بسم الله الرحمن الرحيم

In the Name of Allah

The Most Merciful the Most Compassionate

Eye Tracking in Immersive Virtual Reality Pain Distraction System

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A thesis submitted for the requirements of the degree of Doctor of Philosophy in Computer Science

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By

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ABSTRACT

Nowadays, Virtual Reality (VR) technologies are rapidly advancing as they address new domains such as therapy. Preliminary studies suggest that VR has enormous potential for reducing acute pain during wound care. However, state-of-art VR analgesia systems currently require patients to move a handheld input device. Unfortunately, many severe pediatric burn patients trying to use VR have burned hands and are unable to use a handheld mouse. The main project of this research aims to solve a limitation in existing VR analgesic systems by increasing the illusion of presence and analgesic effectiveness for immobilized children by adding eye-tracking capability for the first time.

After exploring the different eye-tracking technologies, investigating the feasibility of using eye tracking in active or passive forms, and evaluating people's awareness of and attitude toward such technology, an eye-tracking system was developed using an improved control interface to increase interactivity in the VR environment. The research explores the technical requirements of the developed system, in which the recent innovation of an embedded eye tracker in a VR helmet is utilized to implement a laboratory pain distraction system.

In order to assess the effectiveness of the system, a randomized controlled laboratory analog pain study was conducted with healthy volunteers to quantify whether using eye movements to interact in a VR system significantly increases the illusion of presence and increases the analgesic effectiveness of VR distraction during brief thermal pain. Additionally, we designed a fixation detection algorithm that executes within the immersive VR technology, as a step toward another future approach of using eye tracking passively in order to collect eye movements to assess the patient's mental state during painfull medical procedures.

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LIST OF ACRONYMS

ANOVA	Analyses of Variance
AOI	Areas of Interest
AR	Augmented Reality
BCI	Brain-Computer Interface
CPM	Conditioned Pain Modulation
DPI	Dual Purkinje Image
EOG	Electro-Oculography
fMRI	functional Magnetic Resonance Imaging
FOV	Field of View
GPU	Graphical Processing Units
HCI	Human-Comouter Interaction
HD	High Definition
HMD	Head Mounted Display
HMD-ET	Head-Mounted Display Eye Tracking
HM-ET	Head-Mounted Eye Tracking
IDT	Identification by Dispersion Threshold
IR	Infrared
MIS	Minimally Invasive Surgery
msi	Micro-Star International Company
MR	Mixed Reality
NRS	Numerical Rating Scale

NUI	Natural User Interface
OOI	Objects Of Interest
POG	Photo-Oculography
POR	Point of Regard
RAM	Random Access Memory
SDK	Software Development Kit
SMI	SensoMotoric Instruments Company
TM-ET	Tower-Mounted Eye Tracking
UX	User Experience
VAS	Visual Analog Scale
VOR	Vestibulo-Ocular Reflex
VR	Virtaul Reality
VRS	Verbal Rating Scale

Chapter I

Introduction

Virtual reality (henceforth VR) has no generally-agreed-upon comprehensive definition. However, there have been several attempts to define it within academic circles. For instance. Burdea and Coiffet [1] discussed various definitions for VR and summarized them into the following description:

"Virtual reality is a high-end user-computer Interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste."

It is much easier to define VR based on its features, usually referred to as the three I's (or 3Is) [1] that stands for *Immersion-Interaction-Imagination*. The idea behind VR is to give the computer users the illusion that they are inside the 3D computer generated world as if it is a place they are visiting [2]. Although the concept of using computers to create virtual reality experiences emerged a few decades ago, the high expense of the components has limited research and development.

In 1980s, DataGlove was the first VR sensing-glove product from VPL Inc., and it was headed by Jaron Lanier [1]. What followed, were rapid technological improvements exceeding Moore's law prospects for a while and which paved the way for VR to emerge as a real promising technology.

Slater and Wilbur [2] defined immersion as a measurable concept of the VR system capabilities to provide the users with a real-like world. In other words, how immersiveness can be measured objectively depends on technical issues, e.g., calculating the field of view (FOV) or measuring the quality of the goggles' screens displays. VR systems range from low to high immersiveness depending on many elements such as how effectively the user can interact with objects in the virtual world, the I/O devices used for interactions, the quality of the graphics, the FOV of the VR goggles, as well as other elements and features.

This is different from the illusion of going into the virtual world, known as presence. Presence is the users' awareness of being in a virtual place as if they visited it, and can be measured subjectively by asking the users how much they felt of going into the virtual world.

This research developed a system to increase the illusion of presence and effectiveness of VR as a non-drug analgesic for immobilized children by adding eye-tracking capability to previous VR pain distraction system. In order to assess the effectiveness, a randomized controlled laboratory analog pain study with healthy volunteers had been conducted.

On the other hand, eye movements data can be collected to understand the patient's current mental state and study the correlation with how much pain patients are consciously experiencing. Toward this innovation, the eye movements within immersive VR had been investigated, and a fixation detection algorithm had been designed. This introductory chapter will provide a quick look at main technologies and concepts in this thesis. This involves eye tracking systems, eye tracking in VR, and the pain management in VR. Finally, the chapter will shed light on this thesis contributions.

1.1 Eye Tracking Systems

Eye tracking systems detect and record the behavior of one or both eyes of a viewer/user while looking at real-world objects or virtual objects on a screen. The collected information on eye behavior - shapes, positions, and movements - is remarkably exploited in various studies. Such studies were designed to allow users to focus on specific tasks to collect eye data for later analysis and interpretation. Initially, eye movements data were collected by an experimenter through the monitoring of the eye. Eventually, invasive mechanical techniques were used. Eye tracking continues to make breakthroughs via non-invasive methods using optical techniques and the electromagnetic potential of the eye. Recently, data were collected by advanced video-based technology.

Since the rise of advanced HCI, which created effective communication channels between humans and computers, more interaction techniques and devices have been developed through the study of human natural features. Eye tracking became an important tool to provide a controllable and effective channel in real time. Therefore, different interfaces have been designed and developed. As a result, gaze-controlled applications interact using eye-mouse pointing at virtual keyboards, menus, buttons, or another controllable command-based graphical user interface (GUI). The emergence of eye tracking in HCI suited assistive technology. Therefore, interactive eye tracking systems became one of the most promising technologies. Gaze-controlled applications have also become a necessity for individuals with disabilities who are unable to control a computer via traditional hand-motor mediums.

Another method of gaze-controlled applications is concerned with designing attention-aware applications that are more common in gaming and VR. It takes into consideration the feeling of presence in the virtual environment. In such cases, the gaze-controlled methodology is referred to as gaze-contingency. This means that the system often responds in accordance with the user's visual attention.

A new research trend focused on utilizing eye tracking systems using biometric identity recognition techniques to capture eye tracking data reflecting physiological and behavioral characteristics, including: visual attention characteristics, acceleration, geometric, and muscle properties used to create patterns and mathematical models used as biometric features to identify persons [3] [4]. Due to their invulnerability to spoofing attacks, unique individual oculomotor components, as well as the physiological characteristics of the eye hidden from external exposure, these techniques are more interesting than traditional biometric techniques. Furthermore, since the eye is an inseparable organ on the face, there is a possibility of integrating eye movements with the iris, as well as face features into a secure multi-model identity recognition system. Also, new research surrounding the utilization of eye tracking dedicated systems investigates how certain features of eye movements can be employed to detect or monitor health states (for example, concussions).

1.2 Eye Tracking in Virtual Reality

VR is linked to HCI in a wide range of fundamentals. VR increases the bandwidth between humans and computers to bring the simulated world closer to reality.

Although eye tracking systems are compatible with the aims of VR, eye tracking remains rare in current VR systems. This is because the eye tracker components are very expensive. In addition, VRs designers must carry out more possible user actions [5], including looking around, selecting objects, and launching events, which increases software costs and complexity in VR. However, due to advances in both systems, integration between the two is feasible. Besides that, research and market competition are also highly active.

Interaction between the human and the VR interface through eye tracking can be designed according to the demand of the application and the environment context [5][6]. This is achieved in the same way as using eye tracking as an input device with other interfaces. VR presents more challenges with the interaction technique using eye tracking as a gaze-contingent non-command input device. The computer passively observes the user while navigating the environment and exploiting the user's natural eye processing capabilities with no effort from the user. It is a complicated process, especially when considering the lack of standards in VR program integration.

Currently, VR with eye tracking systems can be found in research laboratories. Eye tracking is often utilized as an assessment tool to study aspects of human factors, including inspection performance and visual search strategy in training environments. Eye tracking in VR is utilized as a tool for reducing the expensive computations in graphics rendering and offers valuable felling of presence experience for the user. Tanriverdi and Jacob [6] presented an early study of eye tracking while navigating an immersive virtual world using head mounted display (HMD). The research compared the use of eye tracking and a hand control pointing device to select among opaque 3D objects. The selected object moved forward to the user and allowed the user to inspect it. Looking away from the object, pulled the object to its prior position. The study results indicated no significant differences in subjective preferences between the two modalities. Otherwise, the study found that the interaction with the gaze-controlled interface was significantly faster than a hand-controlled interface. In reverse, hand selection (vs. eye gaze) makes recalling spatial information easier for the participants as a tradeoff for the gaze-controlled interface speed efficiency.

Duchowski et al. [7] introduced novel techniques for binocular eye tracking within VR. These are 3D calibration techniques and 3D eye movements analysis techniques. The study was conducted on an aircraft inspection simulation training application. Eye tracking was inspected for visual search and attention strategies in VR environments. The user's gaze direction and 6 degrees' freedom of head movements are tracked to record the user's fixations within the training simulation environment. The signals of the system were somewhat noisy, but the achieved results from eye movements analysis to process performance statistics showed that the fixations number reduced with the implementation of an improved visual search training strategy. This was due to the learning and adaptation of the required tasks. It demonstrated that eye-tracking data provided valuable measures for training effectiveness.

1.3 Pain management in Virtual Reality

1.3.1 What Is Pain

International Association for the Study of Pain (IASP) [8] defines pain as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage or described in terms of such damage." However, there are many classifications for pain depending on the nature of the study; the general common classification is acute pain and chronic pain. According to IASP, acute pain is defined as "pain of recent onset and probably limited duration. It usually has an identifiable temporal and causal relationship to injury or disease". Chronic pain, on the other hand, "commonly persists beyond the time of healing of an injury and frequently there may not be any clearly identifiable cause." Suffering from pain is subjective, and the response depends on many factors such as the illness condition, emotions, and spirituality of the individual. This suffering can have extreme effects on the patient's quality of life.

1.3.2 Pain Management

Pharmacologic pain medications are currently the most effective and most widely used approach to treating severe acute pain during medical procedures, a widespread problem. Unfortunately, pain medication dose levels are often too small to control the pain, especially for children who are often undermedicated. Pain medications become less effective when used repeatedly (habituation). Higher and higher drug doses are often needed to control the pain of patients receiving multiple wound cares during hospitalization. In addition, undesired side effects of pharmacologic narcotic pain medications, such as nausea and constipation, limit how the dose level increase. This is a common medical problem, and patients suffering from excessive pain during medical procedures need much control and care. One of the most challenging medical conditions for pain control is severe burns, especially in case of children. Those children have major problems with uncontrolled pain during wound care, and there are concerns that such repeated high levels of pain can have long-term health and psychological consequences.

Over the years, several adjunctive non-pharmacological analgesic techniques have been tried [9]. However, only a few of them are evidence-based techniques. One of the most common interventions that were applied to pain reduction is immersive VR distraction, which appears to be unusually effective in reducing acute pain during several different types of painful medical procedures [10], developing effective new non-pharmacologic pain control treatments is an international priority [11][12].

1.3.3 VR Pain Analgesia Systems

The two input devices used most often in VR pain analgesia systems are HMD involving head tracking and a conventional computer pointing device such as a mouse. In head tracking, a sensor such as an electromagnetic sensor, or inertial trackers, sends (x, y, z) coordinates of the patient's head orientation to the computer. The result of the high-speed computer has real time responses to changes received from the input devices and to changes perceived by the computer users. Interacting with objects in the virtual world and seeing their response, gives the user the illusion of going inside the computer-generated virtual world as if they are in that world, a psychological experience known as “presence” or “feeling present” in the virtual world [13][14]. Several studies have shown that VR worlds designed to elicit a stronger illusion of going inside the computer-generated virtual world, are more distracting, and more effective at reducing pain [15][16][17].

One of the most common VR distraction systems, which was the first system designed especially for pain control, is SnowWorld. The SnowWorld system is designed to draw the patient’s attention away from pain by drawing attention to the virtual environment. The logic is that pain requires attention, VR uses up patient's attentional resources, which lead to a reduction in the brain functionality to deal with the received pain signals. The current SnowWorld pain distraction system was developed at the University of Washington's VR Research Center, in collaboration with Imprint Interactive Technology and Harborview Burn Center [18]. It offers an interactive experience through an icy canyon to give the patients the feeling of floating on icy landscapes where the patient in the same time throws snowballs at various virtual objects, such as snowmen, dogs, and penguins.

In 2014, Hoffman and colleagues developed a new portable water friendly battery powered VR system and have begun using it with pediatric burn patients in the ICU interaction scrub tank room at Shriners Hospital for Children in Galveston Texas, USA [19]. The goggles are not worn on the patients' head but are instead held near the patient. The patient looks into the weightless goggles, and the goggles do not even touch the patient. Patients, who do not have burned hands, look around with a wireless mouse to throw snowballs. Burned hands are a very common body part injured in fires, and patients with both hands burned are not able to use a mouse. These patients typically float passively without interaction through SnowWorld. Lack of interactivity significantly reduces how much VR reduces pain [16]. This study aims to enhance the current SnowWorld VR system, to reduce acute procedural pain during painful stimuli for those immobilized patients. This study proposes adding new eye-tracking technology to the existing VR pain distraction software, to make interactive VR pain distraction available to immobile children with burn injuries for the first time. Besides, the system will help in investigating the eye movements during pain as in wound treatments, to assist in the understanding of the VR attention process on the brain [20] during the incoming nociceptive signals transferring from the burn wound to the brain while the wound is being cleaned.

1.4 Research Questions

The primary hypothesis of this thesis is that pain distraction VR with eye tracking has an enhanced analgesic effectiveness when compared with VR systems with no eye tracking. To test this hypothesis, this thesis conducted an analog laboratory pain study with healthy volunteer participants that it is the first controlled study in the PubMed literature to explore whether interactive eye tracking can enhance the analgesic effectiveness of VR distraction.

The thesis also investigates the art-of-state eye-tracking systems and provides a preliminary step toward understanding eye movement patterns during pain by proposing a fixation detection algorithm of eye movements recorded during eye-gaze input within immersive VR.

1.5 Thesis Contributions

- An overview of state-of-the-art eye-tracking technology with a focus on both hardware and software techniques.

- An evaluation of the awareness of eye tracking and attitudes towards it among different categories of users. A new questionnaire was designed for this evaluation.

- A laboratory pain study with healthy volunteer participants to explore whether interactive eye tracking can enhance the analgesic effectiveness of VR distraction.

- An investigation of eye tracking within VR and design of a fixation detection algorithm within immersive VR.

1.6 Thesis Structure

This thesis is structured as follows:

Chapter 2 is devoted to reviewing the existing information about of eye-tracking systems and thier techniques. It provides the reader with the necessary background information to understand the important terms and techniques used through the thesis. It mainly presents the physiology of the eye and the types of eye movements. It also covers current eye-tracking hardware and software technology.

Chapter 3 briefly covers existing VR pain system settings, challenges and related topics in the literature review.

Chapter 4 presents a survey research which has made a preliminary step towards evaluating awareness of eye tracking and attitudes towards it among different categories of users. An online questionnaire was designed and distributed via What's App and social media, targeting the academic population of the city of Jeddah.

Chapter 5 establishes the aim of designing a system to advance the previous VR analgesia systems and solve some of the previous systems' limitations by adding eye-tracking technology. The off-the-shelf, hardware and software, components used in this system are briefly described.

Chapter 6 presents the main hypothesis of this thesis. We predict that adding eye-tracking will give a stronger illusion of presence in VR and make the VR experience more attention demanding, and we hypothesize that VR with eye tracking will reduce pain significantly more effectively than VR with no eye tracking. This study is the largest pain laboratory study using a blind subject design on healthy volunteer participants who were randomly assigned to one of three groups. Both between-subjects design and within-subjects design were utilized in the experiment design.

Chapter 7 is an investigation of eye movements within immersive VR. This chapter also provides a demonstration of a proposed eye fixation detection algorithm applied to eye movements recorded during eye-gaze input within immersive VR. The algorithm was evaluated by comparing it with the standard frame-by-frame analysis technique.

Chapter 8 is the final chapter, which draws conclusions about the implications of the findings, outlines the limitations of this thesis, and indicates opportunities for future work.

Chapter II

Background

To enable eye-gaze interaction, we need to understand basic facts and knowledge about the human eye and techniques to extract data from eye features. This chapter provides a quick look at eye tracking systems and obviously the physiology of the human eye. Then explores related basic hardware methods used in eye tracking. It also discusses the techniques for obtaining eye movement data, software techniques, and considerations to obtain high-level meaning from the collected data. The final section gives a brief list of eye tracking applications.

2.1 The Human Eye: Nature and Movement

The human eye is a unique and complex organ providing ways for people to interact with the world. It is a window to one's mind and individual features. For this reason, it attracts interdisciplinary researchers that attempt to interpret the features and distinctiveness. For decades, several methods and applications were introduced to make use of the eye for research to reach facts and solve some mysteries.

Before describing eye tracking methods and applications, this chapter will review the features of the human eye and eye movements from a gaze-based perspective. From such a perspective, it is essential is to know where the eye is looking (i.e., eye movements among a scene). This is achieved through identifying the apparent eye features. By placing the eye features into a sort of data, researchers can analyze and interpret the results.

As shown in Figure 2.1, the most distinctive visual parts of the eye are the cornea, pupil, and iris. The sclera is the visible white material of the eye. The cornea has a smooth surface where light can clearly be reflected as a light glint. The pupil, in the middle, can adjust its size to control how much light is allowed into the eye retina. The retina is a thin layer of cones and rods cells, which sense light and send impulses to the brain through the optic nerve. At the central back on the retina, a high-resolution area -the fovea- consists of a high density of cones cells responsible for critical vision.

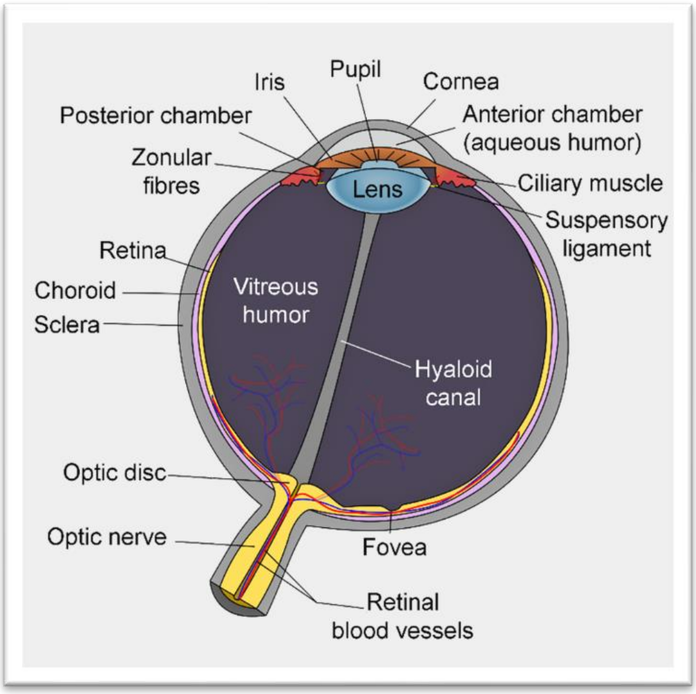

Figure 2.1: Basic human eye anatomy (Adapted from "Schematic diagram of the human eye," 2013. Used under the terms of the Creative Commons Attribution-Share Alike 3.0 license)

Once the eye moves to catch a target, it jumps very quickly. This makes a precise gaze difficult to measure because clear vision is restricted by the size of fovea at one degree (1°). During these quick jumps, vision becomes uncontrollable and almost blinded. When the eye stops to look at the target, it becomes unstable and moves slightly on the target, regardless of what determined gaze is being carried out, as the eye is a biological non-solid organ. During such a case, the eye visually processes the reflexed images on the fovea. In general, eye movements result from complex combinations of oculomotor control via simultaneous contractions and relaxations of six muscles connected to ocular nerves.

Tracking human eyes encompasses several different component technologies, including eye-gaze tracking, spatial eye position tracking, eye closure-state-tracking, pupil-size monitoring, and eye movements tracking [21]. Gaze tracking is the most common technology (used in HCI and VR applications) to determine where the eye is looking . Spatial eye position tracking refers to finding eye coordinates in face images. Eye closure-state-tracking looks at eyelid closure as indicators of eye fatigue, and this can be adopted in monitoring systems. On the other hand, pupil-size tracking refers to the focusing of the eye lens to detect variations in the size of the pupil or the pupil dilation to optimize light level. This can indicate excitement or interest in viewed objects. Eye movements tracking interprets different eye movements collected by eye tracking. These eye movements are mainly classified as: saccades, fixations, microsaccades, smooth pursuit movements, vergence, and reflex action movements.

Saccades are continuous rapid jumps directing the eye toward a target with the visual field higher than the size of the fovea. The usual velocity is 500 degrees per second.

However, the peak angular speed reaches 700 degrees per second [21][22]][23]. Saccadic movements have been investigated extensively in reading and languages research, web contents evaluation for marketing and behavior understanding studies.

Typically, a saccade is followed by a fixation on a target to allow visual processing (i.e., it can be viewed). The eye stops to look at a target reflected on the fovea at the size of 1˚. It remains for a short period usually between 100 ms to 300 ms, but it may last longer than 1000 ms to allow visual processing of the visual field and information acquisition [21][22][23]. Fixation is a critical metric in eye movements since it can indicate cognitive processes as attention draw or either difficulties in understanding. However, intentional long fixation on a target is problematic and causes fatigue.

During fixations, the eye slightly moves, or jitters, on the target with the visual field. These tiny movements are called microsaccades. It is difficult to detect microsaccades; researchers suggest many interpretations and functions [22]. It is believed that they maintain optimal activation of the photoreceptors to covert unconscious attention or may just biological noise [22].

Scanpath is a set of sequence fixations and saccades. These represent the journey of the eye as it travels over a stimulus or specific area of interest. Scanpath illustrates the speed and length of the saccades made between fixations, as well as the number and duration of these fixations to extract further information. Smooth pursuit movements describe the eye as it follows a moving target with the same speed and direction as the target under voluntary control.

The rest of the movements are extraordinary and often used for clinical diagnosis acquisition [22][21]. Vergence movement is a cross-eyed movement focusing on a target in front of the nose to bring the near target onto both retinas. This is where the eye movements reflex actions divide into vestibulo-ocular reflex (VOR) and optokinetic reflex. VOR allows the eyes to remain focused on a target during head movements. For example, when a person looks at a fixed target and keeps looking at it while turning his/her head from left to right, the eyes will move in relation to the head to maintain the target image inputs on the eye fovea.

The second reflex movement of the eye is the optokinetic reflex is a combination of saccades and smooth pursuit [22]. For example, when a person looks at moving target with same speed and direction, i.e., smooth pursuit at the target, until it moves out of the visual field then the eyes jump back to the first position when looked at that target, i.e., saccade, then follow the next target in sequence as looking out of a car window on passing railings.

Table 2.1. summarizes all the types of eye movements and presents some specific characteristics of each movement.

Eye Movements	Definition
Fixation	Looking at a target with visual field at size of 1^{o} for a period > 100 ms
Saccade	Fast jumps toward a target with visual field > 2^{o} and velocity > 500 ^{o}/s
Microsaccades	Tiny movements occur irregularly during fixational eye movements
Smooth pursuit	When the eyes smoothly follow a moving object at a linearly related velocity
Vergence	Eyes move inward, the opposite direction to bring a near target onto retinas
Vestibulo-ocular Reflex	Eyes move in relation to head movements to maintain the target image inputs on the eye fovea
Optokinetic Reflex	Combination of saccades and smooth pursuit movements which allow the eyes to follow moving targets in sequence while the head stays stationary

To build gaze applications, it is necessary to study the nature of eye movements. This knowledge determines which movement to measure, as well as how to use it to control a computer interface, especially as it is completely different from hand motor control. Eye trackers vary in their capabilities of measuring eye movements. Not all eye trackers have adequate accuracy and precision to detect microsaccades or tiny movements; it depends on the purpose of the tracker and other manufacturing factors.

