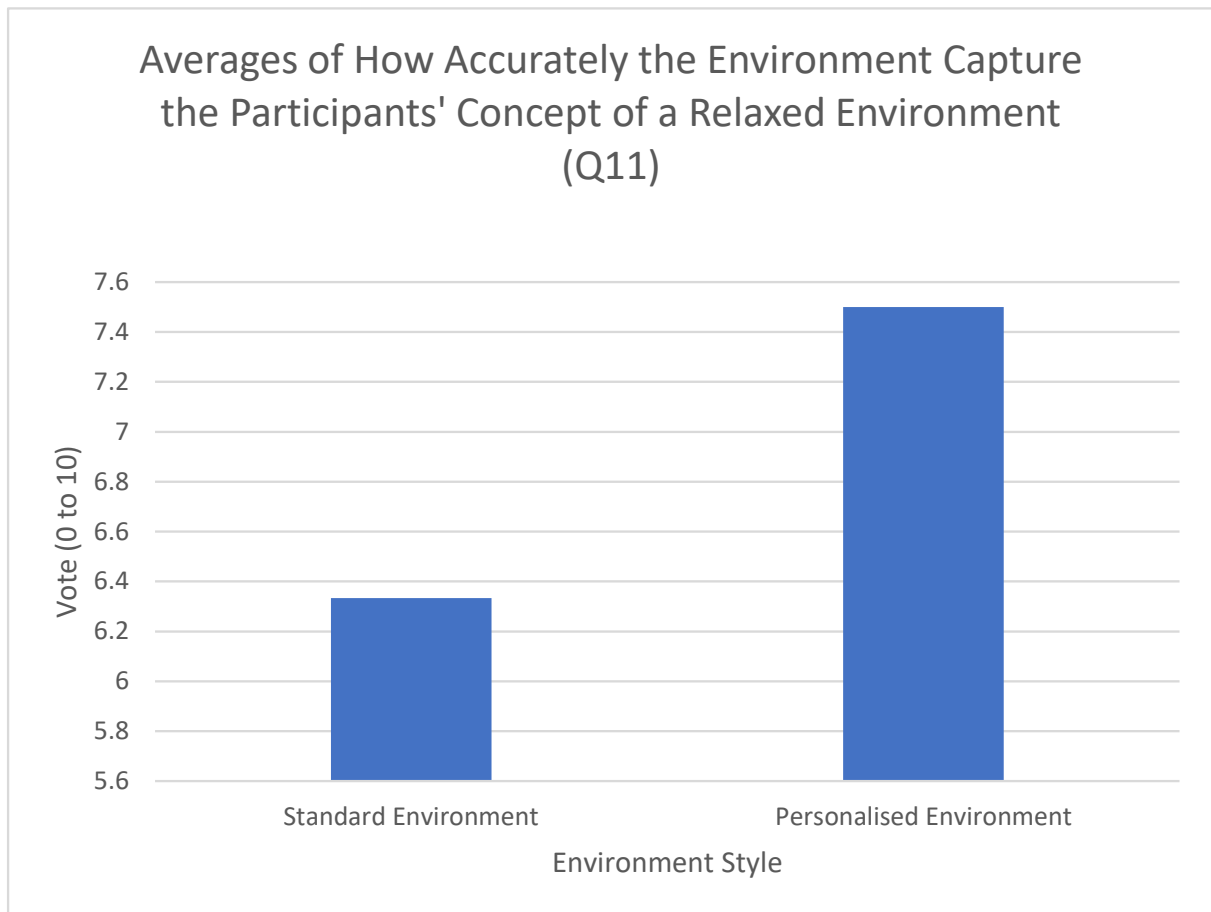


Figure 5.9 Averages of how accurately the environments capture the participants' concept of a relaxed environment (Q11)

5.6 Overview

As discussed, the results achieved show that such solutions have great potential for pain and anxiety mitigation. After only two 5-minute sessions, significantly reduced pain levels were noted across both session variations. This displays the efficacy VR solutions have on pain mitigation and further backs up the results achieved in the literature reviewed. Notably, the architecture proposed throughout this work successfully created multiple default and personal environments at run-time, all of which bestowed a degree of pain mitigation and immersion to the users. It was also noted that the environments were successfully amalgamated with the VR technology, further improving the solution's immersive aspects.

6 Conclusion

This work explores the efficacy of personalised VR solutions for pain mitigation. The research in this domain shows that numerous factors must be considered when devising a non-analgesic pain-relieving solution. Given the issues traditional pain analgesia introduces, the necessity for non-medication-based therapy is further increasing. Therefore, this work aims to further the research available in this domain and presents a novel framework that aims to reduce an individual's perceived pain levels.