2.2 Eye Tracking Technology Methods

Eye-tracking technology continues to evolve and through the years, researchers have built their own eye tracking systems in research laboratories. Recently, companies have started to build and sell eye tracking systems. Afterward, the numbers of eye tracking researchers and community have been intensely grown.

Tracking eye movements requires accurate and reproducible temporal and spatial measurements. The temporal measurements include the speed of the movement, which is usually measured in degree per second (o/s) and occurrence time of the movement (or its period in milliseconds [ms]). The spatial measurement is usually measured in degree of visual angle.

There are four broad categories of eye movements tracking methodologies [22]: (1) magnetic search coil; (2) electro-oculography (EOG); (3) photo-oculography (POG); and (4) video-based eye tracking.

In 1908, Edmund Huey [24] built a device to track the eye during reading by connecting a lightweight metal pointer to an eye contact lens with a hole for the pupil. The pointer moves along with the eye to track eye movements. He provided significant outcomes for eye movements research. This invasive method was developed later and known as magnetic search coil. A wire-coiled contact lens is placed in the user's eyes after local anesthetic (see Figure 2.2). This method recorded high-frequency temporal-spatial resolution through electronic magnetic fields. It was suitable for studying small eye movements such as microsaccades. The electronic magnetic fields were generated by magnetic coils placed near the user's head. For a horizontal field, coils were placed on the sides of the head where the vertical field was set orthogonally to the horizontal one. While it offered high accuracy information, it posed possible health risks. It was used exclusively in clinical sites and provided short recordings [24].

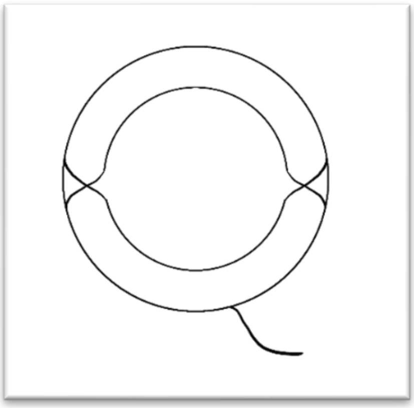

Figure 2.2: Search coil eye tracker

Started in 1960, EOG placed pairs of electrodes to the right and left of the eye for horizontal recording (and/or above and below the eye for vertical recording) of eye movements [25]. It measured the electrical potential difference between the retina and the rest of the eyeball (see Figure 2.3). This was a cheap, non-invasive method capable of recording large eye movements. While clinicians still use this technology, the drawbacks include discomfort of attaching electrodes to the user's face; and the possibility of changing in skin resistance or facial muscle movements due to external factors.

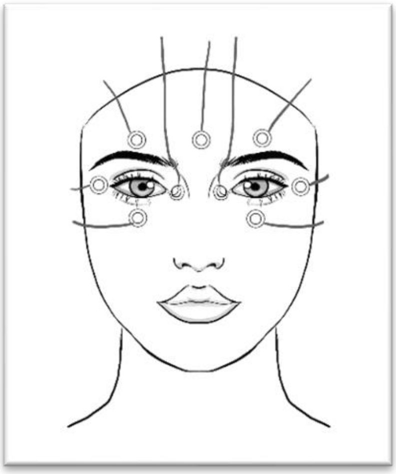

Figure 2.3: Example of electrode placement using EOG

In 1970, eye tracking systems utilized digital technology and image processing. In the beginning, image processing required a special purpose hardware. However, as technology developed, software facilitating automated eye tracking systems was used. POG (and sometimes referred to as video-oculography [VOG]) emerged and was used in clinical research and studies related to cognitive science and medical purposes.

POG is a non-invasive technique using a head-mounted mask equipped with a small video camera. The eye tracking device recorded images of the eye(s) or videos tapes using a variety of optical-based techniques to deliver measurements of distinguishable features of the eye(s). Then, manual investigation and analysis are used. This eye tracking method is rarely mentioned in recent research papers since it has evolved into the modern computerized video-based eye tracking method. However, some manufacturers refer to VOG as the common video-based eye tracking.

2.3 Video-Based Eye Tracking Systems

2.3.1 Types of Video-Based Eye Tracking Systems

Today, many manufacturers offer eye-tracking systems at varying prices due to differing hardware and software factors impacting accuracy and precision. Most commercial eye tracking products are video-based and share the same basic components. A typical product includes one or more video cameras to capture high-resolution images of the eye(s) movement. Trackers need the high-resolution images and high-sampling rate to obtain high-accuracy gaze estimation. The sampling frequency or frame rate of the camera refers to the number of images taken per second and measured in Hertz (Hz). Lately, cameras have become cheaper and include higher resolution and lower latency. However, this implies a faster system, wider-angle lenses, as well as more volume space for head movements. Maintaining this system adds complexity and increases the price. And the price remains the main barrier in the emergence of daily use of high-quality eye tracking.

Video-based eye tracking uses optical-based techniques with light and image processing. Infrared (IR) light sources illuminate the eye(s) to obtain vibrant light reflections from the eye and reduce the effect of ambient light. IR neither disturbs the user’s eye nor causes pupil contraction. This improves eye-tracking accuracy and reliability. Cameras capture illuminated images of the eye(s) movements and send them to a computer. The computer applies techniques and algorithms to filter and denoise the images, as well as extract and analyze the raw data of the eye(s) movements.

Eye trackers can be classified into four main types in terms of hardware: (1) remote eye tracking; (2) tower-mounted eye tracking (TM-ET); (3) head-mounted eye tracking (HM-ET); and (4) head-mounted display eye tracking (HMD-ET).

2.3.1.1 *Remote Eye Tracking*

A static method where the user sits to perform a task in front of a computer monitor, while the monitor presents media scenes designed for eye tracking experiment. Gaze tracking software maps the user's gaze vector as screen coordinates. Some eye trackers can sample the eye position at up to 500 Hz or more. At around 50-120 Hz it is often used for gaze control operates. Remote eye tracking has limited mobility since the user should sit and move within a certain volume space where the tracker can reliably track the eye. It is a trade-off between more head movement or higher accuracy and precision. To overcome this limitation, multiple cameras with large focal lengths are used to increase the user's volume space and grant tracking accuracy. Examples of remote eye tracking are shown in Figures 2.4 and 2.5.

Figure 2.4: Pro TX300 sampling rate of 300/120/60 HZ [26]

Figure 2.5: SMI RED500 sampling rate of 500 Hz [27]

2.3.1.2 ***TM-ET***

TM-ET is a static system requiring the head to be fixated using some sort of hardware to control head movements that influence the user's gaze direction (for example, headrests or bite bars). This restriction results in high accuracy and reliable video-based eye tracking. It operates at a high sampling frequency of 1000-1250 Hz. An example is shown in Figure 2.6.

Figure 2.6: SMI hi-speed TM-ET sampling rate of 1250 Hz [27]

2.3.1.3 ***HM-ET***

HM-ET is a mobile system where eye tracking components are mounted in a helmet, cap, or eyeglasses. It is used in situations where the user can freely move while carrying a recorder or portable computer. Unlike others, HM-ET has a video scene camera at the top in the front of the helmet or on the eyeglasses to record where the user looks. A software overlays the user's gaze coordinates with the scene video to determine the user's gaze locations. An example is shown in Figure 2.7.

Figure 2.7: Tobii Glasses 2 sampling rate of 500-100 Hz [26]

2.3.1.4 ***HMD-ET***

In these devices, an eye tracking system is integrated into VR goggles to real-time interaction with the virtual environment. An example is shown in Figure 2.8. While rare, companies provide these newer systems with custom services in products like SensoMotric Instrument (SMI) [27], Tobii [26], and Sensics integration with Ergoneers eye tracking [28]. These headsets provide a natural, flawless input with the VR environment. It also provides individual customization in image display as eye tracking calculates the inter-pupillary distance to correct the user's 3D rendering.

Figure 2.8: Sensics HMD sampling rate of 30 Hz [28]

2.4 Software of Video-based Eye Tracking

Eye tracking systems are very complicated. The design and implementation methods used in eye tracking software can significantly vary across different systems. Due to numerous intervening factors influencing the quality of collected data, it is hard to compare between these different methods. In general, the video-based eye tracking systems share the main components (or modules) of operations in sequence. Each module uses several techniques and methods to achieve its goals. Eye tracking manufacturers offer different software packages with secret technical details in most cases. This section provides a simple preview on eye tracking software modules. In addition to the types of commercial software. eye tracking software consists of four main modules: (1) image acquisition (2) image processing and features detection (3) gaze estimation and (4) eye movements data analysis (see Figure 2.9).

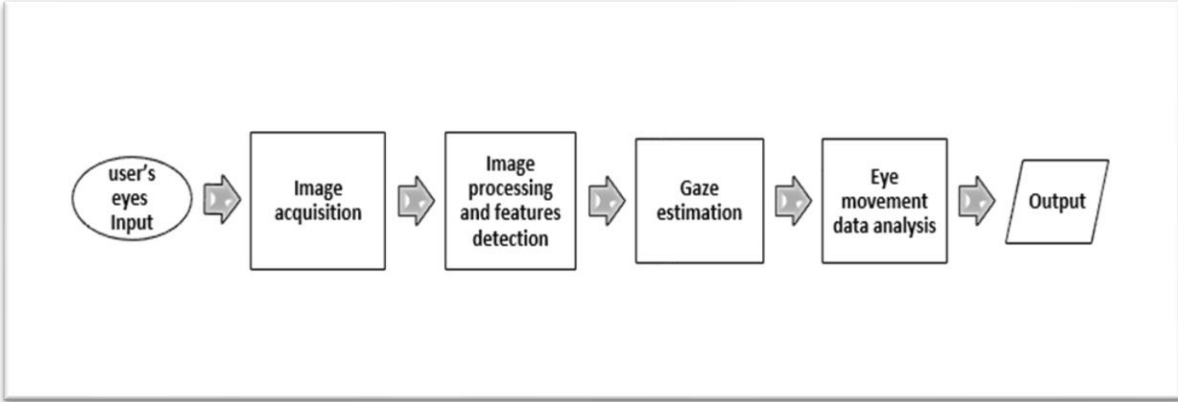

Figure 2.9: Eye-tracking system general flowchart

2.4.1 Image Acquisition

Image detectors and HD cameras with low latencies have made significant jumps in frame rate and resolution that makes information available in images but need to be extracted. This is known as "image processing." Several optical-based techniques in practice are used to acquire the images that enable extracting the required information from the eye(s) and calculating the gaze direction. This depends on the required eye features to be detected. One or more of these optical-based techniques can be used. There are three common techniques: corneal reflection, limbus tracking, and pupil tracking.

- *Corneal Reflection*

The cornea is the protective outer layer of the eye. When light enters the user's eye, some of it is reflected. Several reflexes (known as Purkinje images)[29] occur in the boundaries between the eye lens and the cornea. This is shown in Figure 2.10. The first Purkinje image (P1) is a bright reflection from the outer surface of the cornea (the "glint"). The second Purkinje image (P2) is a large and dim reflection from the inner surface of the cornea. The third and the fourth Purkinje images (P3) and (P4) are reflections from the outer and the inner surfaces of the eye lens, respectively. Corneal reflection is an accurate method for gaze tracking when the eye position inside the camera view. Otherwise, it is difficult to detect.

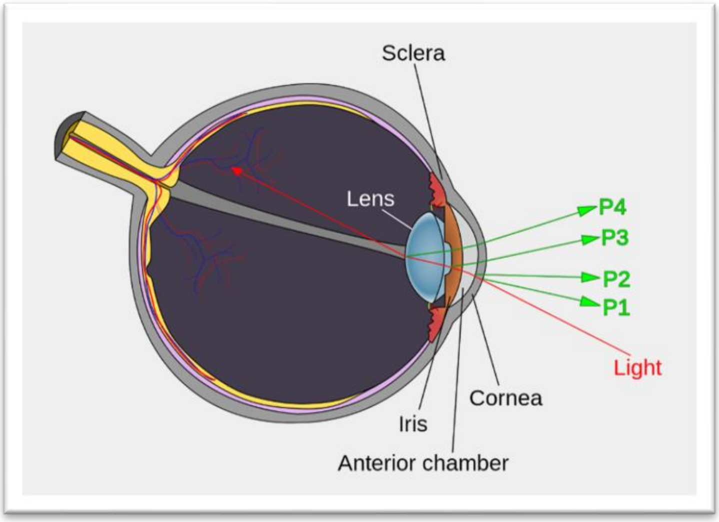

Figure 2.10: Purkinje reflexes (Adapted from "Diagram of four Purkinje images," 2015. Used under the terms of the Creative Commons Attribution-Share Alike 4.0 International license)

- *Limbus Tracking*

The limbus is the boundary between the white sclera against the colored iris. This technique often tracks the position and shape of the limbus with respect to the head. For accurate positioning, the user's head must be immobile, or the device must be affixed. The limbus shape in most users is affected by the eyelid and lashes. This reduces the efficiency of this technique. Its best suits horizontal eye movements.

- *Pupil Tracking*

This technique detects the edge between the iris and the pupil. Therefore, this is no missing data when detecting horizontal or vertical movements. The contrast is relatively lower than tracking the limbus. However, it is usually sharper. The pupil appears in two light affects: (1) dark pupil produced by illuminating the eye with an IR light that is off-axis with the camera direction; and (2) bright pupil produced by illuminating the eye with an IR light that is on-axis with the camera direction [21]. With a variance of eye color, the dark pupil is easier to detect as the edge between some iris colors against the pupil. The bright pupil is easier for other iris colors. Thus, recent eye tracking systems use both techniques to detect, which give a better contrast between the iris and the pupil.

Using a technique to detect one feature of the eye, such as pupil tracking, must hold the head stationary to prevent misinterpreting head movements as eye movements. Therefore, many of those techniques are used in different combinations and settings. One well-known combination technique is the Dual Purkinje Image (DPI) eye-tracking system designed in [29]. This technique relies on locating the positions of the first, the glint, and the fourth Purkinje images. It consists of a complex combination of servo-controlled mirrors and lenses. It provides high frequency and accuracy gaze tracking under controlled ambient light. A majority of eye trackers use a combination of the first Purkinje image, the glint, and pupil detection [29] [23].

2.4.2 Image Processing and Features Detection

In eye image processing, extensive work was done to denoise images and detect eye features (i.e., pupil size, eye blinks, and biometric characteristics). However, accurate detection of relevant features from the captured eye image remains a challenge due to factors such as different resolutions of hardware, distance, position of face and head, and variations in individuals' eyes.

Image processing is expensive. Captured images go through several algorithms, including grayscale conversion, image binarization, denoising, and filtering algorithms. This excludes noise as Gaussian algorithm and increases accuracy and clearer features. Extracting the required features through various algorithms depends on the chosen optical-based technique. Finding contour of the pupil as canny algorithm; other algorithms use a model to fit an ellipse to the pupil contour; segmentation algorithms as Hough transform; algorithms to look for dark areas as using pixels' intensity histogram of the image, or hyper-algorithms to detect glint or other features. Hammoud in [21] offers a detail description of practical case studies and the used image processing algorithms in such cases.

2.4.3 Gaze Estimation

The aim of eye tracking to provide an accurate estimate of the user's gaze, the point where the user's eyes are focused on observed target; or the intersection between the Visual line and the observed target. For decades, different approaches were introduced attempting to obtain an accurate gaze estimation. Two main approaches can be distinguished: (1) Geometry-based methods and (2) Interpolation-based methods [21] [22] [23].

The geometry-based methods use the geometric relationship of the hardware components and the geometric relationship of the eye features. The hardware geometries are assumed to be known because of the fixed camera(s) locations and IR source(s). A common method to calculate the geometric relationship of the eye is by measuring the changing relationship between the detected reflection of the glint and the moving pupil center. Obviously, when looking toward a light source, the position of the glint is very close to the center of the pupil. As the user looks away from the light source, the distance between the glint and the pupil center progressively increases. The light source provides a measure of gaze direction; these measurements translate into the gaze area or the screen coordinates.

Interpolation-based methods use calibration procedures to determine the inherent parameters to calculate the estimated individual user's gaze. It represents an alternative to the complex geometry-based methods. Interpolation-based methods have been commonly applied as a gaze estimation in most eye tracking systems. The user is required to fixate on a specific predefined uniform grid points (or markers) in properly defined gaze area, for example, displayed on the screen or in a real environment with mobile eye tracking apparatus. The data are sampled, and a function is constructed to fit these data points. The quality of the interpolation depends on the constructed function and the selected points.

2.4.4 Data Analysis of Eye Movements

Several detection algorithms and thresholds were proposed to analyze eye movements and obtain high-level meaning metrics. There are some officially released algorithms. One of the most common principles among them is the Identification by Dispersion-threshold (IDT) [23], which detects and clusters fixation points by specifying a maximum distance threshold between these points, and also used in many commercial products.

Another group of algorithms is based on velocity and acceleration calculations to detect an event as fixation, saccade, or smooth pursuit. The speed is calculated with respect to the preceding point. A threshold is used to classify the point as a fixation or a saccade. There are no standards of accurate classification and interpretation algorithms of eye movements, but these algorithms share the same principles and concepts. A rare evaluation research paper by Andersson et al. [30] tested parameters and similarities between accessible algorithms. The work considered a large set of algorithms and was based on specific parameters comparing among them in addition to two human experts.

2.5 Commercial Eye Tracking Software Packages

Eye tracking producers offer different packages like EyeWorks [31] and E-Prime [32] for eye tracking operating, as well as software development kits (SDK) for development. Ideal eye tracking software packages offer tools and utilities to help researchers and developers throughout the development of their projects. Many tools can be used during the designing stage till the statistical variables and metrics of the eye tracking data analysis results. Some tools are suitable for simple task experimental setup. Others are suitable for more complex ones. These tools vary according to eye tracking hardware, tasks to be accomplished, and a hypothesis to be tested. In general, tools are classified using stages of employing into different types [26]:

- **Designing Tasks Tools:** Many commercial software tools provide flexible, user-friendly interface solutions to generate static or dynamic stimulus scenes. This includes text, images, and videos within a controlled timeframe and flows according to project objectives. Some tools provide options to activate areas of interest (AOI) and create conditions. Different tools are used for real-world scenes within mobile eye tracking (i.e., eyeglasses and HM-ET) to set the proper conditions and control for these environments.

- **Interacting and Recording Tools:** Providing calibration validates the quality of eye movements data. Additional tools recording scenes and collecting the gaze data among them and synchronizing with other peripherals when required.

- **Analyzing Tools:** Analyzing tools provide the researcher with technical set-ups to choose between different detection algorithms and thresholds to obtain the required eye movements or metrics. In general, the tools are closed source and cannot access the algorithmic details. Some provide the statistical variables metrics, raw data, and AOI to be analyzed by a statistic package. Most tools hide the data in binary files; they directly provide the result metrics and visual representations.

- **Visualizing Tools:** Visualizing tools provide illustrative results through effective visual forms and dynamic representations. They facilitate information perception, especially with large quantities of data. These include gaze plot, heat maps, animated heat maps, gaze opacity, clustering, and bees-warm. See Figure 2.11.

- **Software Development Kit (SDK):** Some eye-tracking manufacturers provide Analytics SDK, compatible with their products, for developers as a range of tools and libraries. They include empowered applications development using a range of programming languages such as Python, C++, and Matlab on multiple platforms. They also empower integration with different engines and systems.

Figure 2.11: Examples of representatives of eye tracking analyzed data (Adapted from "Eye-tracking heat map Wikipedia" and "Gaze plot eye tracking on Wikipedia with 3 participants",2017. Used under the terms of the Creative Commons Attribution-Share Alike 4.0 International license)

2.6 Considerations

2.6.1 Calibration and Accuracy

Calibration is a vital aspect to obtain accurate and reliable data for user eye movements. It customizes the calculated eye gaze toward the target (or optimizes the position of the fovea on the scene). Calibration is conducted by asking the user to look at a set of points/markers to estimate an individual user's gaze. There are many factors that may cause gaze measurement errors. This is because of individual differences, including the shape of the corneal surface and the shape or size of the eyeball. There also a need to calculate the visual axis as the vector from the fovea to the center of the user's eye lens, which is a difficult task [21].

In geometric-based gaze estimation is not only about eye parameters; the geometry of the hardware is also needed to be encoded before the gaze vector can be calculated. Although commercial eye-tracking hardware parameters are known prior to use, the screen position may vary. Therefore, it is necessary in most cases to display several sets of points/markers for estimating parameters related to the visual scene. The number of these points/markers may change due to many considerations, including the gaze estimation method and the mobility of the eye tracker.

2.6.2 Midas Touch

One of the main complaints against the use of eye tracking interface has been the "Midas touch" problem described in [33]. The Midas problem occurs because it is difficult to decide whether the user is looking at an object for inspection or for invoking an action. Also, it is easy to misinterpret unintentional gaze gesture as eye blinks. Therefore, the gaze-controlled interface must differentiate between the intentional gaze gestures to invoke action and the natural eye movements. Jacob [33] discussed the problem and provided possible solutions, including blinks and dwell time. These solutions need improvement as they may lead to slow interaction and eye fatigue. On the other side, designing a faster solution by decreasing the dwell time may conflict with user cognitive processing. It may cause misinterpretation and increase error response. Therefore, finding a proper neutral interaction technique requires more research and investigation.

2.6.3 Other Differences and External Variations

The light reflected by eyeglasses and contact lenses mislead the detection of corneal reflection or other Purkinje reflexes. Moreover, the observed pupil through them is different from the real one. This leads to error calculations. In addition, the frames of the glasses can partially block cameras from capturing correct images or prevent the acquisition of eye movements data. Another potential reason why that the tracker may be misleading includes eye movements in ambient light. Also, individual differences can mislead collected data, including drooping eyelids; eye fatigue; and heavy makeup. Head movements also change the center of vision. Therefore, versatile eye-tracking methods are required to solve these limitations.

2.7 Eye-Tracking Systems Applications

Eye tracking provides a natural human channel for communication, measures attention, and interest. This makes it a great tool for numerous research areas and applications such as:

- **Computer Science and Engineering:** studying eye movements, data processing and analysis, brain-computer interface (BCI) with eye tracking, biometrics in security, usability research as studying interface design and web pages' evaluation, HCI leading to assistive technology, gaze-contingent research, gaming, and customization applications

- **Neuroscience:** investigating neuronal activity related to eye movements for dementia, brain damage, or related diseases

- **Psychology:** diagnosing psychological or clinical eye disorders, visual attention, visual search, scene perception, reading research, and other natural and intuitive behavior patterns

- **Human Factors:** assessing and measuring visual search, attentional and cognitive aspects of human performance, skills performance and expertise level as in aviation, driving, and surgery

- **Marketing and Advertisements:** evaluating customer preferences and attention.

2.8 Summary

Current eye-tracking technology provides high accuracy and precision tracking of the behavior of the eye. This chapter introduced the main existing technology and focused on video-based eye tracking. Eye-tracking systems are built with different hardware and software components and achieve different purposes. State-of-the-art eye tracking utilization is outlined in the fields of assistive technologies and VR in medicine. This can take the form of gaze-controlled application interfaces, as is the case of assistive technology, expert vs. novice assessment of learning interaction and visual search behavior studies, validity and photorealism evaluation of wide-range VR training environments.

Eye-tracking technology continues to evolve. It will have the most profound influence on the understanding of human behavior, including human vision and cognitive process — besides, the understanding of and technical aspects, including VR systems validity, and optimization.

Chapter III

Related Work

This chapter briefly covers existing settings and challenges in using eye tracking, eye tracking within VR, and previous pain distraction VR systems. However, no data were found on the association between eye tracking and pain in any aspect.

3.1 Eye Tracking as Assistive Technology

HCI creates convenient, effective, and natural communication channels between computer and humans. It mirrors communication in real-word situations rather than current command-based styles using keyboards and pointing devices. More interaction techniques and devices are being developed through the study of human natural features. Eye tracking became an important tool to provide a human computer controllable effective channel in real time. Nevertheless, obstacles and challenges remain and need to be solved before it becomes a daily communication channel. Another challenge is the complexity and cost of designing flawless interfaces and devices that exploit eye features to communicate with computers.

Founding standards for employing eye tracking in HCI is a future mission. However, eye tracking research and consumer demand are rapidly increasing like most technical fields in this age. Therefore, designing gaze-controlled applications are required to define the interaction techniques. These techniques refer to the different methods that a user can utilize the eye tracker to control the interface of that application.

Nowadays, gaze-controlled applications use one of two methods to control a computer interface via eye tracking. The first method is so-called the eye-mouse control technique, which uses the eye tracker as a pointing modality. It replaces the mouse functionality in the same way of pointing at the commands and buttons of pre-existing applications using a GUI or a customized version of the application interface. The eye-mouse mode can be performed via a plug-in software and by modifying the source code of the application.

The action of clicking the mouse on a selection is replaced by another method, another gesture, or another peripheral depending on the aim of the application (for example, an eye blink). The most common method sets a dwell time with a click issued after the duration of the fixation exceeds the threshold time. Using a dwell time, an unintentional fixation may lead to a clicking issue that has been described as the Midas touch. This problem will increase with the short threshold setting for dwell time.

The second gaze-controlled method is “gaze-contingent" control technique. This is a non-command display system in which the system is aware of the user’s gaze and may match its behavior in real-time based on exploiting the user’s visual attention or processing capability. There is no effort from the user (also known as a passive gaze indication). As gaze-control using gaze-contingency is expensive and more complicated, new attention-aware applications must be designed almost from scratch, fact that involves a considerable effort. In many applications, eye movements data are processed and analyzed offline (as in diagnosis and assessment in which the user’s visual behavior is recorded with no user interaction with the world) [7]. In addition, many researchers utilize gaze-contingency in 3D environments and have used different applications to reduce the computations of graphics volume rendering [21]. Two types of gaze-contingency methods for this objective are used: (1) the screen-based methods and (2) the model-based methods. The first is concerned with the manipulation process of image pixels. The latter is an alternative method concerned with the resolution reduction of graphical models or objects preceding rendering.

These gaze-controlled interaction techniques were originally devised for individuals with disabilities that have very limited or involuntary movements in parts of their bodies (especially hands) but who can move their eyes normally. There are many people with severe disabilities who rely on this technology to perform tasks via communication with computers. Eye tracking will benefit the quality of life for disabled individuals. Its technology will also prove beneficial for people without disabilities [34]. In a recent research, Bissol et al. [35] presented an eye-tracking assistive system for controlling and interacting with everyday equipment in home, using the Internet of Things, which was developed based on concepts of user-centered design and usability. The system was tested by conducting experiments on two groups of able-bodies participants and participants with disabilities and scored high among both groups.

Gaze-controlled applications can be tailored to match the abilities of the disabled person or a specific disability. The tailored system can be a hybrid containing features of both eye-tracking interaction techniques (such as the eye-mouse) and the gaze-contingent interface control. To cope with difficulties (such as the Midas touch) and prevent unintentional actions invoking, it is possible to combine another input modality proper to the user with the tailored gaze-controlled system. COGAIN [36] presented ideas to customize and develop framework gaze-controlled software under user participation. COGAIN association promotes research and development in the field of gaze-based interaction in computer-aided communication and control for disabled individuals and the elderly.

A systematic review of 756 studies was conducted [37]. It examined the effectiveness of eye-gaze control for people with physical disabilities, and mainly how children with cerebral palsy can benefit from this technology.

3.2 Eye Tracking within Virtual Reality

It has been a long journey for eye tracking research within the medical field. This is especially true in psychological and ophthalmic research, where it was used as diagnosis and assessment tool for different measures including eye disorders, and attention and cognitive abilities. A majority of VR integrated with eye tracking research in medicine is related to visual inspection to measure performance in pre-existing medical VR simulator environments. VR simulators play an important role in the training and education of surgeons and medical practitioners.

Research in VR with eye tracking has focused on the field of minimally invasive surgery (MIS) training and image photorealism. Law et al. [38] performed a study of surgeons' eye movements in order to assess their skill. They showed many differences in the visual behavior between experts and novices performing the same task on a VR laparoscopic simulator. The results from eye gaze data analysis showed that the experts accomplished a specific task in a shorter amount of time and with fewer errors. Novices required frequent visualization of the instrument to perform the same task. Novices often tracked the movements of the surgical instrument in the simulator rather than the target. Such results and observations could be useful in learning and training.

Eye tracking in MIS simulators has been used to assess the effect of varying the method of the VR visualization on user behavior. Elhelw et al. [39] utilized eye tracking to inspect the users' perception of visual realism, as well as the impact on detecting the importance of specular highlights for improving the photorealism of graphics in medical VR environments. This study found that simple abstraction of 3D visual experience leads to inaccurate training. The use of eye tracking provided an effective way to detect appropriate image features affecting visual realism and allowing improved graphics rendering in training simulators.

Wilson et al. [40] introduced another study using the laparoscopic simulator. It examined the usefulness of gaze training for laparoscopic surgical skills training and tested performance under multitasking conditions. A comparison was conducted among three groups: (1) gaze trained (GAZE); (2) movement trained (MOVE); and (3) discovery learning (DISCOVERY). Results show that the GAZE group learned faster and completed their tasks more quickly than other groups. Variation in performance levels was visible for the benefit of the GAZE group while multitasking. Researchers concluded that training by gaze tracking facilitated learning skills and showed that the participants paid more attention to completing the eye-hand coordination task under multitasking conditions. Studying eye tracking and the gaze of experts during performing complex tasks or multitasking conditions facilitated the determination of a path and techniques of high-performance efficiency of required tasks. This knowledge will ease the learning process and skills acquisition for novices.

Vine et al. [41] supported the utilization of eye tracking to assess the validity of VR training simulation systems and to inspect psychomotor measurements among real-life surgical procedures. This study mainly aimed to investigate the content validity of VR simulators. Researchers conducted the test by comparing visual control metrics of eye tracking taken during transurethral resection of the prostate (TURP) simulated procedures and real TURP procedures. Eye-tracking data were collected from seven surgeons who carried out 14 simulated TURP procedures. Three surgeons carried out 15 real TURP procedures inside operation rooms. The data were analyzed offline to calculate the number of fixations with duration and the percentage of fixation time on the screen. The visual metrics presented a significant difference between the two situations. The number of fixations was significantly higher in the real TURP procedures but with shorter mean duration time than in the simulated ones. Researchers discussed many factors that may lead to this variance, including increased stress levels and complications in real operation rooms. With the VR simulator, the duration of fixation may be due to the information-rich areas of a display that is unlike the real situation. They also suggested that to plan an effective simulated training program, the complexity difference surrounding the two situations, the VR simulators and the real operation rooms should be considered.

Eye-tracking technology has rarely been embedded into a real-life operating room. Therefore, there is a lack of knowledge about the role of visual attention strategies and perception of surgeons in a real surgical environment. Researchers proposed a new type of embedded eye tracking apparatus suitable for use in procedures performed under a microscope [42]. This solution overcomes many challenges facing utilizing eye tracking in operating rooms. Researchers adopted an optical solution and derived fundamental requirements for integrating a binocular eye tracker into a surgical microscope. They highlighted the technical challenges encountered when embedding needed components into the surgical microscope. They stated that the developed solution could be applied to other types of microscopes and ocular-based optical devices. The research demonstrated hardware prototyping through the iterative development cycle of design principles, implementation, and evaluation of five versions of eye tracking surgical microscope.

One of the important advances in MIS simulators involves robotic-assisted fields providing medical practitioners with greater precision and diagnostic capabilities. The gaze-contingent autofocus system, changing focus with only eye-control, has been constructed in the da Vinci surgical robot with the purpose of applying it in future real-life surgeries [43]. The research investigated the usability between eye tracking autofocus method and built-in foot-pedal mechanical focus method. A liquid lens and a Tobii commercial eye tracker were embedded into the da Vinci robot system stereo endoscope. This eye tracking system inserted between the endoscope and the camera head using rapid-prototyped lens mount and an adapter plate. An evaluation of 17 participants revealed that eye tracking autofocus was fast, and the speed of the system allowed for real-time procedures. Participants stated that the focusing capability allowed them a more natural search.

Furthermore, researchers indicated that data acquired from eye tracking allowed them to analyze the effects of motion at the periphery on visual perception during a surgical task. The concept of gaze-contingency use of eye tracking was effective and convenient in human-machine interaction. Results supported the eye tracking ability to improve eye-hand coordination. It revealed a durability advantage of eye-tracking autofocus over mechanical focus due to the absence of movable parts.

The integration of eye tracking at the console of surgical robots has advantages to the human-robot interface in means of functionality and effectiveness. It is worthy of more research and investigation. Many proposals and published papers support this trend. For example, a paper presented a novel integration of gaze as an active input for surgical robot control [44]. In particular, the paper demonstrated technical details and hardware components of eye tracking integration system where a calibration process was carried out to estimate the gaze on the da Vinci's stereoscopic display. A 3D eye-hand calibration designed to estimate the gaze in the surgical scene.

From a technical perspective of using eye tracking in VR, Stellmach et al. [45] proposed a set of gaze visualization techniques with a prototype toolkit for supporting eye movement analysis in static 3D environments similar to heat maps and scan paths that are used in gaze visualizations for 2D contents and investigated the usefulness of their techniques. Boukhalfi T. et al.'s work [46] presented the development of a multimodal BCI at the Montreal Philippe-Pinel Institute for different studies related to forensic psychiatry including the integration of eye tracking glasses within a 4-wall CAVE-like VR environment. Most previous studies including VR and eye tracking, used a semi-immersive VR approach, as in [47] that showed that average 3D gaze errors increased linearly with the distance of the virtual plane.

3.3 Virtual Reality Pain Distraction Systems

Hoffman et al. [48] were the first researchers proposing that VR could reduce pain and they provided the first evidence of VR analgesia during painful burn wound care for two adolescent patients. In later research, Hoffman et al. [20] conducted a study using fMRI to investigate the associated changes in brain activation related to pain using thermal pain stimuli on healthy volunteers under different conditions of using treatments of VR distraction and opioid. The studied conditions are no analgesia, opioid analgesia alone, VR distraction alone, and both (opioid analgesia combined with VR distraction). Results showed that VR distraction alone significantly reduced pain and brain activation related to pain. Likewise, the combined use of both opioid with VR distraction reduced pain more effectively than opioids alone.

Hoffman and his team continued to study these aspects and proved the impact of VR analgesia on various pain problems. In the same time, they enhanced their VR system and explored the feasibility of using VR with more and more challenging patients such as children in the ICU. As in [19] [17], the VR pain distraction systems need to be tailored and adapted to the individual's requirements and the capacities of burn patients. They presented case study experiments with several hardware pieces were specially designed and tailored for special cases of burn patients such as a robot-like arm to hold goggles for the patient which have difficulties to wear helmet or HMD devices.

In the same line, Keefe et al. [12] indicate the importance of understanding the mechanism behind VR effects on pain components. They envision two approaches, first of which is to assure a sufficiently complex and novel display virtual environment (based on the evidence that VR primarily works through distraction). The second approach is to assure highly immersion environment (based on the evidence that VR works through perceiving reality or believing being in a different place).

Subsequently, a considerable number of research studies focused on the use of VR in pain reduction therapy among different samples and cases of a patient having a significant impact. In recent systematic reviews of evidence from randomized controlled trial studies for utilizing VR in pain control [14] [49] [50], researchers recommended VR therapy as a clinical intervention for a variety pain problems reduction with minimal side effects. In addition, results concluded that an interactive distraction is much more likely to provide effective pain management than a passive distraction and indicate that high immersive VR technology, e.g., wide FOV is more effective than the low immersive VR technology. Furthermore, it was suggested [10] that, in the future, with chronic pain and long-term rehabilitation, VR can be used as a complementary treatment with other therapies might prove valuable results. In a recent systemic review paper Dascal et al [51] found that the majority of VR applications in medical settings for inpatients studies including pain management were evidence-based efficiency.

Chapter IV

Awareness and Attitudes Toward Eye-Tracking Technology

This chapter presents the survey research conducted to investigate eye-tracking awareness and attitudes among general users and researchers. To collect data about this topic, an online questionnaire was designed, as this is a common and accepted method in the research community.

4.1 Introduction

The advances in VR and other similar technologies - such as Augmented Reality (AR), Mixed Reality (MR), and wearable devices - demand proper interaction techniques beyond the traditional modalities, which are keyboards and pointing devices (e.g., mouse, joystick, trackball). In these environments, in all respects, designing interaction techniques for realistic user experience (UX) is different from the interaction techniques for GUI screen display. In order to design a realistic interaction technique, many cues taken from natural human interaction behavior have been employed and have led to a new trend in HCI known as Natural User Interface (NUI). In NUI, users interact using both deliberate and unconscious movements[52] in a realistic experience within a virtual environment; natural behaviors such as hand gestures and eye gaze are captured, analyzed and interpreted.

Research in HCI aims to leverage natural human behavior to build NUI, which implies the need for multimodal interactions within the virtual environment. In [53], Turk described the state of the art of human sensory modalities (such as vision, touch, and sound) and the ones relevant to multimodal HCI (such as head motion, gesture, and gaze) that can be employed to interact within the virtual environment. Vision has always been one of the most important human senses, and in the context the graphical representation of VR, AR, and MR, there is no doubt that it is the most important. Recently, advances in eye-tracking systems (primarily video-based eye tracking) have played a great role in HCI to facilitate NUI, where a gaze becomes an interface controller and a window to understand the human mind.

The eye tracking provides users with a convenient natural modality for interaction and is becoming more important as an assistive technology for disabled users [54][55]. It is also a valuable research tool for researchers in multiple fields for a variety of purposes. For decades, using different types of eye-tracking devices, eye movements have been extensively investigated in physiological and psychological studies [24], to define and detect different oculomotor events (e.g. fixations and saccades [23][22]) and find the connection between these events and cognitive processes and perception such as attention, learning abilities, performance, and searching strategies [22][23].

4.2 Methodology

A cross-sectional quantitative research method was used to analyze awareness and attitudes among users toward eye-tracking technology. Descriptive analyses were conducted to identify relevant trends.

Participants were invited to take part in the study, which was designed in Google Forms. During the design and distribution process of the questionnaire, the recommendations of online surveys provided in [56] were taken into account as much as possible. The questionnaire collects participants' data anonymously and provides a short statement of the survey purpose, the expected time needed to complete the survey, and the contact information for the researcher.

The questionnaire is comprised of three parts; please see Appendix A. The first part was addressed to general users and involved six questions, while the second part was dedicated to researchers and included four additional questions. Finally, the third part was addressed to eye-tracking researchers and involved three more questions. In total, the questionnaire had 13 questions. Answers to most questions were provided in a closed-ended and yes/no format. The survey took up to two minutes to complete when answering all the 13 questions, for the case of eye-tracking researchers. The survey was distributed via What's App and social media, targeting the academic population of the city of Jeddah in Saudi Arabia as much as possible. Due to the low number of responses, data collection was postponed for two months after the first distribution.

4.3 Result

Ninety-eight individuals responded to the questionnaire, shared their experience with eye-tracking technology, and expressed their attitudes towards it. Sixty percent of the respondents were women. The mean age of participants was 31 years, with a minimum age of 18 years and a maximum age of 50 years.

4.3.1 General Users Attitudes Towards Eye Tracking

Approximately half of the respondents had heard about eye tracking technology, although a considerable percentage had not. Expectedly, most participants did not know basic facts and theories within eye tracking systems (Figures 4.1 for frequency percentages).

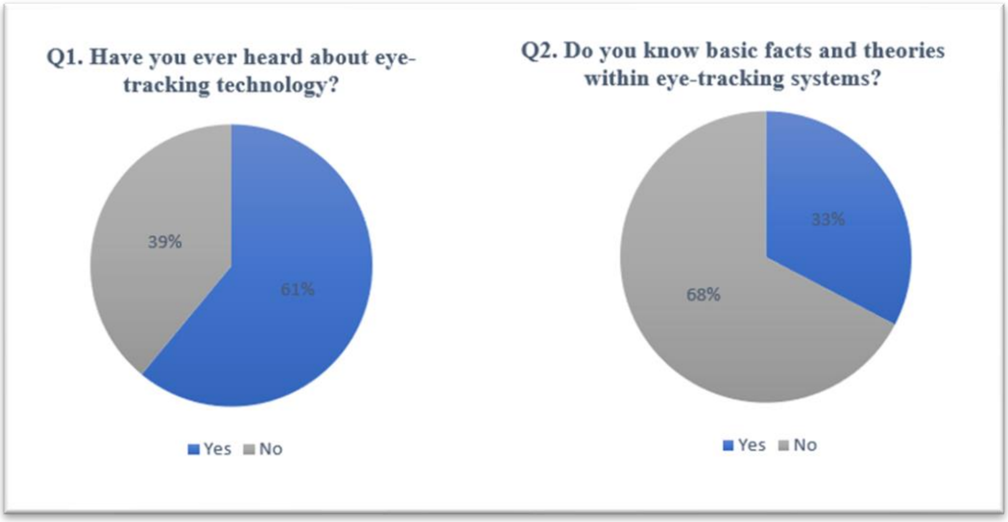

Figure 4.1: Awareness of eye-tracking technology and knowledge of basic facts and theories within eye tracking systems

Nevertheless, 78% of the respondents that eye-tracking technology is useful, even though 70% of them had never used considered eye tracking before. In the same vein, most users were interested in knowing more about eye tracking trends in current research (Figures 4.2 for frequency percentages).

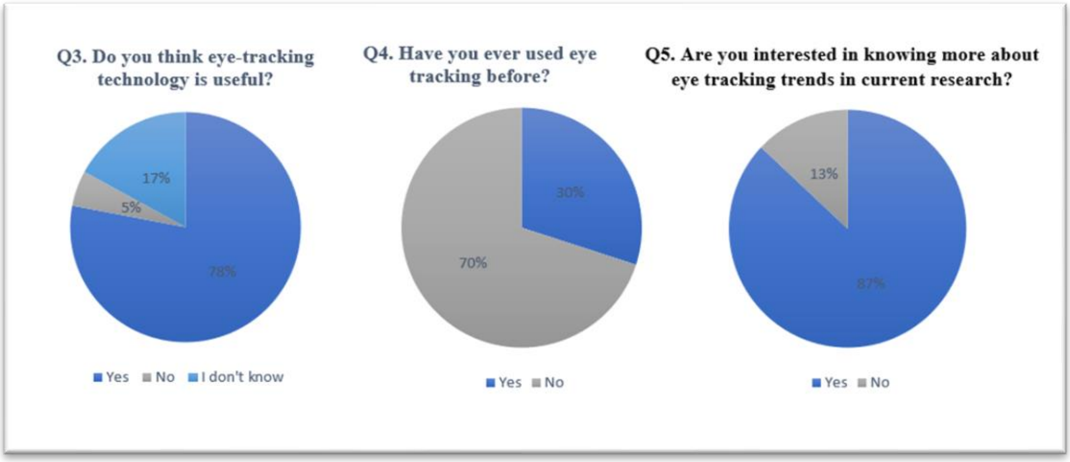

Figure 4.2: Perceived usefulness of eye-tracking technology, prior use of eye tracking, and interest in eye tracking trends

4.3.2 Researchers' Attitudes Towards Eye Tracking

Almost half of the respondents worked in research (47%), with the most frequently reported research area being computer science and technology (Table 4.1 for frequency percentages of research areas).

Table 4.1: Research Areas of Respondents

Research area	**%**
Computer Science and Technology	50%
Computer Science and Technology & Education and Training	11%
Education and Training	11%
Linguistics	7%
Biochemistry and Biology	4%
Computer Science and Technology & Engineering and Human Factors	4%
Education and Training & Linguistics	4%
Neuroscience and Psychology & Education and Training	4%
Psychology	4%
Translation	4%

The majority of researchers knew the areas where eye-tracking technology could be used. However, one-third of them was not sure if they were interested in using eye trackers in their research when it is available, which could be attributed to the particularly low percentage (10%) of researchers who had used eye tracking before in their research (Figure 4.3 for frequency percentages).

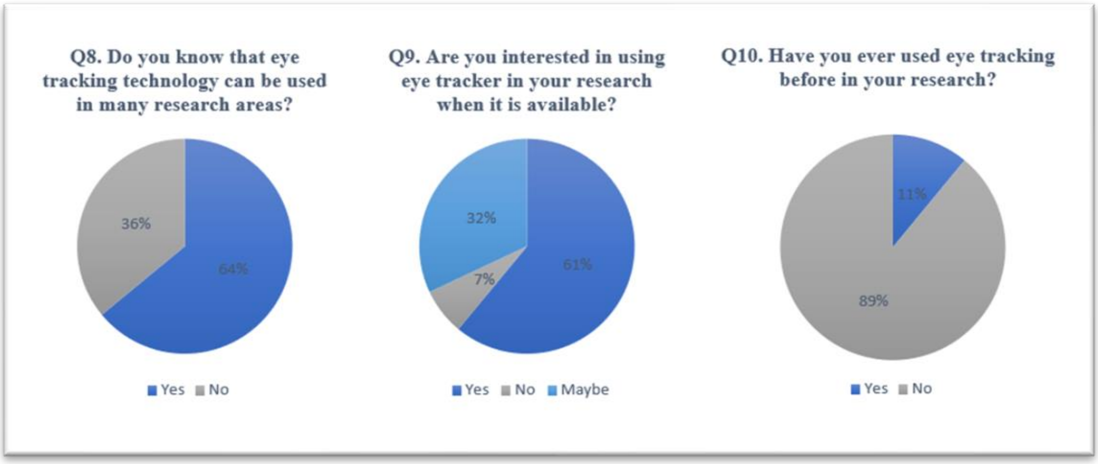

Figure 4.3: Knowledge of eye tracking application, interest in using eye tracker in research, and prior use of eye tracking in research

4.3.3 Eye Tracking Researchers' Attitudes Towards Eye Tracking

Prior to the presentation of the results, it should be stressed that only 3 participants had used eye tracking before in their research, and thus, answers are based on a quite limited number of individuals. Two of the respondents had used eyeglass trackers, whereas the other participant had used head-mounted trackers. Concerning the perceived value of eye-tracking technology to the research of respondents, one participant selected the option of understanding human behavior. The second participant referred to UX and usability, whereas the third respondent chose all six options listed (assessment; UX & usability; evaluation of electronic content; data validation; biometrics & security; understanding human behavior). Finally, eye-tracking researchers were asked to assess eye-tracking technology as a methodology in research in three dimensions: cost, difficulty of data collection, and difficulty of data analysis. Two out of the three respondents considered eye-tracking technology cost to be low, while the other participant perceived it as high. All three eye-tracking researchers though considered the difficulty of data collection and data analysis to be high.

4.4 Discussion

In this research, a preliminary step has been made towards the evaluation of the awareness of eye-tracking technology and attitudes towards it among different categories of users. Of the general users, a moderate percentage had heard about eye-tracking technology, and a lack of familiarity with the facts and theories about eye-tracking systems was observed for most users. Nevertheless, despite the fact that most of them had never used eye tracking before, the usefulness of eye-tracking technology was perceived positively by most respondents, and the majority of general users expressed interest in improving their knowledge about eye-tracking trends. Of the individuals who worked in research, most of them were aware that eye tracking could be used in a variety of research areas, but only a small percentage had used it in their research, and as a result, one third of the researchers were not sure if they were interested in using it when it is available. Finally, only three participants were eye-tracking researchers, and among them, eyeglass and head-mounted trackers had been used. In addition, the eye tracking researchers noted the value eye tracking offers for understanding human behavior and improving UX and usability. However, the data collection and data analysis required for eye tracking was perceived as difficult; lastly, its cost was considered to vary from low to high.

On the whole, eye-tracking technology was perceived favorably, and its usefulness was systematically noted among all user categories. Nonetheless, a considerable number of general users were not aware of it and/or ignorant of basic facts and theories. This result was close to expectations because even though eye-tracking technology has become cheaper, it is still expensive for general consumers. While only a few researchers had adopted eye-tracking technology, this is supported by the perception of eye-tracking technology as a difficult and expensive methodology for quantitative research among researchers, according to the result obtained in this research. Therefore, it's obvious that eye-tracking manufacturers are focusing on the research community as their main consumer, through advertising and providing training, for logical reasons, as a minimum level of standards needs to be established, and further reduction in cost is a must before eye tracking can be adopted within VR and AR at a larger scale. Therefore, eye tracking for general consumers will stay limited until VR, AR, and wearable technologies set foot in the market.