6.1 Discussion of results

By harnessing the potential of user modelling, PCG and VR, the solution presents endless, unique, and personalised environments generated at run-time. The results show that the solution developed successfully reduced participants' perceived levels by 68.9%, comparing well with the results achieved in other studies. This work's introduction of personalisation presents a novel approach in this domain, which, as shown in the results obtained, further reduced individuals' perceived pain intensity levels by a significant 27.5%. As discussed, several parameters that could be used to characterise pain were researched and utilised to develop an effective user modelling solution that generates a personalised VR environment. Although a pain expert's opinion in this domain would have been incredibly beneficial to map pain characteristics to various environmental factors, the personalised environments still performed remarkably well, showing that the implemented user modelling techniques, such as the machine learning algorithm used, can be effectively utilised within this domain. Similarly, the PCG algorithms built and adapted throughout this work generated unique, immersive environments, which performed significantly well. As seen throughout the experimentation phase, the solution built can effectively develop a limitless number of unique environments. These include different settings and terrains, such as forests, valleys, snow, deserts, and mountains and consist of many elements that effectively draw the users' attention. Vegetation, animals, immersive music and sounds are also included as they are known to harness positive emotions and immersion, as outlined by the participants. The experiments conducted prove that these elements are greatly sought for and greatly enrich the immersive experience. Voice commands and breath meditation are also integrated, which further improves immersion. The results show that the solution managed to generate personalised calming environments, which users found captivating and better captured their idea of a relaxing environment when compared to the default environment.

As seen in the literature reviewed in Chapter 3, several aspects can affect the efficacy of pain mitigation techniques, especially those affecting user immersion. Overall, VR proved to be an effective method to further engage participants within an environment. Furthermore, personalisation increased immersion and generated better results. As seen in the literature reviewed, nature, beautiful scenery, mindfulness and meditation, animals, and harmonious sounds are all effective methodologies that can be implemented within such solutions. In addition to this, aspects such as gender, age, and the type of condition are also elements that can alter the efficacy of such solutions. As seen in the results achieved, males responded better to the overall therapy in both standard and personalised environments. As for the age, the groups performed relatively on par, with the participants aged older than 30 achieving slightly better results in the personalised environment. It was also seen that such solutions might not be as effective for individuals suffering from vertigo or similar conditions. This research also shows that interactivity is highly sought after and is paramount in VR pain mitigation approaches. Furthermore, user modelling was an integral aspect of the solution built and helped produce significant results through personalised experiences. Even though the participants were suffering from a multitude of conditions, the participants found the overall VR equipment comfortable.

A survey tool was also built and validated throughout this work. This was employed throughout the experimentation phase to gather a deep understanding of this solution's performance, highlighting any strengths and weaknesses that can be utilised to further the research available in this domain.

Finally, this work supplies a framework which amalgamates user modelling, PCG and VR for pain mitigation. Furthermore, this research fulfilled all of the objectives proposed and delivered an effective solution to the research question outlined in the first Chapter of this document. As with all systems, however, improvements can be made to enrich the users' experience and, therefore, the results achieved.

6.2 Limitations

Several limitations were noted in the solution built, which could have hindered the results achieved. The first was the lack of a pain expert's input when creating the user modelling aspect of this study. Since the pain expert could not participate in this study, the user profiles used were randomly generated and did not accurately capture user preferences, hindering the framework's actual potential. The second limitation pertains to the experiment's limited participant pool. Given that the experiment was carried out on only 6 participants, the results achieved cannot be generalised. Using a larger pool of participants would ensure that the experiment encapsulates a wide array of

individuals, having different demographics and chronic conditions, thus ensuring that the results achieved confidently show that the solution can be effectively used in a real-life scenario.

Another notable limitation was the environment's fluctuating performance. Since the environment is built at run-time, all the computations, instancing, rendering, and baking are processed on the go. This presents numerous performance issues, and significant effort must be spent to manage resources effectively. Even though care was taken to build an efficient and robust solution that utilises as few resources as possible, this work is still quite heavy on the CPU — making it not ideal for entry-level systems. Baking the nav mesh at run-time so that the animals could freely roam the terrain greatly affected performance and rendered the solution useless until a solution was found. The nav mesh is generated only on the participant's current terrain chunk, with the animals also having to be rendered once the nav mesh is baked. This presents slight stutters when the user reaches the current terrain's movement threshold, instructing the environment to generate or re-render another set of terrain chunks and objects. Testing the VR solution was another limitation, which constantly required having the VR HMD connected and initiated per test, which significantly slowed down the development process. Due to the amalgamation of several processes required at run-time, elements affecting system resources were kept as minimal as possible. Therefore, the environment's realism aspect was hindered in favour of better performance. Aspects such as greater details, better models and textures, increased animations, improved lighting, grass, reflections and the number of elements rendered per chunk were all reduced, all of which would have produced an environment which is more aesthetically pleasing and, therefore, more enjoyable.