In research with small sample sizes, it is advisable to treat the observations of such studies as indications and not as conclusive evidence. Nevertheless, the low response to the survey could also indicate the attitudes toward eye-tracking research [56] due to the lack of eye-tracking companies' presence in the area. However, eye tracking provides important distinctions in different areas of research that can't be ignored, in addition to the fact that there is data that can be gathered only using eye tracking. Therefore, research on eye tracking has existed for a long period of time and made considerable progress, particularly since the advancement of video-based eye-tracking systems.

Lastly, it is recommended that further research is conducted, and inferential analyses are applied, so that results can be generalized to the population, and practical implications can be proposed. One more recommendation is to support training and development from both eye-tracking manufacturers and eye-tracking research community to fully benefit from this technology.

Chapter V

Eye Tracking within Immersive Pain Distraction System

The emergence of HMD-ET creates opportunities to conduct new experiments in safe and controlled environments. In this chapter, this technology had been utilized to advance pain distraction system and give a chance to understand the mental aspects of the pain through the eye.

5.1 Introduction

There is growing evidence that adjunctive immersive VR distraction can help reduce the suffering of patients during medical procedures with few or no side effects from the VR [57][48][17]. Patients with large severe burn injuries often have burns on their heads or face that make it difficult or impossible for them to wear a head-mounted VR helmet. To customize VR for burn patients, Hoffman and Magula developed a "robot-like arm" goggle holder, which holds the immobilized VR goggles near the patient's eyes with little or no contact with the patient [19][58].

This chapter tackles the issue of designing a lab system to advance the previous VR analgesia systems and solve some of the previous systems' limitations by adding eye-tracking technology. With the technical advances in the field of eye-tracking technology, it is now possible to use it within VR systems. Due to the development of eye-glass mobile eye trackers with light, small, and high-quality hardware components of cameras and sensors used in them, this hardware can now be fitted into a VR HMD.

The next section provides an introduction to the technical aspects of designing a laboratory VR pain analgesia system with eye tracking, which provides a simple guideline for other researchers in VR analgesic systems. The off-the-shelf components used in this system will be briefly described. In addition, we hope that the new advancements in eye-tracking technology will encourage other VR applications to adopt this technology. Finally, the discussion section will present scenarios for how this system can be used for research purposes. As shown in Figure 5.1, the system workflow can be divided into many stages, which will each undergo iterative development. The overall aim of the project is to develop a more effective analgesic system and help understand different aspects such as eye movement patterns and how they correlate with pain and its related variables.

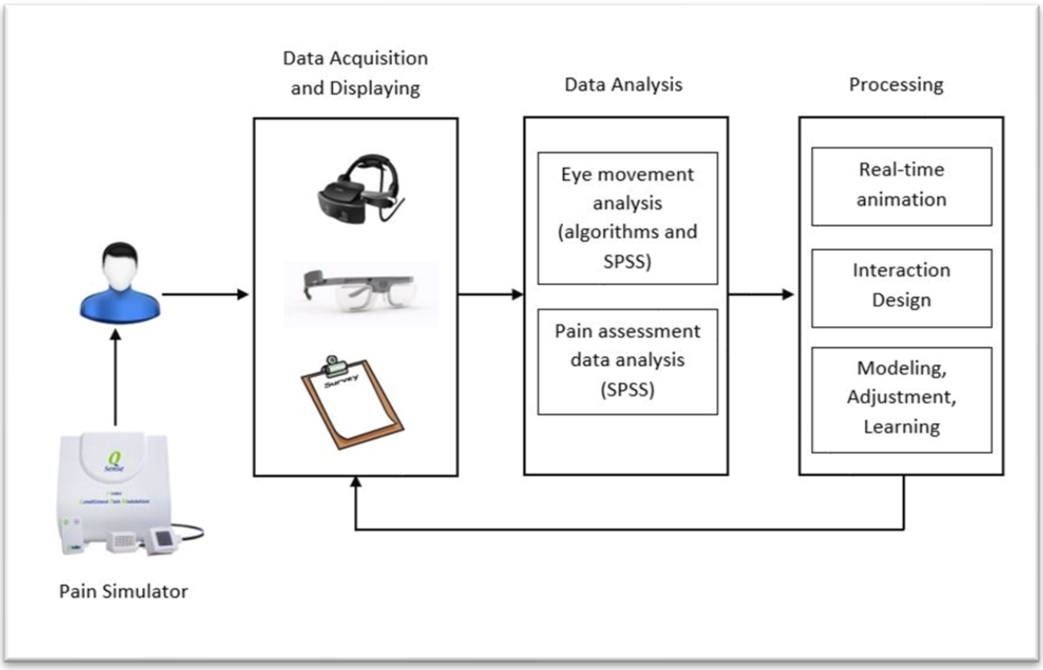

Figure 5.1: Workflow Chart of the system

5.2 Components of immersive virtual reality pain distraction

5.2.1 Hardware

HMD-ET

The popularity of HMDs, such as Oculus, VIVE, and Samsung HMDs, is rapidly increasing for providing more immersion in a VR environment without the need for ample space. On the other hand, the competition between eye-tracking manufacturers in the past decade to advance VR progress has led to significant changes in the hardware. Studies that investigate eye tracking within VR are new and mostly conducted in semi-immersive VR environments. Some eye-tracking manufacturers now offer HMD-ET, which is embedded eye tracking within HMD. SMI [27] and Tobii [26] both offer a service of integrating the eyeglass tracker component into an HMD such as VIVE HMD or Oculus. Ergoneers [28] and another new company called FOVE [59] both offer a ready-integrated eye-tracking HMD package. A different approach is offered by Pupil Lab [60], where small eye-tracking components can be attached or inserted into an HMD. Although the technology is limited, it provides a pool of opportunities for investigation and innovation for researchers in different fields.

PC machine

Despite the progress in graphical processing Units (GPU), it is still challenging to render 3D graphics in a resolution adequate for the resolution of the eye. Currently, minimum requirements should be considered for the machine that will be used to run the VR environment and the eye tracker plugin. Also, it is important to provide a high-frame-rate VR environment in pain analgesic systems, as described in [61], and to avoid VR sickness [62].

Pain simulator

In pain research studies, many experimental pain models have been used to generate brief pain stimuli, such as electrical, mechanical, or thermal stimuli [63]. Nowadays, computerized pain generators are available and provide researchers with new convenient methods and precise protocols for monitoring the stimuli process and tracking the treatment phases. Medoc medical systems [64] offer a range of pain generators or simulators, such as thermal pain simulators which use a thermode to attach them to the human body, and some of these thermal devices support vibratory stimulators. Another computerized pain simulator from Medoc is the algometer, which is a new tool that quantifies pressure response and enables the researcher to perform various pressure test paradigms. The algometer can be utilized in pressure pain studies for a wide range of measures.

Cables and connectors

The system hardware needs a place and some sort of management. Multiple cables are used to connect power to the machines (at least the VR machine and pain simulator device). Some peripherals will require direct power connections, and others can be connected to the computer. All HMDs need multiple cables and connectors to connect the helmet and the tracking sensors. Although some companies provide new solutions for converting the HMD into a wireless one, these solutions still have some limitations, such as adding weight to the heavy helmets or the effect of distance on data transferring. More importantly, using eye trackers within HMDs will not suit the current wireless solutions.

5.2.2 *Software*

VR engine

There are a growing number of tools for designing VR environments. Unity and Unreal engines are the classical tools favored by most developers. VR engines use different programming languages, and some engines support more than one language, such as C++, C#, Java, Python, and Matlab. In general, designing a VR environment requires a lot of effort and time-consuming process, plus it strongly relies on the developer's programming and designing skills.

Eye-tracking SDK

Eye-tracking companies provide SDK to allow designing and customizing the application to interact with the eye tracker. Usually, these SDKs support different programming languages, most commonly C++, C#, Java, Python, and Matlab. Also, eye-tracking SDKs allow integration with different stimulus software, mostly provided by the same company.

Pain simulator utilities

The new computerized pain generators are controlled by software that provides the researchers with a GUI enabling management of pain experiments. Vendors support their products with many tools for different test protocols and methods, as well to facilitate recording and saving input data and results.

5.2.3 *Other materials*

Pain assessment instrument

Pain assessment is an essential aspect of pain management. There are many valid tools to assess different types of pain. The majority of these tools involve some kind of selfreport. The most commonly used tools to quantify the pain experience are verbal rating scales (VRS), numerical rating scales (NRS), and visual analog scales (VAS) [65].

5.3 Implementation

This current VR pain analgesia system with eye tracking was implemented in the Virtual Reality Center at Effat University in the City of Jeddah, Saudi Arabia. The main goal of the system is to utilize eye-tracking technology to solve some current limitations in VR pain analgesia systems and to employ this technology to understand some mental aspects of pain.

The system uses msi laptop with GeForce GTX 1080 8 GB, Intel Core i7 7th Gen (2.80 GHz), 16 GB RAM, connected to an HMD standard helmet from VIVE HTC [66] with a FOV of 110 degrees, a resolution of 1080 × 1200 pixels per eye, and a refresh rate of 90 Hz, with two base stations for motion tracking. The HMD integrated with a pair eye trackers from SMI which track the subject's gaze in the 3D environment with a typical accuracy of 0.5°. Each eyepiece of the goggles is trimmed with a small ring of six infrared lights positioned in a circle around each eye. In addition to the low-energy infrared lights, miniature infrared cameras mounted on the same ring record the pattern of lights with an infrared camera. These miniature cameras can make real-time digital video streams of the six small dots of infrared light reflected off the outer surface of the subject's eyes (the cornea).

The tracker works with the C++\C# SDK for various VR engines. The setting platform is the Windows 10 operating system, and the 3D application development tool used is Unity. Therefore, eye-tracking data are recorded in the Unity VR engine relative to an origin coordinate at the upper left corner of the HMD screens, as specified by the SMI plugin documentation. As the participants look at different objects in the computer-generated world, the pattern of infrared dots changes shape. The VR computer can tell, from the pattern of dots, where the participant is looking. Because the eye tracking system only uses light in the narrow bandwidth of infrared, the video camera is able to ignore confusing reflection noise from the visible spectrum, which improves eye tracking accuracy.

The chosen pain simulator was a controlled thermal computerized Medoc thermal pain stimulator, Medoc Q Sense [67], connected to another msi laptop Intel Core i7 7th Gen (2.80 GHz), 16 GB RAM. A thermode is strapped around the wrist or leg of a participant, with the thermal surface of the thermode in direct contact with the skin. The system is controlled by software to generate painful stimuli triggered such that the temperature rises to painful levels, controlled by different programs such as hold and ramp.

SnowCanyon [68] with eye tracking interaction was specifically designed in Unity with the SMI SDK and C# to eventually make this unusually simple human-computer interface (eye tracking) available for laboratory study and for future clinical use in pediatric burn patients during wound care, when they are heavily medicated, in severe pain, and often have burn injuries to their hands, making it difficult to use a traditional hand controlled mouse or trackball computer input device to interact with the virtual world during burn wound cleaning. A demonstration for the system is shown in Figure 5.2.

Figure 5.2: Demonstration of the VR analgesia system with eye tracking

5.4 Discussion

The usage scenarios and advantages of this system in research are: (1) Solve the problem of immobile children unable to interact with the VR environment during burn wound care. (2) Study the effects of eye-tracking interactivity on pain. (3) Design different eye interaction techniques to increase the efficiency of VR analgesia. (4) Investigate eye movement within a VR environment, and (5) Collect eye movements data about the patient's current mental state and study the correlation with how much pain patients are consciously experiencing.

The system was developed to a general framework so that users could easily tailor it for their own research project or other usage scenarios, such as understanding the effect of different VR environments on pain and understanding the effect of different interaction techniques and input modalities on pain.

Furthermore, on reviewing the literature, no data were found on the association between eye movements and pain. That makes this system the first of its kind and opens doors for many questions to be investigated. The interaction with eye movements can be utilized in both active gaze and passive gaze forms when studying the association with pain. Using active gaze, a specific eye movement measure can be utilized to control the interface as an intentional input instead of hand pointing devices. Using passive gaze, the system is capable of dynamically adaptating to the virtual environment in order to tailor the UX to a particular user. In addition, it is able to record eye movements to study different aspects of pain.

Initially, this system is employed to examine the primary research hypothesis of exploring whether interacting with virtual objects in VR via eye tracking makes VR more effective compared to passive VR. From a passive gaze perspective, eye movement is investigated in VR in order to design a fixation detection algorithm as a step toward developing the system for future scenarios.

Chapter VI

Effect of Eye Tracking Interaction within Pain Distraction System

The aim of this chapter is to study the main hypothesis of this thesis: adding eye tracking gives a stronger illusion of presence in VR, thus making the VR experience more attention demanding, and this reduce pain significantly more effectively than VR with no eye tracking. To test this hypothesis, a randomized controlled laboratory analog pain experiment with healthy volunteers was conducted using a paradigm described by [16].

6.1 Introduction

The current laboratory thermal pain study with healthy volunteers explores for the first time, whether interactive eye tracking can enhance the analgesic effectiveness of VR distraction. SnowCanyon with eye tracking [68] was specifically designed to eventually make this unusually simple HCT with eye tracking available to pediatric burn patients during wound care when they are heavily medicated, in severe pain, and often have burn injuries to their hands, making it difficult to use a traditional hand controlled mouse or trackball computer input device to interact with the virtual world during burn wound cleaning. In the future, using eye tracked VR goggles, burn patients with both hands burned, who cannot use a computer mouse, will be able to interact with VR, using their eye movements as the human-computer interface. The current study with healthy volunteers explores whether interacting with virtual objects in VR via eye tracking makes VR more effective compared to passive VR (no eye tracking) for reducing pain during brief thermal pain stimuli. If so, the results would implicate an attentional mechanism for how VR reduces pain.

For investigating the effect of VR analgesia, pain assessment is conducted during the VR system utilization. There are several valid qualitative instruments to address pain affects, one of the well-known simple tools is the Visual Analogue Scale (VAS), which is a response scale can be used in questionnaire as a straight line with start and end points restricting extremes such as start point ‘no pain’ and end point ‘worst pain’. Another tool is Graphic Rating Scale (GRS) which contains descriptive terms such as ‘nothing at all,’ ‘mild,’ ‘moderate,’ ‘severe’ or a numerical scale, e.g. (0 to 10) [9] [69] [70]. Such rating scales are valid for subjective characteristics, as in pain components, that cannot easily be uniformly measured. They have been shown strong associations of those numeric scales or descriptive terms measures with the related symptom severity, thus it can also be used after treatment to detect its effects on the related symptom.

6.2 Methodology

The methodology approach taken in this study to investigate the formulated hypothesis consists of series of procedures that are presented in the following sections.

6.2.1 Hardware and Software Requirements Specification

The powerful commercial competition in video games led to an acceleration of speed, miniaturization and price drop for GPU and CPU. It became obtainable to rely on off-the-shelf devices as the VR engine. As the case in this study, the experiment was carried out using a gaming laptop msi GeForce GTX 1080 8 GB, Intel Core i7 7th (2.80 GHz), 16 GB RAM, Windows 10 operating system connected to HMD with

FOV 110 degrees from HTC, with 1080 x 1200 pixels per eye resolution and refresh rate 90 Hz replaced the previous expensive goggles used in the older version of the system [19]. The HMD integrated with SMI eye-tracking 250 Hz [27] works with the SDK C++\C# for various VR engines like Unity, shown in Figure 6.1. A new version of SnowWorld game has been integrated with SMI SDK to use the eye-tracker to select a virtual object in the virtual environment by looking at it.

Figure 6.1: HTC VIVE Integrated with SMI Eye-Tracker

To generate a pain, a commercially available Medoc Q-Sense conditioned pain modulation (CPM) [67] system thermal pain computerized stimulator offers a scientifically validated measure of thermal sensory thresholds, and many other features; is applied as a heat-pain stimulus. The ramp and hold test stimulation method used to design the heat-pain programs for the experiment via Medoc software. The device connected to another laptop, and it attaches to a subject via a thermode, Medoc Q-sense and a screen capture of the software is shown in Figure 6.2.

Figure 6.2: Computerized Medoc Q-sense Pain Simulator

6.2.2 Experiment Procedures and Design

6.2.2.1 *Pain Assessment*

Before each participant goes through one of the experiment settings, their tolerant temperature of heat-pain is individually measured. Pain sensitivity will be assessed using Medoc Q-Sense CPM briefly applied by placing the thermode on a participant's arm calf. When the thermode is heated to a predefined threshold, 44°C for the first stimulus controlled by the software, the heat continues for 10 seconds before cooling down. Afterward, the participant logs responses to a pain rating questionnaire. Subsequently, the participant chooses to stop or increase the temperature of the previous treatment (by 0.5^{o}C or 1^{o}C) and undergoes the same treatment until the participant chooses to stop and the last temperature is set as the tolerant temperature threshold for this participant.

Next, a pain stimulus is applied to each participant at this individual tolerant temperature threshold during exposure to one of the experimental settings. Afterward, as mentioned before, the participant logs responses to a pain rating questionnaire; please see Appendix B.

The pain rating questionnaire assessed seven variables, which reflected the experience of participants during exposure to the experimental settings (Table 6.1). It should be noted though that a pain stimulus would be evaluated with the first four variables, as the last three were relevant only to VR settings. Responses were given on an 11-point Likert scale, ranging from 0 (none) to 10 (extreme) by the response to related questions, please psee appendix B. In order to attempt to identify the occurrence of any simulator sickness, participants were asked to rate any nausea or sickness. Zero responses to nausea were reported, but a few responses of slight dizziness at the beginning of VR experiences were reported. Thus variable dizziness was assessed.

Higher levels of negative variables indicated a lower distraction and a lower analgesia effect, whereas higher levels of positive variables indicated a higher distraction and a higher analgesia effect.

Table 6.1: Variables Assessing Pain Levels and Associated Relationship with Analgesia

Variables	Relationship with Analgesia
1. Time spent thinking about pain	Negative
2. Pain unpleasantness	Negative
3. Worst pain	Negative
4. Fun	Positive
5. Dizziness	Negative
6. Went inside the virtual world (Presence)	Positive
7. The reality of virtual objects (Realism)	Positive

6.2.2.2 ***Experimental Settings***

A systematic experiment was conducted to measure if adding eye-tracking to a VR system reduces participants' pain. The experiment comprises three different settings: first setting (No VR), second setting (VR + no eye-tracking), and third setting (VR + eye tracking). During the entire duration of the experiment, each participant remains seated in place with a thermode placed in their left-hand calf. Participants are not allowed to use their hands to interact with the VR environment.

In the first setting (No VR), the participant undergoes the heat-pain stimuli where the thermode is placed on the participant's arm calf at a tolerant temperature threshold, decided before as described in pain assessment, without VR. The heat continues for 10 seconds then begins to cool down. Then, the participant logs responses to a pain rating questionnaire.

In the second setting (VR + no eye-tracking), the participant undergoes the heat-pain stimuli where a thermode is placed on their arm calf at a tolerant temperature threshold, as decided before, and looks into the VR goggles to the VR pain distraction world. They are slowly floated through the 3D computer-generated world, with eye-tracking turned off. The heat continues for 10 seconds before beginning to cool down. Then, the participant logs responses to a pain rating questionnaire.

Lastly, the third setting (VR + eye tracking) uses the identical procedure in the second setting, but eye-tracking will be enabled here. While the participant looks into the VR goggles, an important eye-gaze calibration process takes a few seconds for each individual to obtain accurate eye movements. At this step, the participant is asked to track a moving redpoint, i.e., a calibration dot shown in a blank screen. The system records this motion, to map the participant's actual gazes with the accurate positions of the calibration dot during the motion. Afterward, the participant in VR can aim snowballs at objects in VR by simply looking at the virtual objects. Essentially, the "cursor" or reticle crosshair, follows the patient's eye fixations. So if the patient looks at a Snowman in VR, the virtual snowballs hit the Snowman, and the virtual snowman reacts (with special animated effects) when hit by a snowball.

6.2.2.3 ***Subjects Design***

Sixty healthy volunteer participants were recruited and randomly assigned to one of three groups: A, B, and C. The participants signed consent forms that were obtained and authorized by IRB of Effat University's protocols and guidelines, which is a private University for female students in Jeddah, KSA, please see Appendix C. The experiment was designed to take advantage of two common design methods between and within the subjects' design. The three groups will pass through the three settings in a specific order, as shown in Figure 6.3.

Within-Subject Design. Here, the investigation includes all of the participants who were exposed to all three settings. There are 40 participants exposed to (No VR), (VR + No eye-tracking) and (VR + eye-tracking) settings. Within-subjects' design has been conducted using the data collected from groups B and C. To ensure that the design undergoes a streamlined process, the twenty subjects' data in the control group (No VR) will not be collected here, as they were not exposed to VR treatments.

Between Subject Design. The investigation here considers three groups; each consists of completely different twenty participants. A test has been conducted at second treatment, where group A was exposed to the setting (No VR), group B was exposed to the setting (VR + No eye-tracking), and group C was exposed to the setting (VR + eye-tracking). Also, another test has been conducted at third treatment, where group A was exposed to the setting (No VR), group B was exposed to the setting (VR + eye-tracking), while group C was exposed to the setting (VR + No eye-tracking).

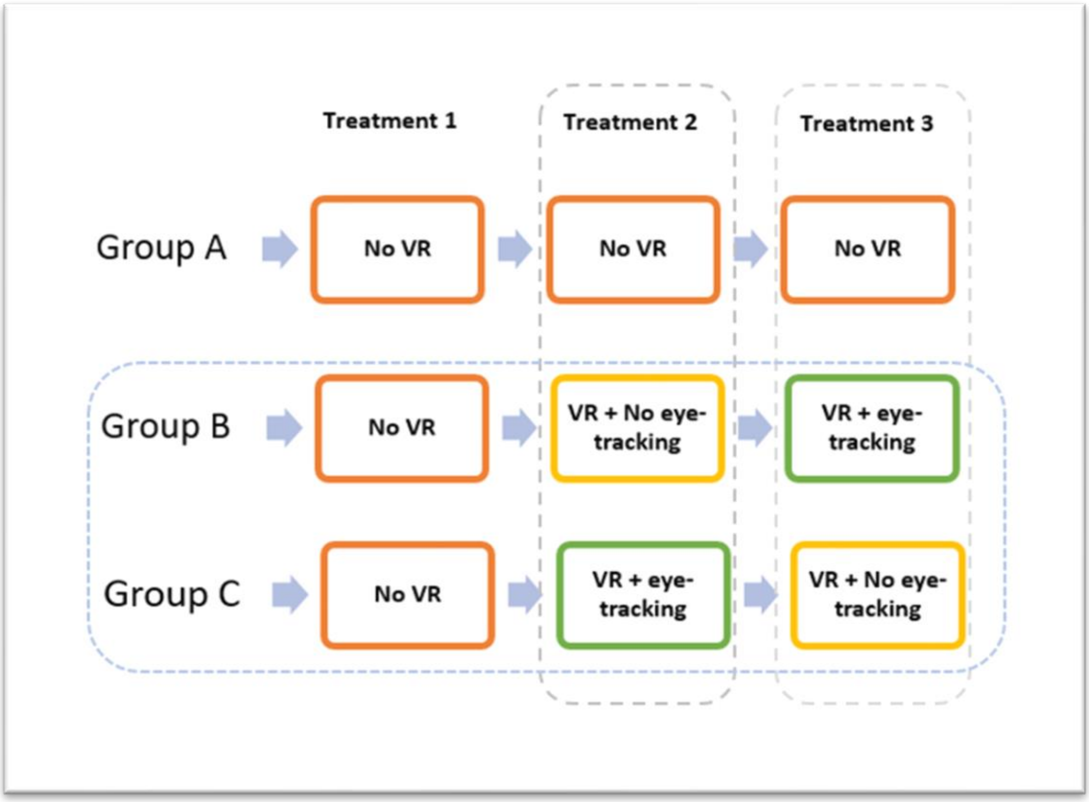

Figure 6. 3: Methodology Subjects' Design Process

6.2.3 Data Analysis

SPSS was employed and the level of $p = 0.05$ was considered significant. For within-subjects' design, four one-way repeated analyses of variance (ANOVAs) and three paired samples t-tests were employed. In reference to between-subjects' design at second treatment, four one-way between subjects' ANOVAs and three independent samples t-tests were performed. Finally, the same analysis at third treatment four one-way between subjects' ANOVAs and three independent samples t-tests were employed. Post hoc procedure tests were performed when indicated, to determine where the differences lie.

6.3 Results

Prior to proceeding with inferential analyses, descriptive analyses were conducted to identify the age and the tolerant temperature threshold of participants at each design. Considering that between subjects in the two different treatments included the same participants (Figure 6.3). In both designs, mean age of 22 years and mean tolerant temperature threshold value of 47^{o} C was reported (Table 6.2). Considering the homogeneity observed in age and tolerant temperature threshold across designs and among groups, it was speculated that these variables would not exert an undue influence on the subsequent inferential analysis.

Table 6.2: Descriptive Statistics for Age and Tolerant Temperature Threshold among Groups for Designs

	Age				Tolerant temp threshold			
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Participants in within subject (B and C)	21.48	1.54	18	24	47.23	0.95	44.50	48.50
Group A	22.60	2.96	18	30	47.23	0.73	45.50	48.50
Group B	21.85	1.57	18	24	47.48	0.64	46.00	48.50
Group C	21.10	1.45	18	23	46.98	1.15	44.50	48.50

Note. *M* = Mean; *SD* = Standard Deviation; *Min*= Minimum; *Max* = Maximum.

6.3.1 *Within-Subjects' Design*

In order to examine if there is a statistically significant difference in analgesia levels among experimental settings, One-way repeated ANOVAs were employed to investigate if there is a statistically significant difference as assessed by the variables time spent thinking about pain, pain unpleasantness, worst pain, and fun. Paired samples t-tests were used to determine if there is a statistically significant difference as assessed by the variables: dizziness, presence, and realism.

Assumption testing. Before proceeding with the inferential analyses, their relevant assumptions were explored. One-way repeated ANOVA requires approximately normally distributed data and sphericity. Normal Q-Q plots revealed approximately normally distributed data in all experimental settings for all variables, although a less satisfactory distribution was observed for time spent thinking about pain variable in the second setting (VR + no eye-tracking) and third setting (VR + eye tracking). However, taking into account that ANOVA is robust to deviations from normality in large sample sizes ($N > 30$), no further action was deemed necessary [71].

As far as paired samples t-test is concerned, differences between paired variables should be approximately normally distributed. Normal Q-Q plots displayed approximately normally distributed differences in all variables between second setting (VR + no eye-tracking) and third setting (VR + eye tracking), although a less satisfactory distribution was observed for the variable dizziness. Nevertheless, considering that paired samples t-test is robust to deviations from normality in large sample sizes ($N > 30$), no further action was deemed necessary[71].

One-way repeated ANOVAs. Four one-way repeated ANOVAs were conducted to assess if there are any statistically significant differences in time spent thinking about pain, pain unpleasantness, worst pain, and fun variables among three experimental settings (N = 40). Descriptive statistics showed that the first setting (No VR) concentrated the highest levels in time spent thinking about pain, pain unpleasantness, and worst pain variables and the lowest levels of the fun variable. In contrast, exposure to the third setting (VR + eye tracking), gathered the lowest levels in time spent thinking about pain, pain unpleasantness, and worst pain variables and the highest levels in fun variable (Table 6.3).

Table 6.3: Means and (Standard Deviations) for Time Spent Thinking about Pain, Pain Unpleasantness, Worst Pain, and Fun Variables among Experimental Settings

Method	Variable			
	Time spent thinking about pain	Pain unpleasantness	Worst pain	Fun
First setting (No VR)	1.93 (2.13)	4.43 (1.58)	6.25 (1.13)	1.53 (2.22)
Second setting (VR + No eye-tracking)	0.59 (1.21)	3.30 (2.02)	5.03 (1.69)	3.68 (2.13)
Third setting (VR + eye tracking)	0.50 (1.04)	2.48 (1.87)	3.92 (1.95)	5.50 (2.27)

Inferential analyses indicated statistically significant differences in all four variables among experimental settings. Particularly, a statistically significant difference in time spent thinking about pain, [F (1.45, 56.42) = 19.19, p < 0.001, η_p^2 = 0.33], pain unpleasantness [F (2, 78) = 35.03, $p < 0.001$, $\eta_p^2 = 0.47$], worst pain [F (1.70, 66.17) = 51.61, $p < 0.001$ $\eta_p^2 = 0.57$], and fun variable [F (1.72, 66.89) = 83.87, $p < 0.001$ $\eta_p^2 = 0.68$], was identified. Considering that statistically significant differences were revealed, Bonferroni post hoc tests were subsequently consulted to determine where the significant differences lie.

Regarding time spent thinking about pain variable, pairwise comparisons indicated a statistically significant difference between first setting (No VR) and second setting (VR + No eye-tracking), *[Mdf* = 1.34, 95%CI [0.64, 2.04], $p < 0.001$], as well as between first setting (No VR) and third setting (VR + eye tracking), *[Mdf* = 1.43, 95%CI [0.66, 2.20], $p <0.001$].

Concerning pain unpleasantness variable, a statistically significant difference between first setting (No VR) and second setting (VR + No eye tracking), [*Mdf* = 1.13, 95%CI [0.56, 1.69], $p < 0.001$], between first setting (No VR) and third setting (VR + eye tracking), *[Mdf* = 1.95, 95%CI [1.34, 2.56], $p < 0.001$], as well as between second setting (VR + No eye tracking) and third setting (VR + eye tracking), [*Mdf* = 0.83, 95%CI [0.25, 1.41], $p = 0.003$], was identified.

Proceeding with worst pain variable, results revealed a statistically significant difference between first setting (No VR) and second setting (VR + No eye tracking), [*Mdf* = 1.23, 95%CI [0.68, 1.77], $p < 0.001$], between first setting (No VR) and third setting (VR + eye tracking), *[Mdf* = 2.33, 95%CI [1.64, 3.02], $p < 0.001$], as well as between second setting (VR + No eye tracking) and third setting (VR + eye tracking), [*Mdf* = 1.10, 95%CI [0.64, 1.56], $p < 0.001$].

Finally, in reference to fun variable, a statistically significant difference between first setting (No VR) and second setting (VR + No eye tracking), [*Mdf* = -2.15, 95%CI [-3.01, -1.29], $p < 0.001$], between first setting (No VR) and third setting (VR + eye tracking), *[Mdf* = -3.98, 95%CI [-4.82, -3.13], $p < 0.001$], as well as between second setting (VR + No eye tracking) and third setting (VR + eye tracking),[*Mdf* = -1.83, 95%CI [-2.39, -1.26], $p < 0.001$], was observed (Figure 6.4 for significant differences).

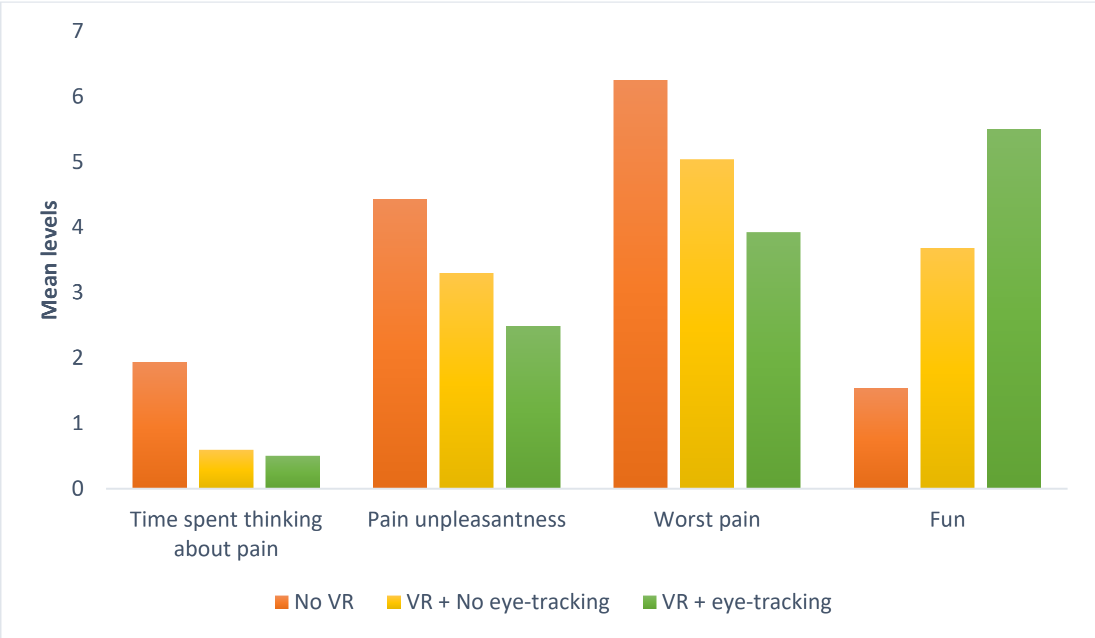

Figure 6.4: Mean differences among experimental settings

Overall, the findings suggested that first setting (No VR) elicited the most negative experiences, whereas third setting (VR + eye tracking) generated the most positive experiences. It was also observed that second setting (VR + No eye tracking) elicited less negative experiences first setting and less positive experiences than the third setting. Therefore, it could be inferred that third setting (VR + eye tracking) was the most effective.

Paired samples t-tests. Three paired samples t-tests were conducted to assess if there are any statistically significant differences in dizziness, presence and realism variables between the settings (VR + No eye tracking) and (VR + eye tracking) where (N = 40). Descriptive statistics showed a minor difference in dizziness variable [Mdf = -0.18, 95%CI, -0.51 to 0.16] and a substantial difference in presence [Mdf = -1.50, 95%CI, -2.12 to -0.88] and realism variables [Mdf = -0.90, 95%CI, -1.33 to -0.47]. Particularly, second setting (VR + No eye tracking) gathered slightly lower levels in dizziness variable, while third setting (VR + eye tracking) concentrated significantly higher levels in the presence and realism variables (Table 6.4).

Table 6.4: Means and (Standard Deviations) for Dizziness, Presence, and Realism Variables Between Settings (VR + No eye tracking) and (VR + eye tracking)

Method	Variable		
	Dizziness	Presence	Realism
Second setting (VR + No eye-tracking)	0.08 (0.35)	4.23 (2.17)	3.53 (2.00)
Third setting (VR + eye tracking)	0.25 (1.01)	5.73 (2.56)	4.43 (2.37)

Inferential analyses indicated a non-statistically significant difference in dizziness variable, [$t (39) = -1.05$, $p = 0.30$, $d = -0.17$]. However, a statistically significant difference in presence [$t (39) = -4.90$, $p < 0.001$, $d = -0.78$] and realism variables [$t (39) = -4.20$, $p < 0.001$, $d = -0.66$] was identified (Figure 6.5 for significant differences). Consequently, results suggested that third setting (VR + eye tracking) elicited significantly higher levels of positive experiences and was a more efficiency than the second setting.

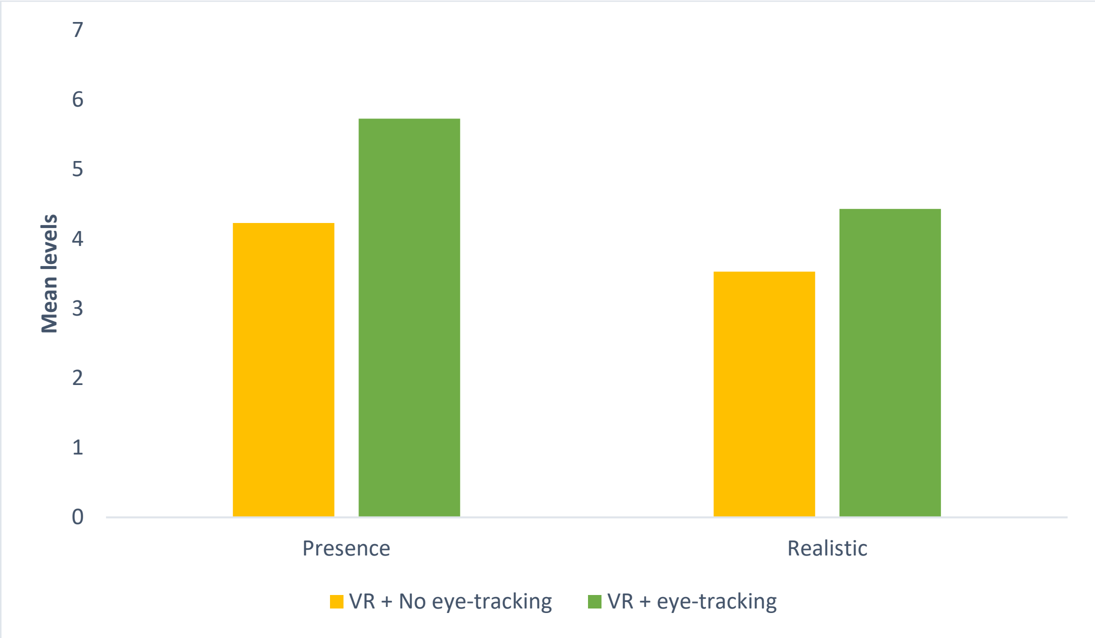

Figure 6.5: Mean differences in experimental settings (VR + No eye tracking) and (VR + eye tracking)

6.3.2 Between-Subjects' Design (Second Treatment)

In order to examine if there is a statistically significant difference in analgesia levels among experimental groups; where group A exposed to first setting (No VR), group B exposed to second setting (VR + No eye-tracking) and group C exposed to third setting (VR + eye-tracking); four one-way between subjects' ANOVAs and three independent samples t-tests were conducted. One-way between subjects' ANOVAs were employed to investigate if there is a statistically significant difference in distraction levels among the three experimental groups, as assessed by the variables time spent thinking about pain, pain unpleasantness, worst pain, and fun. Independent samples t-tests were used to determine if there is a statistically significant difference in analgesia levels between group B and C, as evaluated by the variables: dizziness, presence, and Realism.

Assumption testing. Prior to proceeding with the inferential analyses, the relevant assumptions were explored. One-way between subjects' ANOVA requires approximately normally distributed data and homogeneity of variances. Normal Q-Q plots revealed approximately normally distributed data in all experimental groups for all variables, although a less satisfactory distribution was observed for time spent thinking about pain variable. However, taking into account that ANOVA is robust to deviations from normality when group sizes are equal, no further action was deemed necessary [71].

As far as independent samples t-test is concerned, approximately normally distributed data and homogeneity of variances should be present. Normal Q-Q plots displayed approximately normally distributed data in the presence and realism variables for both groups. However, normal Q-Q plots, in conjunction with Shapiro-Wilks normality test, suggested non-normal distributions in dizziness variable for both groups (S-W < 0.001). However, considering that independent samples t-test is robust to deviations from normality in equal group sizes, no further action was deemed necessary [71].

One-way between subjects' ANOVAs. Four one-way between subjects' ANOVAs were conducted to assess if there are any statistically significant differences in time spent thinking about pain, pain unpleasantness, worst pain, and fun variables between group A (n = 20), group B (n = 20), and group C (n = 20). Descriptive statistics showed that group A reported the highest levels in time spent thinking about pain, pain unpleasantness, and worst pain variables and the lowest levels of the fun variable. In contrast, group C displayed the lowest levels in time spent thinking about pain, pain unpleasantness, and worst pain variables and the highest levels of the fun variable (Table 6.5).

Table 6.5: Means and (Standard Deviations) for Time Spent Thinking about Pain, Pain Unpleasantness, Worst Pain, and Fun Variables Among Experimental Groups

Group	Variables			
	Time spent thinking about pain	Pain unpleasantness	Worst pain	Fun
Group A	1.65 (2.13)	3.95 (1.99)	6.10 (1.41)	2.70 (2.49)
Group B	0.70 (1.26)	3.05 (1.57)	5.10 (1.71)	3.30 (2.00)
Group C	0.65 (1.35)	2.80 (2.24)	4.05 (2.19)	5.45 (2.26)

Inferential analyses indicated a non- statistically significant difference in time spent thinking about pain [Welch's F (2, 36.67) = 1.73, p = 0.19, $\eta p2$ = 0.077] and pain unpleasantness variables [F (2, 57) = 1.92, p = 0.16, $\eta p2$ = 0.063]. Nevertheless, a statistically significant difference in worst pain [F (2, 57) = 6.49, p = 0.003, $\eta p2$ = 0.19] and fun variables [F (2, 57) = 8.18, p = 0.001, $\eta p2$ = 0.22] was revealed. In order to identify where the significant differences in worst pain and fun lie, Tukey's post hoc tests were subsequently consulted [71]. Regarding worst pain, pairwise comparisons indicated a statistically significant difference between group A and group C, [Mdf = 2.05, 95%CI [0.68, 3.42], p = 0.002]. Concerning fun, a statistically significant difference between group A and group C, [Mdf = -2.75, 95%CI [-4.47, -1.03], p = 0.001], as well as between group B and group C, [Mdf = -2.15, 95%CI [-3.87, -0.43], p = 0.011], was identified (Figure 6.6 for significant differences).

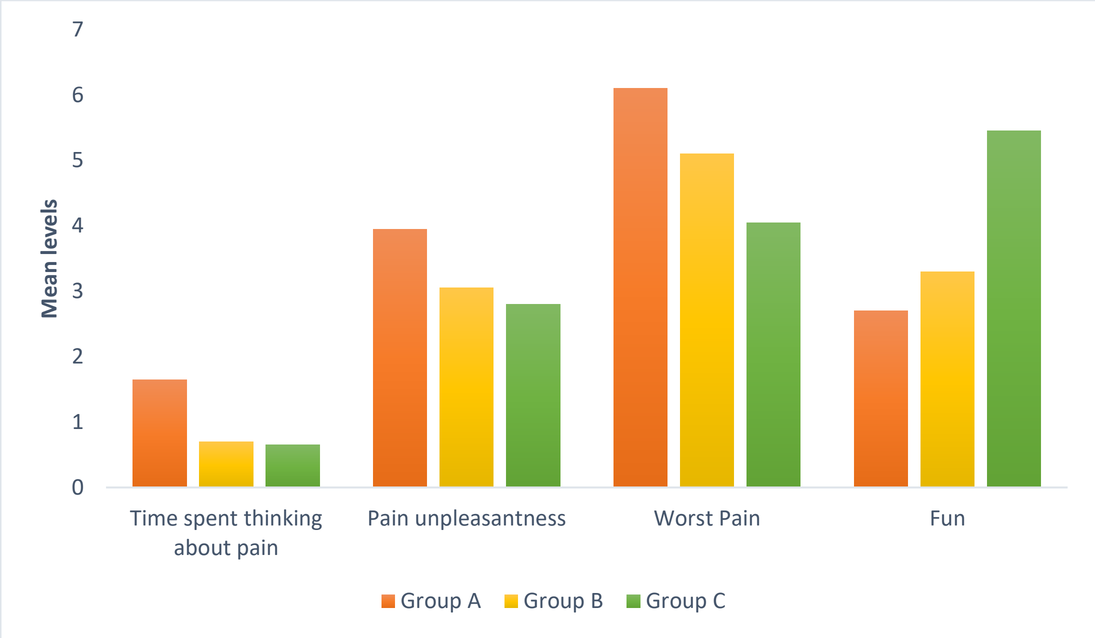

Figure 6.6: Mean differences in experimental experience among groups (second treatment)

To sum up, findings showed that group A reported the most negative experiences, whereas group C displayed the most positive experiences. It was also observed that group B reported less negative experiences than group A and less positive experiences than group C.

Independent samples t-tests. Three independent samples t-tests were conducted to assess if there are any statistically significant differences in dizziness, presence, and realism variables between group B (n = 20) and group C (n = 20). Descriptive statistics showed a minor difference in dizziness [Mdf = 0.050, 95%CI, -0.25 to 0.35] and realism variables [Mdf = -0.65, 95%CI, -1.93 to 0.63], while a substantial difference in presence variable, [Mdf = -1.50, 95%CI, -3.05 to 0.046], was identified.

Particularly, group B displayed higher levels in dizziness variable, whereas group C reported higher levels in the presence and realism variables (Table 6.6).

Table 6.6: Means and (Standard Deviations) for Dizziness, Presence, and Realism Variables Between Group B and C

Group	Variables		
	Dizziness	Presence	Realism
Group B	0.15 (0.49)	3.75 (2.02)	3.30 (1.98)
Group C	0.10 (0.45)	5.25 (2.75)	3.95 (2.01)

Inferential analyses indicated non-statistically significant differences in dizziness [t (38) = 0.34, p = 0.74, d = 0.11], presence [t (38) = -1.97, p = 0.057, d = -0.64], and realism variables [t (38) = -1.03, p = 0.31, d = -0.33]. However, it should be stressed that a large effect size was reported for presence variable. Thus, it may be speculated that group C displayed higher presence levels than group B.

6.3.3 Between-Subjects' Design (Third Treatment)

In order to examine if there is a statistically significant difference in analgesia levels among experimental groups, where group A exposed to first setting (No VR), group B exposed to third setting (VR + eye-tracking) and group C exposed to second setting (VR + No eye-tracking), four one-way between subjects' ANOVAs and three independent samples t-tests were conducted. One-way between subjects' ANOVAs were employed to investigate if there is a statistically significant difference in analgesia levels among the three experimental groups, as assessed by the variables time spent thinking about pain, pain unpleasantness, worst pain, and fun. Independent samples t-tests were used to determine if there is a statistically significant difference in analgesia levels between group B and C, as evaluated by the variables: dizziness, presence, and realism.

Assumption testing. Before proceeding with the inferential analyses, their relevant assumptions were explored. One-way between subjects' ANOVA requires approximately normally distributed data and homogeneity of variances. Normal Q-Q plots revealed approximately normally distributed data in all experimental groups for all variables, although a less satisfactory distribution was observed for time spent thinking about pain variable. However, considering that ANOVA is robust to deviations from normality when group sizes are equal, no further action was deemed necessary [71].

As far as independent samples t-test is concerned, approximately normally distributed data and homogeneity of variances should be present. Normal Q-Q plots displayed approximately normally distributed data in the presence and realism variables for both groups. However, normal Q-Q plots, in conjunction with the Shapiro-Wilks normality test, suggested a non-normal distribution in dizziness variable for group two (S-W < 0.001). Nevertheless, considering that independent samples t-test is robust to deviations from normality in equal group sizes, no further action was deemed necessary [71]. It should be also stressed that in group C, all participants reported dizziness values of 0, which entails that no standard deviation was calculated for this group.

One-way between subjects' ANOVAs. Four one-way between subjects' ANOVAs were conducted to assess if there are any statistically significant differences in time spent thinking about pain, pain unpleasantness, worst pain, and fun variables between group A (n = 20), group B (n = 20), and group C (n = 20). Descriptive statistics showed that group A reported the highest levels in time spent thinking about pain, pain unpleasantness, and worst pain variables and the lowest levels of the fun variable. In contrast, group B displayed the lowest levels in time spent thinking about pain, pain unpleasantness, and worst pain variables and the highest levels of the fun variable (Table 6.7).

Table 6.7: Means and (Standard Deviations) For Time Spent Thinking about Pain, Pain Unpleasantness, Worst Pain, and Fun Variables Among Experimental Groups

Group	Variables			
	Time spent thinking about pain	Pain unpleasantness	Worst pain	Fun
Group A	2.20 (2.46)	4.50 (2.01)	6.55 (1.54)	2.60 (2.64)
Group B	0.35 (.59)	2.15 (1.39)	3.80 (1.74)	5.55 (2.33)
Group C	0.50 (1.28)	3.55 (2.40)	4.95 (1.70)	4.05 (2.24)

Inferential analyses indicated statistically significant differences in all variables among experimental groups. Particularly, a statistically significant difference in time spent thinking about pain [Welch's F (2, 30.68) = 5.24, $p = 0.011$, $\eta p2 = 0.22$], pain unpleasantness [F (2, 57) = 7.16, $p = 0.002$, $\eta p2 = 0.20$], worst pain [F (2, 57) = 13.84, $p < 0.001$, $\eta p2 = 0.33$], and fun variables [F (2, 57) = 7.50, $p = 0.001$, $\eta p2 = 0.21$], was revealed. In order to identify where the significant differences lie, post hoc procedures were subsequently consulted.

In reference to time spent thinking about pain variable, Games-Howell post hoc test showed a statistically significant difference between group A and group B, [Mdf =

1.85, 95%CI [0.42, 3.28], p = 0.010], as well as between group A and group C, [Mdf = 1.70, 95%CI [0.17, 3.23], p = 0.027]. Regarding pain unpleasantness variable, Tukey's post hoc test indicated a statistically significant difference between group A and group B, [Mdf = 2.35, 95%CI [0.85, 3.85], p = 0.001].