Although the results achieved are greatly encourageable, the initial perceived pain level question could have been misunderstood by some participants, who might have believed it to pertain to the general severity of their pain and not that felt at that particular moment. This explains the significant difference between the first and the last recorded pain levels for some participants. This being said, the difference between the perceived pain readings in the standard and personalised environments could not have been affected by such misunderstandings and still display the significant benefits such systems introduce. This shows that since the evaluation tool is entirely based on self-assessment, the results achieved are highly dependent on the participants' honesty and are very subjective, introducing the possibility of bias and inaccuracy.

6.3 Future Work

Due to the environment's visual limitations, future work within this domain should look into using other game engines, such as Unreal Engine, better known for their realistic graphics and performance. Proper consideration must be taken when selecting the device to be used. The device must be commercially available and effective for the solution developed. This work required several downgrades for the solution to run smoothly on the VR device. These included reducing the number of draw calls, polygons, and vertices within the scene, even though proper quality and performance-driven approaches were utilised throughout the development process. GPU instancing is also not favoured by this device as it increases the number of draw calls made. This was noted when rendering a batch of grass, which significantly reduced the frames per second from an average of 80FPS to an average of 20FPS. Notably, it was found that the headset has issues with rendering vegetation, although Meta does not back up this information and was only available through forums. Even though performance should be highly prioritised in such solutions, the participants expressed that a realistic environment would have been much more effective. Even though this is highly subjective, options should be made available for better-looking models to be rendered and utilised based on the participant's preference. The current architecture already consists of ways to handle the level of detail for the terrain generated; extending this to the models used might produce a further level of customisation that addresses such issues.

Most notably, future work should enhance the proposed solution's personalisation and user modelling aspects. Accurate data should be utilised to train the classifiers, which helps generate personalised environments that accurately capture the users' requirements and preferences. Through this, better immersion can be achieved, improving the results achieved and unlocking the architecture's pain-mitigating potential. The participants' data can also be added to the solution through a correction system, where the solution further adapts to what the participant likes and evolves based on that specific user. Different machine learning approaches should also be looked into, furthering our understanding of the parameters and algorithms best suited for such solutions.

All participants outlined the importance of animals, vegetation and sounds within the experience. Consequently, future work should consider integrating more of these elements within the environment, enhancing the immersive elements. Apart from this, the importance of interactivity was strongly emphasised through the evaluation. Users strongly require an element which keeps them engaged throughout the experience, especially when employed for pain mitigation.

As for the evaluation method, extended experimental phases should be

implemented, which would shed light on the efficacy of such solutions over a longer period, showing the different results achieved, if any, as the users get acclimated with the built environments. This work's notable strength is its generation of endless, unique, and personalised environments. A more extended testing phase would, therefore, test whether the implemented techniques manage to retain the participants' engagement when compared to a standard, non-changing version of the environment, even after a considerable number of uses. This would show that such a solution can be effectively employed without worry for a significant period of time, as is most commonly required by individuals suffering from chronic pain.

Additionally, VR meditation should be further integrated within the personalisation framework built into this work, which only makes use of breathing exercises and mindfulness techniques.

6.4 Final Remarks

This research successfully developed an efficient pain management framework that significantly reduces an individual's perception of pain. Pain and the need for non-analgesic pain management are prevalent issues in our daily lives. This work showcases how technology can significantly benefit digital health. With the use of appropriate tools, strategies, and quality software engineering, the domain of digital health can dramatically enhance an individual's quality of life.

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Appendix A Self-Assessment Evaluation Tool

Innovative Pain Management Techniques

Questions for Participants | Pre-Experience

Age:
Please specify your age in years.

Gender:
What is your gender identity (Male/Female/Other)?

Race/Ethnicity:
How would you describe your race or ethnicity?

Do you commonly experience any kind of pain?

On a scale of 0 to 10, with 0 being "no pain" and 10 being "the worst pain imaginable," how would you rate how you're feeling right now? Please mark this in the scale shown below.

No Pain

Moderate Pain

Worst Pain

012345678910

If you've answered more than 0 on the above scale, which body part would you say you most feel it in?

If you commonly experience pain, for how long does it usually last? Please answer in a method you feel most comfortable in (minutes, hours, days).