Proceeding with worst pain variable, Tukey's post hoc test revealed a statistically significant between group A and group B, [Mdf = 2.75, 95%CI [1.49, 4.01], p < 0.001], as well as between group A and group C, [Mdf = 1.60, 95%CI [0.34, 2.86], p = 0.010]. Lastly, concerning fun variable, Tukey's post hoc test showed a statistically significant difference between group A and group B, [Mdf = -2.95, 95%CI [-4.78, -1.12], p = 0.001] (Figure 6.7 for significant differences).

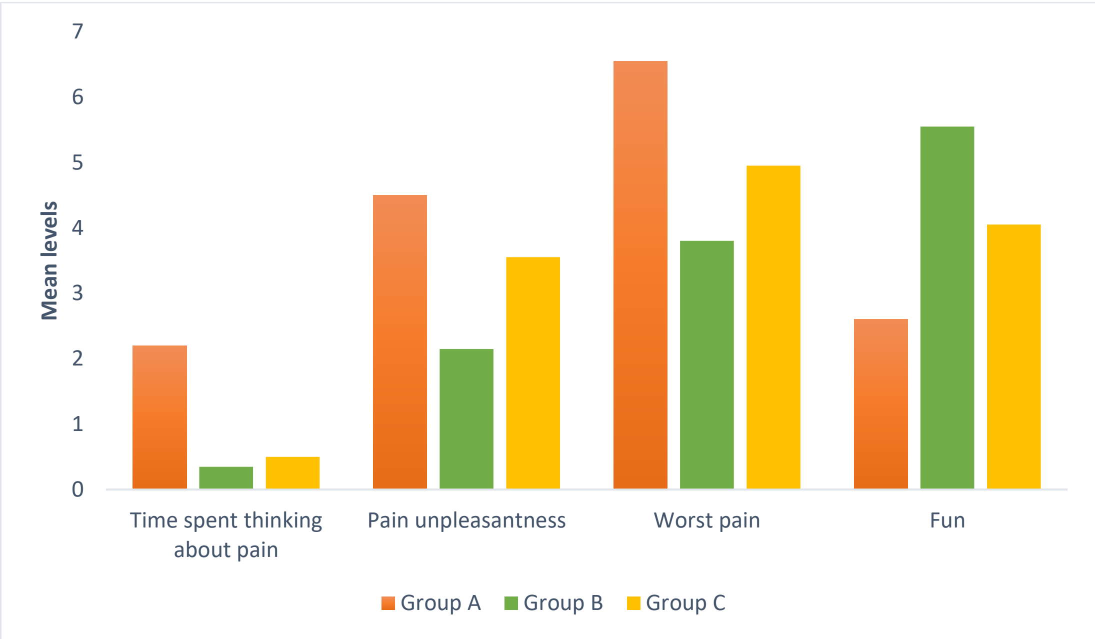

Figure 6.7: Mean differences in experimental experience among groups (third treatment)

Overall, results suggested that group A reported the most negative experiences, whereas group B displayed the most positive experiences. It was also observed that group C reported less negative experiences than group A and less positive experiences than group B.

Independent samples t-tests. Three independent samples t-tests were conducted to assess if there are any statistically significant differences in dizziness, presence, and realism variables between group B (n = 20) and group C (n = 20). Descriptive statistics showed a minor difference in dizziness variable [*Mdf* = 0.40, 95%CI, -0.23 to 1.03] and substantial differences in presence [*Mdf* = 1.50, 95%CI, 0.034 to 2.97] and realism variables [*Mdf* = 1.15, 95%CI, -0.37 to 2.67], with group B displaying higher levels in all variables (Table 6.8).

Table 6.8: Means and (Standard Deviations) for Dizziness, Presence, and Realism Variables Between Group B and C

Group	Variables		
	Dizziness	Presence	Realism
Group B	0.40 (1.35)	6.20 (2.33)	4.90 (2.65)
Group C	0.00 (0.00)	4.70 (2.25)	3.75 (2.05)

6.4 Discussion

The present study was completed to assess the effect of three experimental settings on analgesia levels across one within subjects and two between subjects' designs. Specifically, the first setting involved (No VR) distraction, while the second and third settings involved VR with a different configuration. In the first subject design test, all participants were exposed to all experimental settings. In the second and third design tests, each participant was randomly allocated to one of three groups. Group A was exposed to (No VR) only, while group B was exposed more to (VR + No eye-tracking) and afterward to (VR + eye-tracking). Conversely, group C was exposed to (VR + eye-tracking) and then to (VR + No eye-tracking).

The researchers speculated that exposure to the first setting (No VR) would lead to pain stimulus as a control group, whereas exposure to the second and third settings would result in a higher analgesia effect. Findings consistently supported the aforesaid hypothesis. To elaborate, in all tests, it was shown that participants with (No VR) concentrated the highest levels of negative experiences and the lowest levels of positive experiences. In contrast, it was observed that, independently of exposure order, the third setting (VR + eye-tracking) was the most effective analgesic setting, as it elicited the lowest levels of negative experiences and the highest levels of positive experiences. VR immersive systems were found to be efficient analgesic treatment at different levels as they are influenced by interactivity [16][50]. Although the interactivity with eye-tracking in this study was limited by selecting and shooting the visual objects, the reduction in pain components and increasing of fun was significantly approved among a non-interactive setting. This results of the current study are consistent with an attentional mechanism of how VR reduces pain [72][73].

Moreover, in VR components, statistically significant differences were reported in presence in two experimental designs: within subjects and between subjects (third treatment). Contrary to expectations, the independent t-tests were employed for between subjects (second treatment) and between subjects (third treatment) to assess VR components' variables did not show similar inferential analysis even though the descriptive analysis of both tests showed the same inclination. That results may due to the small sizes of the groups, which did not allow for statistical significance to be obtained. Overall, it is noticeable in this study that eye-tracking is effective in presence, which is distinctive among other interaction modalities that did not associate with presence in previous studies [16][61]. It is important to bear in mind that eye-tracking in this study employed one interaction technique, therefore adding more interaction and control techniques by eye-tracking could result in more strong illusion of presence [13] which is the main factor influences the analgesia of VR [14]. Unfortunately, the role of eye-tracking in presence is difficult to in at this point and several important issues remain for future research.

In addition, for the advantage of eye tracking to increase analgesia effect for immobile patients, we suggest using eye-tracking in both perspectives as an input device and an assessment method within VR analgesia systems which may indicate cognitive differences associated with the VR components or with pain components. Another advantage of using eye tracking is that it allows assessing studies' variables with other instruments or modalities, as a complementary tool, to perceive cognitive and physiological signs that are important to furthering our understanding of the efficiency and the role of different VR settings. Nevertheless, this research did not compare the eye-tracking as an interaction modality to other modalities, or with different eye-tracking interaction techniques.

Limitations. Although the within-subjects study design reduces noise variance and increases statistical power, for the within-subjects' analyses, in the current study, the researchers and subjects were not blinded to the treatment condition, an important limitation [74][75]. When participants in the current study received their second VR experience (during Third treatment), at that point, participants now had enough information to figure out what the study was about, and that awareness could potentially have influenced/biased participants' pain ratings during their second virtual experience (Third treatment VR condition). However, on the positive side, the current study provides converging evidence from both the within-subject analysis and the between groups analysis, supporting the primary hypothesis.

Chapter VII

Eye Movement within Virtual Reality- Fixation Detection

This Chapter investigates the eye movements in VR. It also presents a demonstration of the application of a proposed eye fixation detection algorithm to eye movements recorded during eye gaze input within immersive VR, and compares it with the standard frame-by-frame analysis for validation.

7.1 Introduction

7.1.1 What is eye movement

Analysis of eye movement data recorded by eye trackers has been shown to be a valuable tool for diagnosis and psychological research mainly into cognitive processes including attention, perception, performance and decision making. Early eye-tracking studies investigated image perception and text reading, where human eye movement data were collected and then analysed offline to detect the oculomotor events for assessing and interpretation. Eye-tracking technology is increasingly being used as a complementary tool with other modalities, such as eye tracking with EEG, to improve methodology or increase the certainty of psychophysiological measures by providing more information about the individual's behavior and how they process information. Also, a considerable amount of literature showed that using eye tracking is a successful method for measuring critical aspects in clinical diagnosis and medicine [76][77][78].

Eye gaze provides a natural input modality for interacting with computers and provides more potential attention than traditional input modalities, which has led to increased interest in eye tracking within the HCI field. There are two main streams in HCI regarding eye tracking usage: active gaze and passive gaze. Active gaze indicates the use of real-time gaze, where the eye gaze is used as a computer interface controller to provide a convenient input modality for individuals, primarily to aid disabled people when interacting with computers. Different methods were applied to select and generate user actions by detecting eye movements and other eye features. Active gaze can also be combined with other hand or foot input modalities [79] to tailor a system and accomplish the desired goal. On the other hand, with the advances of technology, eye tracking can use passive gaze to evaluate UX by studying the perception of digital contents in games, websites, learning content and more. Also, UX can be enhanced by passive gaze, or what is also known as gaze-contingecy, where changes are applied in the display at the user focal point in response to the user's eye movements – such as in foveated rendering [80], to reduce the computational cost of generating high resolution 3D graphics in the display area, or in designing adaptive response environments [81][82], where the user is enabled to interact with the environment at a high response level by predicting the user's intention based on his/her eye movements.

Most eye movement studies use classical 2D stimuli and visualization, but 3D studies are growing, and many approaches and proposals already exist to deal with different eye-tracking devices interacting with VR stimuli. Next, this study will investigate whether eye movement analysis techniques are useful for new 3D studies.

7.1.2 Eye movement analysis

During the eye-tracking experiment, the data sample is represented as a stream of data that exhibits specific behaviors which can be used to detect oculomotor events. The oculomotor events can be detected using defined general principles observed and accumulated through decades of research, which have led to statistical descriptions of ocular events which can be used to identify the eye movement behavior. It is important to determine specific limits or thresholds before the detection of eye movement events. These thresholds of eye movement event detection have no standards or accurately defined values, but can be determined by trial and error, or by experience, or taken from literature in the same paradigm, which may lead to subjective results whether the analysis is performed manually or algorithmically [23][30][83]. However, algorithms aid in accurate identification of the events, reduce biases and are cost effective. The proposed and designed algorithms in eye movement research are based on general principles for detecting oculomotor events. The gaze coordinates (x, y) for a given stimulus display are calculated and represented as a data sample, and based on the spatial and temporal characteristics of these gazes, events can be detected. Frequent events include fixations and saccades, along with their associated characteristics such as fixation duration and saccadic amplitudes. Fixation is represented as a group of consecutive gaze points resulting from the eye stopping to look at a target, where the fixation duration is the time window between onset and offset of a fixation, which in most studies is bounded between 200 and 400 ms and rarely less than 100 ms. A saccade is represented as spaced-out gaze points where no visual processing can occur because of the rapid jumps in the eye movement toward a target.

The spatial characteristics of eye movements are the velocity and dispersion of eye gazes, and the duration (which is a temporal characteristic). To measure the velocity, it is required to sample gaze data at a high rate. This allows the velocity between consecutive gaze points to be calculated. Then, thresholds can be applied to this velocity to detect and classify events. Fixations are indicated by low velocities between consecutive gaze points (<100 °/s), while saccades are indicated by high velocities (>300 °/s)[30]. Dispersion is also used to identify fixations and saccades because tightly clustered data points tend to indicate a fixation, whereas data points (which are more widely spread spatially) tend to indicate a saccade.

Sometimes, specific oculomotor events other than fixation need to be detected, depending on the research paradigm and the domain of the application such as pupil size and eye closure. However, in eye movement research, detection algorithms are often not described clearly, and their measurements rely mainly on the hardware specification and the research objectives. This makes it challenging to perform a meaningful comparison of algorithms for movement detection. To address this problem and create a road map of algorithmic validation, Salvucci and Goldberg [83] proposed a novel classification of fixation identification algorithms based on the principal techniques used in implementations of these algorithms.

On the other side, the majority of eye movement research utilizes commercial analysis tools provided by the eye tracker manufacturers. In commercial software, the detected oculomotor events, mainly fixations, represented using different gaze visualization techniques include scan paths, areas of interest (AOI), and attentional or visual maps.

Attentional maps: visual form representations based on different aspects of eye movement data, such as spatial or temporal characteristics, which facilitate information perception such as in gaze plots and heat maps.

AOI: refers to the selection of segments or sub-regions of the displayed content, depending on the study hypothesis, to distinguish what is more interesting for individuals by labeling the gaze points associated with the selected segment and studying the duration threshold to determine the numbers and duration of fixations on those segments.

Scan path: shows a time-ordered set of eye movements where a sequence of saccades can be represented as connected lines between successive fixations represented as circles.

7.1.3 Eye movements in 3D virtual reality

VR technology provides the opportunity to conduct, in realistic environments, experiments which would be very expensive or unsafe to conduct in real environments. Thus, the ability to use eye tracking and detect oculomotor events within these environments will open a new door for researchers to dig deep inside human behavior and UX, to support training and education, and many other applications, in safe and convenient environments.

On the other hand, despite all the advantages of VR for scientific research, creating these environments is still a significant issue that consumes a lot of time and effort, as a given research goal typically requires specific visual objects and characters. Also, studying eye movements within a specific scientific experiment necessitates defining the visual behavior to be measured and its significance to the research questioned: primarily, the eye metrics, such as fixation or pupil size, and their characteristics that are associated with the visual behavior. Consequently, combining VR environments with eye-tracking technology will increase complexity and will be time-consuming.

One of the possible solutions to reduce the time and cost in such a complex environment is to use off-the-shelf components and suitable VR environments from previous related studies. However, eye-tracking studies have mainly represented the gaze coordinates as (x, y) on 2D display representing the contents of the environment. This means that the tools available for visualization and analysis in this context are not adequate for analysis of eye movements in a 3D environment [84], as they can only be applied to scenes which are composed of frames. However, measuring and analyzing eye movements in an immersive VR is relatively new sub-field in eye-tracking research. In this area of research, the stimulus within the VR environment contains visual objects or scenes for specific purposes, and the experiment aims to test a hypothesis through objects which are known as objects of interest (OOI) or through specific AOI in the scene, similar to the principles of experiments with head-mounted eye-tracking systems. Eye-tracking studies in real environments are still time-consuming, as the display will be video recorded, and must then be examined manually such as frame-by-frame. The frame-by-frame analysis is an appropriate tool, acceptable in the analysis of eye movements on video records. However, it has a significant drawback for researchers conducting an eye-tracking experiment involving video recording, where the gaze coordinate must be checked in each frame to see whether it is located on a specific predefined AOI or not. This is very time-consuming so only small samples can be taken [85][86]. The same method of video recording and manual analysis is applied to eye movement within the VR environment [45][83].

Currently, there is an ongoing effort to develop eye-tracking systems that are adequate to emerge with immersive VR. In 2018, embedded 60-120 Hz eye trackers in high-performance HMDs appeared on the ground: these are FOVE [59] eye tracking VR headset, SMI [27] and Tobii [26]. These HMDs with embedded binocular eye trackers (HMD-ET) include multiple infra-red sources and use the pupil-corneal reflection technique to measure the distance from the corneal reflected light "glint" to the extracted pupil center, then calculate the gaze direction by measuring the changing distance between the glint and the moving pupil center to allow free tracked head movements in the helmet. The accuracy and reliability of these new devices depend on all the hardware and software technologies utilized to build these systems. Until now, this emerging technology has been still in development, and there are many challenges for researchers in designing adequate environments and software tools for analysis and visualization of eye movements that utilize and take advantage of such technology. Unfortunately, this technology also has no technical limitation on producing massive quantities of hardware and tools with a variety of techniques same as the previous eye-tracking systems [87], and most manufacturers do not disclose the algorithmic solutions in their products. Therefore, the difficulty of comparing studies of eye tracking in 3D will continue, just as in 2D classical studies.

Unlike eye tracking in a classical 2D environment, several streamed data can be generated using HMD-ET that can be used for more in-depth analysis of eye movements and additional understanding of human behavior compared to classical 2D. Point of regard (POR) for example, is the gaze point mapped on the projected image on an HMD screen, identical to 2D gaze, but with a 3D vector ray-casting representing the direction from a virtual camera origin for both eyes to the POR. Another example is 3D vectors representing the actual direction of both eyes when looking at the physical world and their origins at the center of the eye's balls. Currently, reading these streamed data is only possible by creating a client-side file dump [27].

This research proposes a simple methodology to detect eye fixations and OOI using HMD-ET in current VR environments. To validate the proposed algorithm's analysis of eye movements within VR, its outcome was compared with a frame-by-frame gaze location analysis outcome.

7.2 Methodology

7.2.1 Hardware and software requirements specification

The hardware requirements are: msi laptop with GeForce GTX 1080 8 GB, Intel Core i7 7th Gen (2.80 GHz), 16 GB RAM, connected to HMD from VIVE HTC [66] with the FOV 110 degrees and 1080 x 1200 pixels per eye resolution and refresh rate 90 Hz. The HMD integrated with a pair eye tracker from SMI which track the subjects' gaze in the 3D environment with a typical accuracy of 0.5° [27]. This tracker works with the SDK C++\C# for various VR engines. The setting platform is Windows 10 operating system, and the used 3D application development tool is Unity. Therefore, eye-tracking data were recorded in Unity VR engine concerning the origin coordinate at the upper left corner of the HMD screens as set by SMI plugin documentation [27]. The recorded eye-tracking data was sent to a dump file which was processed by the implemented proposed algorithm in Matlab. Tools used for video recording and manual analysis are ApoweREC [88], Kinovea [89] and MS Excel. Finally, SPSS was employed for statistical tests.

7.2.2 Participants

Five participants, three males, and two females, age 26 ± 8.2 years (Mean ± SD), volunteered in the experiment. All participants are healthy, with no motor or neural abnormalities.

7.2.3 Stimuli

The task scene is a VR environment used to demonstrate gaze interaction with Unity provided by SMI [27] including an eye-tracking plugin. The scene is presented as a room with cube-shaped objects on the walls (Figure 7.1). Although in VR all visual objects are named, some of the cubes were defined ahead as OOI (i.e., MiddleObj, CornerObj, RightMidObj, LeftObj, LeftMidObj, and BackObj) for the purpose of comparison between the eye movement analysis methods. The eye-tracking plugin software represented the participant's gaze point on the display as a small pointer-like blue circle (gaze cursor).

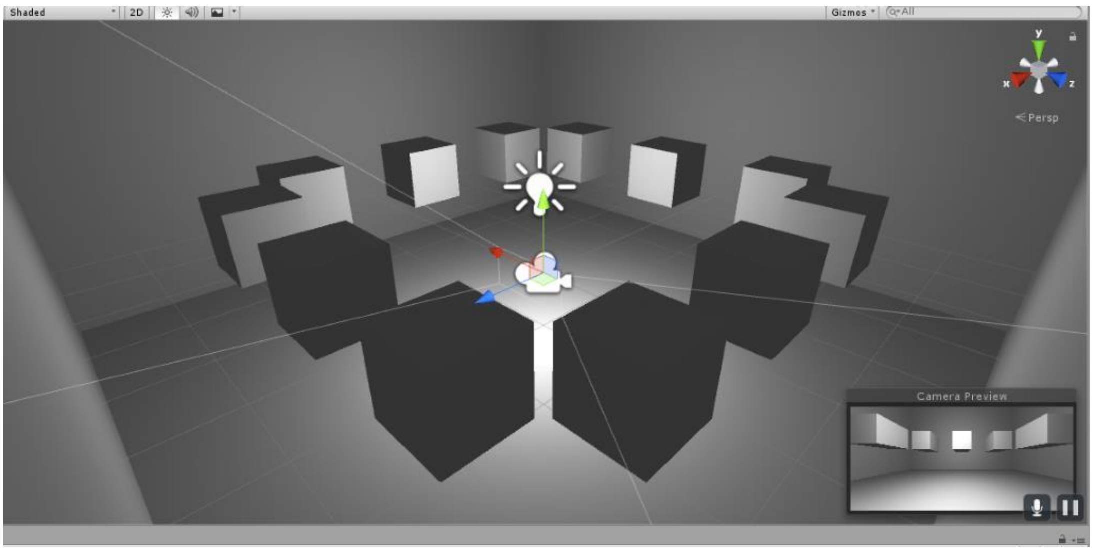

Figure 7.1: The Scene with OOI

7.2.4 Experiment procedure

Each participant was given a brief explanation of the simple task that they would be required to complete, in which they wear the helmet, complete the calibration procedure and look around for one minute, fixing their gazes on the objects on the walls freely and unaware of the defined OOI. After each participant understood the instructions for the task, the HMD-ET was adjusted to the participant and then calibrated. We used a standard calibration procedure where each participant was instructed to stare at a red point which appears at the beginning and keep tracking its movement. Once the calibration procedure has succeeded, the virtual room was presented to the participant's view.

In each participant session, in the same order, the eye-tracking data streams were recorded in a dump file during the experiment. A complete video recording of each participant's view contents was also saved. When a task was completed, the dump file was analyzed offline using the proposed algorithm, and the video record was analyzed using the manual gaze location detection in the frame-by-frame analysis.

7.2.5 Eye movement data analysis methods

7.2.5.1 *Proposed dispersion-based algorithm*

The proposed methodology to detect fixation and OOI in VR environments using HMD-ET is based on several of the previously known principles in the literature. The main steps of the proposed algorithm are reading streamed data, denoising, fixation detection, and OOI hit detection. Eye tracking data stream collected into the dump file consists of the following:

- POR contains a list of triplets (t, x, y), where (x, y) is the gaze coordinates on the display of the projected image acquired at a time t.
- A 3D vector of ray-casting originating from the participant’s eye to which determine where the participants are looking at a time t.
- OOI hit information at a time t.

The algorithm was implemented in Matlab according to the previously determined measures.

Measurements used in the implementation

In streamed eye movement data, there is always some noise or undesirable data depending on factors such as the equipment used and the environment. Therefore, denoising is essential to remove such data. Here, to denoise the data, blinking data were eliminated. When a participant's eye is closed, the pupil diameter is zero, so the tracker returns coordinates (0,0). Also, any data points outside the boundaries of the environment were eliminated.

To detect gaze fixation, we used the concept of dispersion-based on its usage in 2D fixation detection. Choosing a suitable threshold depends on the hardware and the experiment specifications. Here, an HTC HMD was used with FOV of 110 degrees and a resolution of 1080 x 1200 pixels per eye. In most HCI eye-tracking studies, the typical fixation size is one degree, so to convert the threshold of one degree into pixels using Pythagoras theorem, one degree is approximately equivalent to 15 pixels in this display. The precision of the fixation size, which can be determined by dispersion between the coordinates of successive concussive gazes, can be varied depending on the required task and the virtual objects in the VR.

The distance between two concussive gazes is calculated using the Euclidean distance of the gaze coordinates (x, y) as follows:

$$Distance = \sqrt{(\mathrm{x2} - \mathrm{x1})^2 - (\mathrm{y2} - \mathrm{y1})^2} \quad (1)$$

According to the literature, the minimum duration of fixation is 100-250 ms. Again, the duration can be varied depending on many factors, such as stimulus complexity and the required task to be accomplished. The HMD used has a 90 Hz refresh rate, which means 90 gazes recorded per second, so nine gazes can be recorded in 100 ms.

Consequently, when more than nine gazes are found within the determined threshold (15 pixels), it forms a cluster, which represents a fixation within the corresponding timestamp. The 3D vector of ray-casting originating from the participant's eye is traced to check if an OOI is hit when the event occurs. When fixation forming coincides with the ray-casting hitting the OOI, the fixation is assigned to the OOI.

The output of the algorithm

In addition to the detection of the start and end time, and number of gazes in each fixation, the proposed algorithm was able to detect small fixations that are difficult to detect manually. It also; shows the corresponding OOI that was fixated on. Table 7.1 shows a sample of a subject eye movement data analysis result.

Table 7.1: Sample of a Subject Eye Data Analysis Results

Fixation number	Start time	End time	Number of gazes	VR gazed Object
1	5044993648	5544835018	46	MiddleObj
2	5556967656	5868983875	29	MiddleObj
3	5884932396	6172970413	27	Wall
4	6340949537	6977161453	58	Wall
………	………	………	………	………
……….	………	………	………	………
29	16885017742	17452929603	52	LeftObj
………	………	………	………	………
42	21744883050	22213063436	43	RightMidObj
………..	………	………	………	………

The graphical representation of the timeline shows the gazes in the X and Y plane during a time slot and the corresponding 3D vector of the ray-casting direction in the 3D environment (sample shown in Figure 7.2).

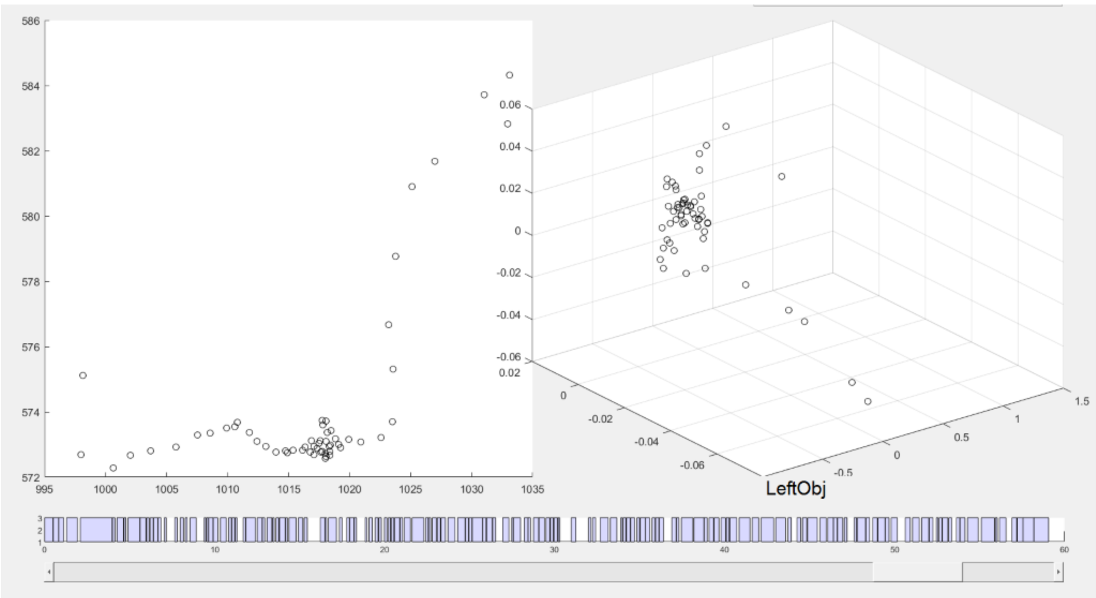

Figure 7.2: Gaze direction and POR gazes in the selected timeslot

7.2.5.2 *Frame-by-frame analysis*

The video software Kinovea used for the frame-by-frame analysis shows 1800 frames per one minute for each participant's view content. Each frame was checked for the gaze cursor location and was coded into a spreadsheet by assigning the gaze to one of the predefined visual objects that overlay the gaze cursor. When the gaze cursor was located outside those OOI or when there was no signal for the gaze cursor, it was assigned to None OOI (Figure 7.3).

The minimum fixation threshold implemented in the first method was 100 ms, which is equivalent to 3 frames of 1800 frames per minute. Therefore, at least three consecutive frames should be encoded for the same OOI to form a fixation, and the number of frames indicates the length of the fixation duration. Please see Appendix D for more output detail.

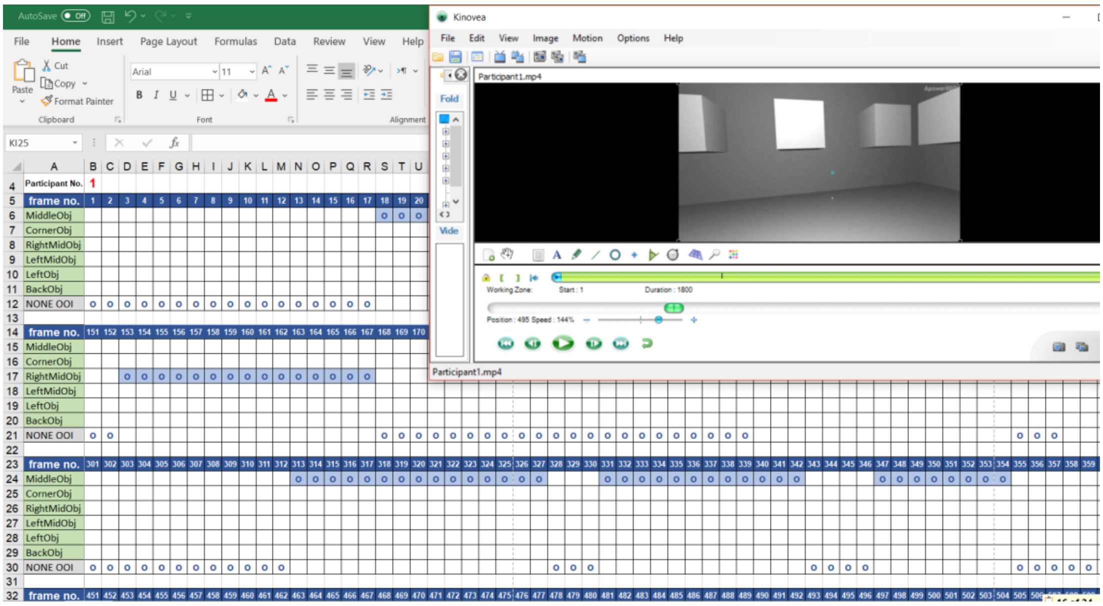

Figure 7.3: Frame-by-frame analysis spreadsheet

7.2.6 Comparison method

Summary of both analysis output is shown in Table 7.2. The number of fixations in the frame-by-frame analysis is much less than in the algorithm, as long fixations were recorded in the frame-by-frame analysis in cases where there were several consecutive small fixations on the object which only can be detected by the algorithm. Also, sometimes consecutive fixations were found in the frame-by-frame analysis due to the absence of the gaze cursor signal. To compare between the two methods, the total duration of fixations on each corresponding OOI for each participant was calculated in MS Excel, using the number of frames in frame-by-frame analysis and using the number of gazes in the proposed algorithm (see Table 7.3). The fixation durations were compared in SPSS to validate the proposed algorithm with frame-by-frame analysis using a Pearson correlation and a paired sample t-test.

Table 7. 1: Number of Fixations on OOI for Participants

Participant No.	OOI Name	No. of fixation (algorithm)	Total gazes	No. of fixation (manual analysis)	Total Frames
Participant 1	MiddleObj	22	667	17	233
	CornerObj	16	380	10	162
	RightMidObj	15	390	13	157
	LeftObj	19	622	8	140
	LeftMidObj	3	99	2	38
	BackObj	0	0	0	0
Participant 2	MiddleObj	21	887	11	322
	CornerObj	33	864	16	344
	RightMidObj	10	571	6	203
	LeftObj	14	351	8	178
	LeftMidObj	13	437	9	180
	BackObj	4	159	2	40
Participant 3	MiddleObj	26	1243	17	411
	CornerObj	26	894	16	391
	RightMidObj	24	1030	7	355
	LeftObj	12	293	8	135
	LeftMidObj	12	490	5	210
	BackObj	0	0	0	0
Participant 4	MiddleObj	23	1259	9	381
	CornerObj	33	1024	13	320
	RightMidObj	11	604	5	247
	LeftObj	13	824	5	266
	LeftMidObj	4	170	3	108
	BackObj	0	0	0	0
Participant 5	MiddleObj	11	496	8	196
	CornerObj	48	1270	19	461
	RightMidObj	7	124	1	8
	LeftObj	10	204	5	105
	LeftMidObj	2	171	2	30
	BackObj	0	0	0	0

Table 7.2: Total Duration of Fixations on OOI for Participants

	OOI	Frame-by-frame total durations	Fixation detection algorithm total durations
Participant 1	MiddleObj	7767	7411
	CornerObj	5400	4222
	RightMidObj	5233	4333
	LeftObj	4667	6911
	LeftMidObj	1267	1100
	BackObj	0	0
Participant 2	MiddleObj	10733	9856
	CornerObj	11467	9600
	RightMidObj	6767	6344
	LeftObj	5933	3900
	LeftMidObj	6000	4856
	BackObj	1333	1767
Participant 3	MiddleObj	13700	13811
	CornerObj	13033	9933
	R	11833	11444
	LeftObj	4500	3256
	LeftMidObj	7000	5444
	BackObj	0	0
Participant 4	MiddleObj	12700	13989
	CornerObj	10667	11378
	RightMidObj	8233	6711
	LeftObj	8867	9156
	LeftMidObj	3600	1889
	BackObj	0	0
Participant 5	MiddleObj	6533	5511
	CornerObj	15367	14111
	RightMidObj	267	1378
	LeftObj	3500	2267
	LeftMidObj	1000	1900
	BackObj	0	0

7.3 Results

Pearson correlations were carried out for each pair of OOI (e.g., MiddleObj in algorithm output versus MiddleObj in frame-by-frame output). The results for this analysis are shown in the Table 7.4.

Table 7.3: Pearson Correlations

Pair (OOI in algorithm – OOI in frame-by-frame)	**Correlation**	**Sig.**
MiddleObj - MiddleObj	0.984	0.003
CornerObj - CornerObj	0.929	0.022
RightMidObj - RightMidObj	0.980	0.004
LeftObj - LeftObj	0.808	0.098
LeftMidObj - LeftMidObj	0.940	0.018
BackObj - BackObj	1.000	0.000

Very significant and strong correlations are exhibited between the two methods. This indicates that both methods are very similar in terms of fixation duration. The exception to this is LeftObj, which exhibits a non-significant correlation ($p = 0.098$). However, the correlation coefficient is nevertheless strong ($r = 0.808$).

Proceeding with a t-test for evaluating differences across the two methods. This procedure is summarized in Table 7.5. No significant differences were found across both methods for any of the paired OOIs. As such, it can be said that the output of the proposed fixation detection algorithm and frame-by-frame analysis are statistically identical in terms of fixation duration.

The fixations duration percentage results of the fixation detection algorithm and frame-by-frame method, for the six OOIs in the analysis, can be found in Figure 7.4, confirming that the proposed analysis algorithm produces similar results of the frame-by-frame analysis.

Table 7.4: Paired Samples T-Test for The Proposed Algorithm and Frame-by-Frame Analysis

Pair (OOI in algorithm – OOI frame by frame)	Mean	Std. Dev.	Std. Error Mean	t	df	Sig. (2-tailed)
MiddleObj - MiddleObj	171.1	931.3	416.5	0.411	4	0.702
CornerObj - CornerObj	1337.8	1379.8	617.1	2.168	4	0.096
RightMidObj - RightMidObj	424.4	973.5	435.3	0.975	4	0.385
LeftObj - LeftObj	395.6	1698.7	759.7	0.521	4	0.630
LeftMidObj - LeftMidObj	735.6	1094.3	489.4	1.503	4	0.207
BackObj - BackObj	-86.7	193.8	86.7	-1.000	4	0.374

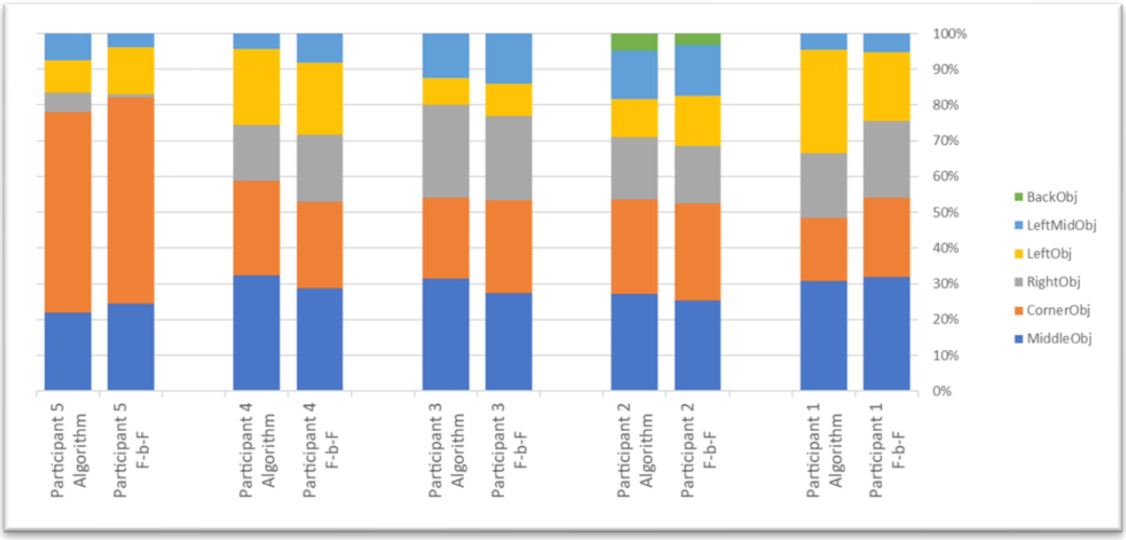

Figure 7.4: Duration percentage for OOIs in the fixation detection algorithm and frame-by-frame analysis

7.4 Challenges and limitations

Eye tracking within VR is a promising technology to provide users with a more natural and convenient way to interact than using traditional input methods. However, in both VR technology and eye-tracking technology, there are many challenges and barriers that holdback the accessibility and availability of these technologies. As expected, the integration of such technologies would lead to more challenges. Here we will discuss some challenges and limitations that may face eye-tracking systems within a VR environment.

7.4.1 Calibration

Calibration requires the users to fixate their eye gaze on reference sequence of points. The calibration data reflects some of the biometrics attributes of the individual's eyes and the eye tracker hardware geometry. With any application of eye tracking, calibration has always been identified as a very tedious task and an obstacle to usability for applications in daily-life. Recently, calibration-free gaze estimation eye tracking has become a hot topic in computer and technical research. The problem would be exacerbated in a 3D environment, therefore, many approaches have been proposed, such as by Vidal et al. [90], who proposed an innovative technique to determine OOI by simply matching eye pursuit movement to the object movement, which can suit interfaces with motion and does not require accurate calibration. More about how the speed and trajectory of this method impact the gaze accuracy has been investigated in [91]. Another approach is to predict gaze by using visual saliency in head-mounted eye trackers to reduce calibration drift, but in a constrained setting [92]. However, most of the studies in this area have aimed to improve the standard technique of points-based calibration.

7.4.2 Budget and cost

Despite the technological advances of eye-tracking systems, and the long-term studies in this field, designing eye-tracking experiment is still expensive. Integrating this technology with other expensive technology such as VR technologies will certainly put more pressure on research budgets. In fact, many factors can contribute to the cost of eye tracking in VR research, i.e., the hardware, software, skills, and experience.

Nowadays, HMD-ETs are very limited, and the prices vary ($600 – $50000), but so do their accuracy and reliability. These systems also impose specific requirements for the computers and devices connected to them.

For the software, designing a VR environment and the software to analyze eye movements or to design different eye gaze interactions techniques is very time-consuming and a monumental effort is required, as it needs to deal with the SDKs of the systems and many tools that mostly need expertise and competence. On the other hand, commercial analyzing software is also expensive and can increase the cost.

Lastly, dealing with eye tracking and eye movement research needs time to learn and acquire the required expertise to design and execute an experiment. In addition, eye-tracking technology within VR tends to be used in multidisciplinary research, requiring a team of researchers across several disciplines to conduct the research and obtain results that include scientific input.

7.4.3 Increased complexity

In classical 2D eye-studies some problems such as Midas touch and smooth pursuit detection are still undergoing investigation and researchers are working on solving these issues. Within 3D VR, the dynamics and complexities of these environments would increase the complexity of the previous problems and other problems. Eye tracking in VR is more than an interaction modality: it can be used for a human factor assessment or diagnosis [76][38], content evaluation [41][93][94], environment adaptation [81][82], or for foveating rendering [80]. Many of these applications of eye tracking require data recording and data analysis online or offline. Recording eye tracking data and other data from the system and performing the required calculations can slow down the VR environment. Also, when working with data from multiple sources, it is vital to ensure the data is perfectly synchronized, which is time-consuming and open to the risk of human error [46]. In some VR studies, it would be challenging to map the gaze fixations onto a geometrical model when dealing with 3D gaze [94][47].

Another important challenge that can have a big impact on eye tracking within VR is what is usually described as motion sickness, VR sickness or cybersickness. This is where some users experience symptoms or uncomfortable feelings when they are in a VR environment, such as dizziness, fatigue, eye strain, and nausea. Although researchers have proposed important developments and ideas to solve this problem [95][96], there is still no practical solution preventing VR sickness. This is why, it is so important to investigate the impact of VR sickness on eye movements and how it can affect the accuracy of the gaze, and hence the research result.

7.5 Summary

Eye movement analysis in VR is still a new research area among eye-tracking studies. We presented an initial investigation of eye gaze within the VR environment and demonstration of the proposed fixation detection algorithm within current VR environments using SMI HMD-ET. Continuation of the proposed algorithm development will be considered for future eye movement analysis study.

In VR, the position of a pixel within a projected scene will reflect different objects each time rendering occurs. One of the solutions to this issue lies in the ray-casting originating from the participant’s eye; it is a convenient technique for finding where the user is looking, thus providing the opportunity to study of user's gaze behavior in VR environments. This ray-casting can be utilized to get the hit information for an OOI, when it exists, and determine the gaze direction inside the VR world.

The results of the proposed algorithm indicate the possibility of utilizing the same principles of eye movement analysis algorithms that are applied to the spatial or temporal characteristics of gazes in 2D to study eye gaze behavior in a 3D environment, in conjunction with the time of events and ray-casting, in many applications. Nevertheless, further investigation into the data stream recorded by eye-tracking devices in immersive VR needs to be considered in future work to utilize these data streams efficiently.

To validate the proposed algorithm, the result of its analysis was compared with frame-by-frame manual analysis, which is employed and recognized as a tool to analyze eye movement data with the similar technology, of eye tracking-devices mounted on the head like eyeglasses — the results of both methods correlated very highly, using Pearson and paired t-tests. Nevertheless, there are many differences between the two methods that cannot be ignored. Despite the effort and time spent on the frame-by-frame analysis, it is not useful in determining an actual number of fixations and their spatial and temporal characteristics. With such drawbacks, algorithmic solutions for eye movement analysis are required. While this is difficult in the natural environment using head-mounted eye tracking, the integration of eye tracking with immersive VR represented in HMD-ET technology provides an alternative solution for many cases. With the tremendous advance of graphics, VR offers a safe and controlled realistic environment, which has allowed many costly or dangerous research studies to be transferred from nature to the laboratory and eye-tracking studies are not an exception with the emergence of this HMD-ET. Moreover, it opens the door for discoveries and research in different multidisciplinary fields.

Lastly, it is worth mentioning that many applications or studies require a precise selection of visual objects from within a dense visual field or an estimation of fixation depth, such as in joint attention and visual communication studies [97][94]. These requirements demand for a new paradigm and innovative approaches to analyzing eye movements within the depth of the virtual environment.

Chapter VIII

Conclusion and Future Work

In the previous chapters of this thesis, each topic's limitations and contribution have been introduced and discussed individually. This chapter will summarize the work done in this research and the future direction of eye tracking as an interaction modality and evaluation tool within VR pain distraction system.

In this thesis, a pain distraction VR system with eye tracking was designed and implemented to explore the feasibility of solving existing limitations in previous systems and to improve understanding of pain. This research has opened new opportunities that can help in many unexpected research areas and has expanded the usage of eye tracking beyond common uses in research.

The topic of eye tracking systems and related works were reviewed in Chapter 2 and Chapter 3. Chapter 4 presented a preliminary step towards the evaluation of people’s awareness of eye tracking and attitudes towards it among different categories of users. The results supported the usefulness of eye tracking and favorable attitudes towards it among most users, but the low response to the survey could also indicate negative attitudes toward eye-tracking research and a lack of awareness of the technology. The chapter ended with a short discussion about the limitations facing this technology as it expands.

In Chapter 5, technical requirements and implementation of a lab system were represented. The system was employed to examine the primary hypothesis of this thesis: to explore whether interacting with virtual objects in VR via eye tracking makes VR more effective compared to passive VR. In addition, the system was employed to design an algorithm as a step toward developing the system for the future scenarios mentioned in the chapter discussion section.

The experiment conducted to test the main hypothesis was presented in Chapter 6. The results showed that eye tracking increased the immersiveness of the VR system, which increased how effectively VR reduces acute pain. As predicted, interactive VR with eye tracking was significantly more effective at reducing participants' worst pain ratings in between-subjects and within-subjects designs. The results showed some differences in between-subjects and within-subjects groups analysis in some pain assessment tool variables. However, on the positive side, the research study provides converging evidence from both the within-subjects analysis and the between-subjects analysis, supporting the primary hypothesis.

A new method to detect eye fixations and OOI using HMD-ET in VR environments was presented in Chapter 7. The proposed algorithm's analysis of eye movement outcomes, within VR, was compared with a frame-by-frame gaze location analysis outcome for validation. A summary and a discussion of this methodology can be found in the last section of the chapter.

Whether the research results generalize to clinical patient populations is an important topic for future research, (e.g., whether eye tracking increases VR analgesia effectiveness for pediatric burn patients during burn wound care). In the laboratory thermal pain study of this thesis, eye movements were used to tell the computer what the participant was looking at in the VR. In future studies on VR analgesia systems, eye-tracking technology can also be used to collect data about the patient's current mental state. Nevertheless, collecting eye movement data in the VR environment is still challenging, and more investigation into the data stream recorded by different eye-tracking devices needs to be considered to utilize these data streams efficiently. In this thesis, we only implemented a fixation detection algorithm, but more algorithms would be required for different eye metrics that can be studied during pain experiments. For example, pupil size, fixations, saccades, eye blinking, and other eye movements may correlate with how much pain patients are consciously experiencing. For future work, we predict a large reduction in successful eye fixation on target objects in SnowCanyon when a burn patients pain becomes so extreme that the patient's attention shifts away from VR and onto their pain.

Additional research and development in the current system are recommended.

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Appendices

Appendix A – Awareness Questionnaire

Gender: ○ Male ○ Female

Age: -------

Q1 - Have you ever heard about eye-tracking technology?

○ Yes ○ No [if Q1 answer is NO, submit]

Q 2 -Do you know basic facts and theories within eye-tracking systems?

○ Yes ○ No

Q 3 -Do you think eye-tracking technology is useful?

○ Yes ○ No ○ I don't know

Q 4- Have you ever used eye tracking before?

○ Yes ○ No

Q 5 - Are you interested in knowing more about eye tracking trends in current research?

○ Yes ○ No

Q 6 - Do you work in research?

○ Yes ○ No [if Q6 answer is NO, submit]

[if Q6 answer is YES, go to RESEARCHER PART]

Researcher part:

Q7 -What is your research area ?

□ Computer Science and Technology

□ Neuroscience and Psychology

□ Engineering and Human Factors

□ Marketing and Advertising

□ Education and Training

□ Other………………………………………….

Q8 -Do you know that eye-tracking technology can be used in many research areas including the previous list in question 7?

○ Yes ○ No

Q9 -Are you interested on using eye tracker in your research when it is available?

○ Yes ○ No ○ Maybe

Q10- Have you ever used eye tracking before in your research?

○ Yes ○ No [if Q10 answer is NO submit]

[if Q10 answer is YES go to Eye Tracking Research part]

Eye-Tracking Research Part:

Q11- Please select the eye tracker/s you used:

□ Tower

□ Remote

□ Eye Glass

□ Head-mounted

□ Mobile Phone Eye Tracker

Q12- What is the value that eye-tracking technology adds to your research?

- □ Assessment
- □ UX and Usability
- □ Evaluation electronic content
- □ Data validation
- □ Biometrics and Security
- □ Understanding human behavior
- □ Other…………………………

Q13- How do you assess eye-tracking technology as a methodology in research at the following:

COST	○ low	○ medium	○ high
Difficulty of data collection	○ low	○ medium	○ high
Difficulty of data analysis	○ low	○ medium	○ high

Appendix B – Laboratory Pain Assessment Questionnaire

(1) How much TIME did you spend thinking about your pain during this most recent pain stimulus?

0	1	2	3	4	5	6	7	8	9	10

(0 = none of the time, 1–4 = some of the time, 5 = half of the time, 6–9 = most of the time, and 10 = all of the time).

(2) How UNPLEASANT was the most recent pain stimulus you just receive?

0	1	2	3	4	5	6	7	8	9	10

(0 = not unpleasant at all, 1–4 = mildly unpleasant,
5–6 =moderately unpleasant, 7–9 = severely unpleasant, and 10 = excruciatingly unpleasant).