Figure A.1 1st page of the Survey tool built: used to capture user demographics and pain characteristics (if any)

Questions for Participants | Post-Experience [these questions are given after each VR experience (both standard and personalised)]

1. Were you experiencing any form of pain prior to this experience?
2. Have you ever done meditation?
3. Have you ever done meditation using Virtual Reality (VR)?
4. Describe your Virtual Reality (VR) Meditation Experience? Please tick in the table below, you can select more than one option.

Description	Checkbox
I found it extremely captivating	
I found the experience interesting but not as engaging	
I was comfortable	
The experience took too long	
I found the meditation helpful	
Other (please describe your thoughts):	

5. Which elements of the Virtual Reality (VR) environment did you enjoy most? Please tick in your answers in the table below.

Description	Checkbox
Sound	
Landscape	
Interactivity	
Meditation	
Time of Day	
Weather	
Visual effects	

Figure A.2 2nd page of the Survey tool built: used to capture the user's experience and pain (if any) after both the standard and the personalised experiments

Animals	
Calmness	

6. Which elements of the Virtual Reality (VR) environment did you enjoy least? Please tick in your answers in the table below.

Description	Checkbox
Sound	
Landscape	
Interactivity	
Meditation	
Time of Day	
Weather	
Visual effects	
Animals	
Calmness	

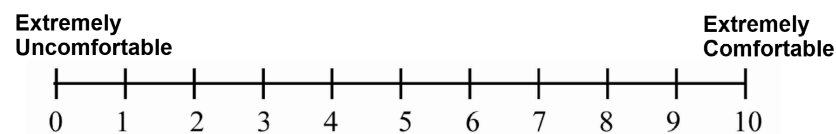
7. Which elements did you notice in the Virtual Reality (VR) environment? Please tick the elements you noticed in the table below.

VR elements	Checkbox
Trees	
Clouds	
Sky Colour	
Snow	
Plants	
Water	
Animals	

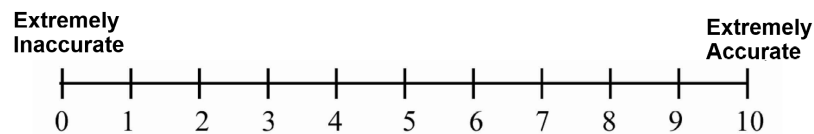
Figure A.3 3rd page of the Survey tool built: used to capture the user's experience and pain (if any) after both the standard and the personalised experiments

Grass	
Mountains	
Desert	
Meditation Available	

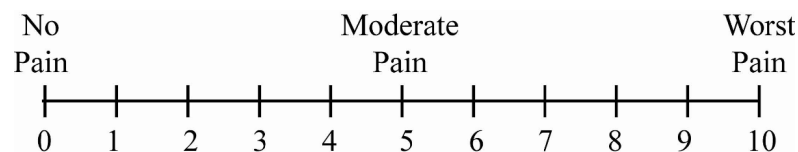
8. Would you be willing to use Virtual Reality (VR) for relaxation?
9. If you could suggest any improvements or changes to the Virtual Reality (VR) experience to make it more effective, what would they be?
10. On a scale of 1 to 10, how comfortable were you using the Virtual Reality (VR) technology, including the headset and controls? With 1 being "not comfortable at all" and 10 being "very comfortable". Please mark this in the scale shown below.



11. On a scale of 1 to 10, how accurately do you think that Virtual Reality (VR) accurately captured your idea of a relaxing environment? with 1 being "not accurate at all" and 10 being "extremely accurate". Please mark this in the scale shown below.



12. On a scale of 0 to 10, with 0 being "no pain" and 10 being "the worst pain imaginable," how would you rate how you're feeling right now? Please mark this in the scale shown below.



Show this last question after the personalised VR experience.

Figure A.4 4th page of the Survey tool built: used to capture the user's experience and pain (if any) after both the standard and the personalised experiments

13. Following this experience, what are your views about VR experiences for pain management, relaxation, or meditation?

Figure A.5 5th page of the Survey tool built: used to capture the user's opinion about VR-based treatment

Appendix B Extra Figures

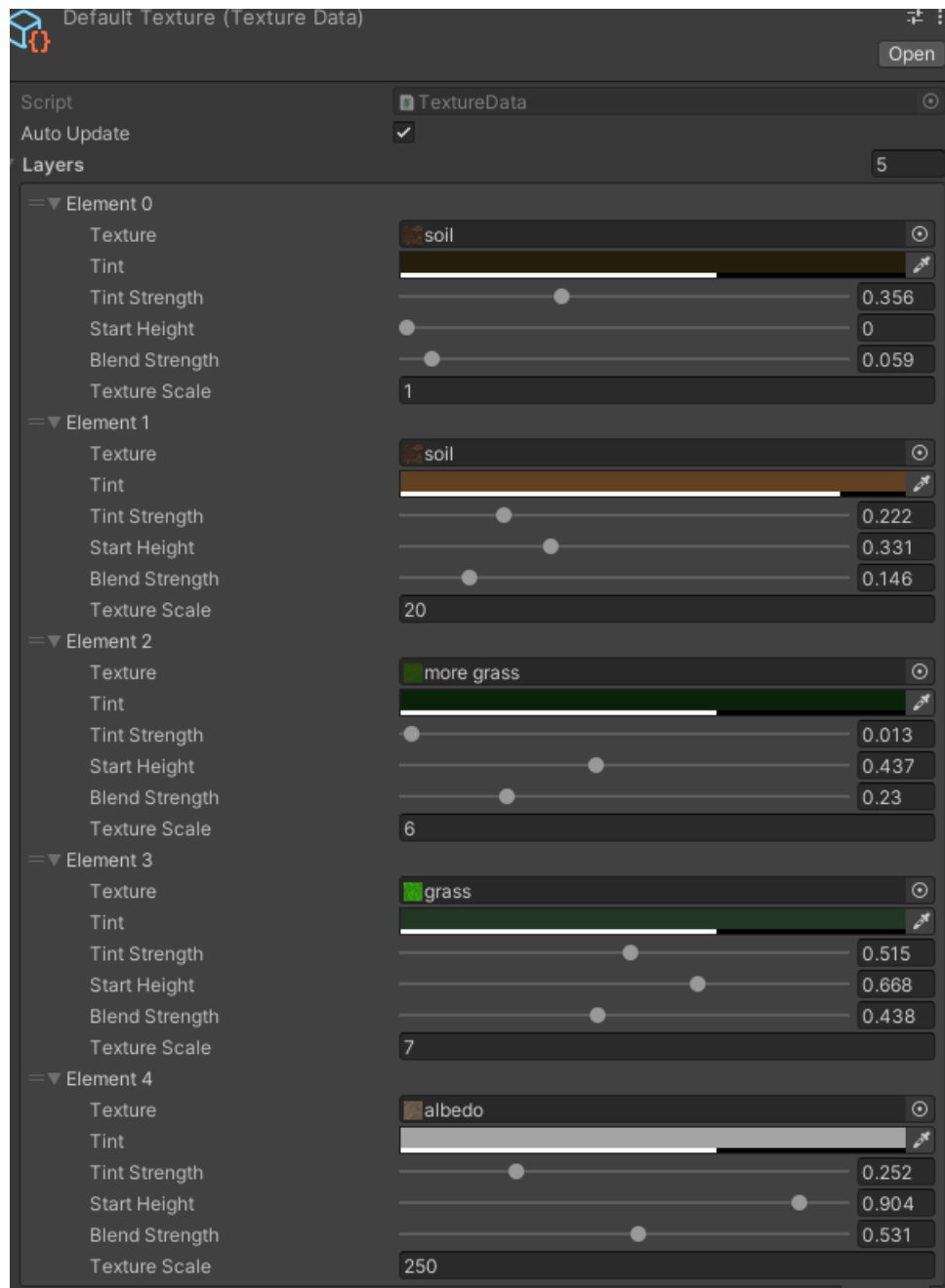


Figure B.1 Colourisation settings used to show an example of a colourised terrain chunk

Appendix C Extra Tables

Day	VR Program	Audio Only Program
1	Breath of Hope	Welcome to Mindfulness
2	Breathing Life	Breathing in Five Senses
3	Well-being Relaxation	Well-being Relaxation
4	Dolphin Healing	Releasing Pain
5	Focus Game	Body Scan
6	Paced Breathing	Breathing in Five Senses
7	Awareness of the Mind	Awareness of the Mind
8	Intro to Pain Education	Intro to Pain Education
9	Dream Garden	Cosmic Journey
10	Building Breath	Mindful Breathing
11	Mallorca	Empower
12	Body Scan	Body Scan
13	Breathing Portal	Releasing Pain
14	Compassion Relaxation	Compassion Relaxation
15	Mindful Breathing	Mindful Breathing
16	Let's Talk About Pain	Let's Talk About Pain
17	Deep Relaxation	Breathing in Five Senses
18	Harm Alarm	Harm Alarm
19	Empowerment	Empowerment
20	Dream Maker	Breathing in Five Senses
21	Power of the Mind	Power of the Mind

Table C.1 Therapy program outlined in [61]