(3) Rate your WORST PAIN during the most recent pain stimulus you just receive

0	1	2	3	4	5	6	7	8	9	10

(0 = no pain at all, 1–4 = mild pain, 5–6 = moderate pain, 7–9 = severe pain, 10 = excruciating pain).

(4) How much FUN did you have during the most recent pain stimulus you just receive?

0	1	2	3	4	5	6	7	8	9	10

(0 = no fun at all, 1–4 = mildly fun, 5–6 = moderately fun, 7–9 = pretty fun, 10 = extremely fun).

(5) To what extent (if at all) did you feel NAUSEA or DIZZINESS as a result of experiencing the virtual world during the most recent VR session?

0	1	2	3	4	5	6	7	8	9	10

(0 = no nausea at all, 1–3 = mild nausea, 4–6 = moderate nausea, 7–9 = severe nausea, and 10 = vomit).

(6) While experiencing the virtual world, to what extent did you feel like you WENT INSIDE the virtual world?

0	1	2	3	4	5	6	7	8	9	10

(0 = I did not feel like I went inside at all, 1–4 = mild sense of going inside, 5–6 = moderate sense of going inside, 7–9= strong sense of going inside, 10 = I went completely inside the virtual world).

(7) How REAL did the virtual objects seem to you during the most recent VR session?

0	1	2	3	4	5	6	7	8	9	10

(0 = Not real, 1–4 = mild sense of real objects, 5–6 = moderate sense of real objects, 7–9= the objects almost real, 10 = the objects seem real)

Appendix C – IRB Documentations

Request Approval

Najood Ali Al Ghamdi
PhD student, KAU
Nalghamdy0004@stu.kau.edu.sa
JANUARY 11, 2018

Dean of Graduate Studies and Research
Akila Sarirete, PhD
PO Box 34689
Jeddah 21478

Dear Dr Akila,

I ask your approval for my research entitled "**Virtual reality passive and eye tracking interaction during thermal pain**". In this study, participants will have to provide detailed information about level of pain and virtual reality presence after experiencing a tolerant temperature using thermal sensory device, with or without wearing a HMD with an embedded eye tracker to enter a virtual reality distraction game. I have checked the University's policies on doing research involving human participants, feel that my research processes will not result in any harm or discomfort for the participants. Furthermore, I have taken all precautions to guarantee that participants are safe, and their rights are respected.

The necessary 'informed consent forms' are prepared; thus, all participants will be required to formally, through signing this form, indicate their consent to participating in this study. Participants will be given the opportunity to withdraw from the research at any time prior to the publication of the research findings. The matter of how data will be collected and stored will be clarified for participants. The final thesis and possible significant elements of the project will be published and therefore openly accessible; however, no individual respondents will be identified or identifiable. The information provided by individual participants will not be made available to their employers or managers. Where key themes or ideas are drawn out, they will not be attributed to individuals. Similarly, individual case-study institutions or departments will not be named.

Yours Faithfully,

Najood Ali Al Ghamdi

Application for Approval for Use of Human Participants in Research

The following statements are of central concern to all Effat University researchers (all faculty, staff and students) as well as all external research collaborators.

This form must be completed for all research projects to be conducted at Effat University. That is, whether researchers will use human participants in their research or not; and whether researchers received grant money from Effat University or are conducting research on their own.

Objectives of the Research Ethics Guidelines

1. Increase the knowledge of those engaging in research, or considering doing so, as to the various ethical issues involved through and in conjunction with Effat University, and promote responsible conduct of research.
2. Raise awareness regarding local and international standards with regard to promoting responsible conduct of research.
3. Research should be conducted in accordance with universal ethical standards while taking into consideration core Islamic values, and the laws of the Kingdom of Saudi Arabia.
4. Ensure that all research conducted at Effat University is consistent with the Research and Ethical Guidelines. All research projects must be approved by the Research Ethics Institutional Review Board (REIRB).
5. Provide appropriate protection for researchers, research participants, and Effat University

Main Roles of the Research Ethics Institutional Review Board (REIRB)

This section introduces researchers to the main functions of the REIRB.

1. The REIRB is guided by the approved Research Ethics Guidelines for Effat University;
2. The REIRB is responsible for the fair promotion, review, and approval (or denial) of research proposals based on these Research Ethics Guidelines;
3. In cases where a research proposal requires changes (due to ethical considerations), the REIRB will help foster and support the revision process;

4. The REIRB will be responsible for reviewing the final research report. This will be handled in a separate document called the Research Project Completion Report (to be submitted to the REIRB).

Please provide the following information:

1. Name of faculty or staff members and/or student(s) conducting research
   Najood Al Ghamdi, PhD student

2. College, department, and major (or affiliation)
   KAU, VR Research Center, KACST

3. Research Advisor (required for students)
   Dr. Wadee Al Halabi, Associative professor

4. Purpose of the research
   The purpose of this research is to study the subjective experience of brief thermal stimuli with different settings of virtual reality environment.

5. Targeted population of participants with identified characteristics (if relevant)
   Healthy participants

6. Will you be using any forms of electronic media, recordings, or photographs that may reveal the identity of the participants? YES **NO (√)**

If yes, please explain how the confidentiality of the participant/s will be protected. In addition, give details regarding who will have access to these media.

7. What, if any, is the identified risk level to the participants, researchers, or Effat University?
   (Please mark one).

Minimal: []	**Moderate: [√]**	High: [ ]
No readily identified risks.	*Potential needs for debriefing related to minor physical or psychological distress.*	*Any research design where deception is used or possible follow up services may be needed for participants.*

In addition, what is the plan to minimize or control for these risks?
Possible side effects of participation include stress, discomfort, or mild nausea. If the participant experiences any of these side effects, we will try to relieve them. If this is not possible, we will end this case early.

9.a. Will your research involve human participants? **YES [√]** NO ( )

9.b. If yes, please submit a copy of the proposed informed consent form; If no, please explain why
Submitted.

10. Please submit a written research proposal in an appropriate discipline-specific format (MLA, APA, …), and any paper-based evaluations, assessments, inventories, or surveys that are to be used in conjunction with the research.
Submitted.

11. Discuss any assessment tools, instruments, assessments, or surveys that may be used with this research. Is special permission needed to utilize these tools (copyright, permission, or credentials)? If yes, please submit proof, or explain, how you have dealt with this issue.
Identical equipment and stimulus have been used in numerous published studies.
All the equipment and tools are available in VR research center and no more needed permissions, but all needed credentials will be cited in the research paper. The tools are:
- **Virtual reality environment (laptop, HMD, 3D game)**
- **Eye tracker (embedded in the HMD)**
- **Thermal sensory thresholds device (Medoc Q-Sense)**
- **Pain assessment questionnaire**

12. Briefly explain your proposed research methodology.
- **In this study, we are measuring participant’s tolerant temperature of a thermal pain. The pain stimulus is very brief where the baseline pain is 44º C threshold in the current study and applied to the participant's arm.**
- **The participant will randomly be assigned to one of three groups, two additional brief pain stimuli treatments in each group.**
- **Two of these groups will involve experiencing two different settings of virtual reality environment during the treatment while one group will not.**
- **The researcher will ask the participant to answer a pain rating questionnaire about how painful she found the stimulus.**

13. If deception is involved, discuss your plan for debriefing or any follow up services which may be needed by the participants after the data has been collected.
    Not relevant.

14. Identify any potential conflicts of interest, and provide a plan to address (minimize risk associated with) these conflicts should they occur (if relevant).
    Not relevant

15. Identify any outside organization, institution, or individual parties that will be collaborating with the applicant.
    KAU, Faculty of Computing and Information Technology.

This next section is to be completed by members of the REIRB:

Research Ethics Review Committee decision regarding research proposal

Approved	Provisionally Approved	Approval Denied

Suggestions and proposed modifications from the Research Ethics Review Committee to the researchers with regards to addressing any ethical issues or improvements to the research design.

If the proposal has provisional approval, please state the aspects of the project that should be changed to obtain approval. If the proposal has been denied, please provide an explanation for the denial.

<u>Signatures and Date of REIRB Committee Members</u>

Final Checklist for Submission:

Application For Approval For Use Of Human Participants In Research completed
Informed Consent Form (if applicable)
Research Proposal
Research Instruments (i.e. interview schedule, questionnaires, assessments and inventories, if applicable)
Copyright permission and/or credentials

معهد البحوث والاستشارات
Research & Consultancy Institute

جامعة عفت
EFFAT UNIVERSITY

Informed Consent Form for Participation in Research

I, (Name)__________________________, consent to my participation in the research project entitled **(Virtual reality passive and eye tracking interaction during thermal pain)**. The purpose of the research project has been explained to me.

I understand that my participation in this project will involve being tested for a thermal pain level under a tolerant temperature with or without wearing a HMD for a VR game, and participation in this experiment need to undergo the process three number of times for a period of 15 minutes. During my participation, I will be asked to provide detailed information about the level of pain and VR presence.

I understand that some of what I say during this study may be used in the analysis and writing of the final report (i.e. published research results).

I understand my anonymity and confidentiality will be preserved at all times, and that the comments and responses to questions that I give will be reported in general (i.e. without reference to me). I will not suffer any negative consequences as a result of my participation in this research project.

I understand the interview transcripts will be safely stored in a locked filing cabinet in the office of the principal investigator. Computer documents and software that contain confidential records about research participants will be stored in a password-protected folder on the chief investigator’s computer accessible only to him/her. Backup copies will be stored in a locked filing cabinet in his/her office.

I understand that I am free to withdraw and discontinue participation at any time.

I understand if I have any concerns about this research I can contact the chair of the Research Ethics Institutional Review Committee (REIRC) at Effat University.

Signed by:

....

Date ....

Proposed Consent Form

Virtual Reality passive and eye tracking interaction during thermal pain

Investigators

- Wadee Al-Halabi, Ph.D., Effat University, Kingdom of Saudi Arabia. walhalabi@effatuniversity.edu.sa
- Hunter Hoffman, Ph.D., Research Scientist at University of Washington, Seattle WA. hoontair@gmail.com
- Najood Al-Ghamdi, MSc., Ph.D. student at King Abdul Aziz University, Kingdom of Saudi Arabia.
  Nalghamdy0004@stu.kau.edu.sa;
  "Please be advised that we cannot guarantee the confidentiality of e-mail."

Investigator's statement
We are asking you to be in a research study. The purpose of this consent form is to give you the information you will need to help you decide whether or not to be in the study. Please read the form carefully. You may ask questions about the purpose of the research, what we would ask you to do, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. When all your questions have been answered, you can decide if you want to be in the study or not. This process is called "informed consent." We will give you a copy of this form for your records.

PURPOSE OF THE STUDY

The purpose of this research is to study the subjective experience of brief thermal stimuli perception in healthy volunteers. The Study will measure whether or not psychological techniques using virtual reality with different setting are effective in reducing the experience of pain.

STUDY PROCEDURE

If you agree to participate in this study, we will first briefly measure your tolerant temperature as your pain threshold (PHASE 1), and after that, you will receive brief thermal pain stimulation under two conditions.
PHASE 1. In this study, we are measuring participant's tolerant temperature of a thermal pain. Pain sensitivity will be assessed by using heat-pain thermal sensory thresholds device (Medoc Q-Sense) briefly applied to your arm. We will measure the temperature threshold and how much heat is applied to your arm before you identify that the heat is painful. In other words, the researcher will place a small bar with a

metal plate connected to the device (thermode) on your arm, as shown in the photo below. With your permission, the researcher will start a computer software which controls the device signals and temperature thresholds to heat the thermode. When the thermode is heated up to a predefined threshold, the heat continues for 10 seconds then cools down. immediately after the thermode is cooled down or if you stop the heat stimulus when you said "stop", the researcher will ask you to answer a few quick pain ratings. Subsequently, you will choose to increase the temperature of the previous treatment (by 0.5^{o} to 1^{o} C) and undergo a new treatment or to stop and choose the last temperature as your tolerant temperature threshold. If you choose to continue, you will be assigned to another treatment with higher temperature threshold. The procedure will be repeated till you decide to "stop" or the researcher will stop when the temperature reaches 47^{o} C regardless you ask to continue.

You are free to stop the thermal pain treatment and study at any time if you decide you don’t want to do it. Feel free to tell the experimenter you want to stop at any point during the study and you can stop with no problem. The pain stimulus is very brief and is by definition “about to be painful”, where the baseline pain is 44^{o} C threshold in the current study. Also, it is worth mention that the thermal pain generator device is widely used in clinical pain research, e.g., to measure individual differences in sensitivity to pain.

PHASE 2. You will randomly be assigned to one of three groups (two additional brief pain stimuli in each group). Two of these groups will involve experiencing virtual reality during the treatment while one will not. There are three different conditions in the whole experiment.
Group A will undergo condition 1, then condition 1 again.
Group B will undergo condition 2, then condition 3.
Group C will undergo condition 3, then condition 2.

Condition 1: The researcher will start the software of the heat-pain thermal sensory device while the thermode placed on your arm at tolerant temperature threshold (decided in Phase 1). The heat continues for 10 seconds then begins to cool down. The researcher will ask you to answer the pain ratings about how painful you found the stimulus.

A heat-pain thermal sensory thresholds device and how it will be used

Condition 2. You will be given the opportunity to experience virtual reality distractions during the experiment. In virtual reality distractions, you will briefly enter a computer-generated, 3D environment. This environment is designed to give you the illusion that you are inside the 3D computer-generated world as if it is a place you are visiting. You will be able to experience the program for at least 2 minutes and you have to be immobile while you are in the virtual world.
At the same time, the researcher will start the software of the heat-pain thermal sensory while the thermode placed on your arm at your tolerant temperature threshold (decided in Phase 1). The heat continues for 10 seconds then begins to cool down and next you will answer pain ratings about how painful you found the stimulus.

Condition 3. You will be given the opportunity to experience virtual reality distractions during the experiment. In virtual reality distractions, you will briefly enter a computer-generated, 3D environment. This environment is designed to give you the illusion that you are inside the 3D computer-generated world as if it is a place you are visiting. You will be able to experience the program for at least 2 and you will be able to interact with the virtual world by selecting virtual objects with your eyes and shooting using a trigger.
At the same time, the researcher will start the software of the heat-pain thermal sensory while the thermode placed on your arm at your tolerant temperature threshold (decided in Phase 1). The heat continues for 10 seconds then begins to cool down and next you will answer pain ratings about how painful you found the stimulus.

With all of these pain stimuli in the present study, we are not measuring how much pain you can tolerate in each condition. This is a different measure. In the current study, each time we apply the tolerant temperature (decided in Phase 1).
Numerous published medical studies using identical equipment and stimulus durations have found no significant tissue/skin damage. Each participant can expect to participant in the two phases of the experiment, and the entire experiment is designed to take 15 minutes or less after consent has been completed.

RISKS, STRESS OR DISCOMFORT

Possible side effects of participation include stress, discomfort, or mild nausea. If you do experience any of these side effects, we will try to relieve them. If this is not possible, we will end the virtual reality study early. Answering questions about your pain may seem personal and may cause distress. You may refuse to answer any questions at any time. A risk to study participation is a breach of confidentiality. The researchers will take care to protect subject confidentiality.

ALTERNATIVES TO TAKING PART IN THIS STUDY

Taking part in this study is voluntary. If you choose not to take part you will not be penalized. If you choose to be in the study, you may quit at any time.
There are alternatives to participating in the present study. If you choose to not take part in this study, you may sign up for other Psychology studies (if available).

If important new information is found that might change your decision to be in the study, we will tell you.

BENEFITS OF THE STUDY

You will not benefit from participating in the study. You may find this study interesting. It is hoped that the results of the present study will one-day benefit patients with severe burns undergoing painful wound care. However, the present study will have no direct benefit for the present participants, and some participants may find it stressful and/or may experience discomfort.

OTHER INFORMATION

Your participation in the study will remain confidential. All of the information that you provide will be confidential. We will initially write your initials on the pain rating forms temporarily, to help keep the test forms organized, but these initials will be torn off once the test forms are organized. No permanent link will be kept between the participant's data (e.g. pain rating) and the participant's name. All links between the patient's name and their answers will be destroyed when the data are analyzed, if not sooner.

As a result, it will not be possible to know with confidence which data goes with which person. In any publication of study data, subjects will not be identified by name.

Government or university staff sometimes review studies such as this one to make sure they are being done safely and legally. If a review of this study takes place, your records may be examined. The reviewers will protect your privacy/ The study records will not be used to put you at legal risk of harm.

معهد البحوث والاستشارات
Research & Consultancy Institute

جامعة عفت
EFFAT UNIVERSITY

Invitation for Participation in Research

Dear Participant,

I am working on **Virtual Reality passive and eye tracking interaction during thermal pain project**. This project is part of my Ph.D. research, conducting it at Effat University.
As part of this project, this survey collects information on whether or not psychological techniques using virtual reality with different setting are effective in reducing the experience of pain. Your voluntary participation will be highly appreciated and you have the right to withdraw from participation at any time.

The survey should take approximately **15** minutes and all information provided will be confidential and anonymous; besides the information is solely used for this project only.
Your participation is highly valued, as it will help collect the information needed, which would eventually benefit to immobile patients under a painful procedure, to increase the public understanding of eye tracking and also benefit to the professionals in the field.

Ethics Approval Decision No. RCI_REC/ 31. January.2018/10.1-Exp.43

For further detail please contact:

Dr. Wadee Alhalabi
Effat University
Email: walhalabi@effat.edu.sa

Najood Alghamdi
KAU
Email: nalghamdy0004@stu.kau.edu.sa

Appendix D– Fixation Detection

Sample: Eye tracker output data stream

6352932840 1077.817 614.1189
6352932840 Wall 4.99999 0.1329658 -0.130842

6360892956 1077.153 615.433
6360892956 Wall 4.99999 0.1152325 -0.1275376

6376963448 1076.184 617.2438
6376963448 Wall 4.99999 0.09121561 -0.1190369

6384937941 1075.892 617.2206
6384937941 Wall 4.99999 0.0911777 -0.1170259

6396943505 1076.436 617.7554
6396943505 Wall 4.99999 0.08412981 -0.1210858

6404955099 1076.514 617.8923
6404955099 Wall 4.99999 0.08387089 -0.1210802

6417225939 1075.978 618.056
6417225939 Wall 4.99999 0.08196735 -0.1157944

……..

……..

Sample: A participant eye movement analysis proposed algorithm result

Fixation number	Start time	End time	Number of gazes	OOI
1	5044993648	5544835018	46	MiddleObj
2	5556967656	5868983875	29	MiddleObj
3	5884932396	6172970413	27	Wall
4	6340949537	6977161453	58	Wall
5	7145010721	9020989311	169	Wall
6	9032875687	9189106173	15	MiddleObj
7	9300976778	9680955892	35	MiddleObj
8	9725374209	9824894205	10	Wall
9	9949075534	10652999910	64	Floor
10	10664885823	11012945171	32	Floor
11	11044969749	11201152931	15	Wall
12	11256904349	11433298545	17	CornerObj
13	11457119530	11701116737	23	CornerObj
14	11720935403	11888927976	16	CornerObj
15	12092985475	12204990108	11	CornerObj
16	12696897334	12852967820	15	RightMidObj
17	13025176509	13217336965	18	RightMidObj
18	13317200149	13436941825	12	RightMidObj
19	13597153761	13961016007	33	RightMidObj
20	14428959872	14528837896	10	Wall
21	14572973779	14684951977	11	Wall
22	14696983513	14952855038	24	MiddleObj
23	14964953821	15233047955	25	MiddleObj
24	15389076238	15733153209	32	MiddleObj
25	15868964914	16036955168	16	MiddleObj
26	16057207921	16225153189	16	Wall
27	16257146695	16368912951	11	Wall
28	16728885111	16865711540	13	LeftObj
29	16885017742	17452929603	52	LeftObj
30	17556961598	17849022340	27	LeftObj
31	17857232890	18000932363	14	LeftObj
32	18129026502	18416870665	27	Wall
33	18460954141	18560840050	10	Wall
34	18660931872	18825022764	16	Wall
35	18861002820	19208878052	32	MiddleObj
36	19221107153	19332971728	11	MiddleObj
37	19421163261	19844935997	39	MiddleObj

38	19968942949	20237031517	25	MiddleObj
39	20316955456	20501025014	18	CornerObj
40	21264882142	21532962363	25	RightMidObj
41	21552851985	21641504040	9	RightMidObj
42	21744883050	22213063436	43	RightMidObj
43	22392841284	22548970205	15	Floor
44	22817151991	22972993376	15	Floor
45	22992847288	23240861655	23	Floor
46	23253064321	23396991968	14	Floor
47	23909056874	24000893160	9	Floor
48	24133018372	24324989611	18	Floor
49	24493015575	24669008611	17	Floor
50	24704843972	24860972893	15	Floor
51	25040871320	25193143546	15	Wall
52	25265040123	25396996987	13	Wall
53	25440971942	25597289153	15	Wall
54	25632983064	25941007168	29	Wall
55	25956997892	26100985364	14	Wall
56	26201107795	26573126330	34	Wall
57	26668996007	27360906472	63	Wall
58	27464882815	27617039099	15	Wall
59	27641057649	27765272368	12	Wall
60	27857078046	28100974151	23	Wall
61	28144961628	28332971359	18	Wall
62	28368920343	28625127173	24	MiddleObj
63	28772994066	29192847034	39	MiddleObj
64	29340949057	29784868807	41	MiddleObj
65	29801062661	29989020915	18	Wall
66	30021011174	30188970819	16	Floor
67	30213020442	30805398852	54	Floor
68	30816869692	31016848351	19	Floor
69	31049156755	31384985147	31	Floor
70	31409020393	31584884501	17	Wall
71	31988993470	32356974904	34	LeftObj
72	32524948463	32612966082	9	LeftObj
73	32624905792	33048893253	39	LeftObj
74	33260999911	33480931728	21	LeftObj
75	33497051843	33629024476	13	LeftObj
76	33805273976	34108935412	28	Wall
77	34132949788	34457151514	30	Floor
78	34544883916	34769031849	21	Wall
79	34805070804	34980960420	17	Wall

80	35016895955	35225030439	20	Wall
81	35260984525	35357039709	10	Wall
82	36032874116	36309033177	26	Wall
83	37049034074	37189077199	14	RightMidObj
84	37285102702	37460980724	17	RightMidObj
85	37728831380	38205230201	44	RightMidObj
86	38332963993	38712885137	35	RightMidObj
87	38945516779	39032892080	9	Wall
88	39080844774	39248863781	16	Wall
89	39280999200	39504913394	21	Wall
90	39525008466	39761102137	22	Floor
91	39897203697	40052966241	15	Wall
92	40084943979	40396943966	29	Wall
93	40409073357	40645004710	22	Wall
94	40788958791	40969136870	17	Wall
95	40988970377	41180976861	18	Wall
96	41204997730	41456877140	24	Wall
97	41948975439	42196972646	23	LeftMidObj
98	42220957804	42364986088	14	LeftMidObj
99	42512835821	43189014808	62	LeftMidObj
100	43248907675	43828960521	53	LeftObj
101	43848842259	44040852918	18	LeftObj
102	44140949842	44408914120	25	LeftObj
103	44432872844	44721170108	27	LeftObj
104	44844960943	45113069918	25	LeftObj
105	45157026785	45321024460	16	Wall
106	45357086139	45773035572	38	LeftObj
107	45905112088	46544881569	58	LeftObj
108	46677007245	47064871809	36	LeftObj
109	47201102760	47940996990	67	LeftObj
110	48061339710	48641073483	53	LeftObj
111	48788980260	48977097121	18	CornerObj
112	49313048876	49537130026	21	MiddleObj
113	49636970486	49892987171	24	MiddleObj
114	49937368850	50508947725	52	MiddleObj
115	50664840125	51033012631	34	MiddleObj
116	51120841961	51448994527	30	CornerObj
117	51456941657	51680829416	21	CornerObj
118	51701034401	52004982447	28	CornerObj
119	52092964356	52261274146	16	CornerObj
120	52673097897	52821002355	14	Wall
121	52856912846	53345277348	45	CornerObj

122	53365063086	53580965223	20	CornerObj
123	53769217041	54037178537	25	CornerObj
124	54072861318	54485002751	38	CornerObj
125	54504875214	54728922509	21	CornerObj
126	54853228127	55212957735	33	CornerObj
127	55680878412	55980943327	28	RightMidObj
128	56105073177	56504885798	37	RightMidObj
129	56640945619	57065030471	39	RightMidObj
130	57089008209	57312842171	21	RightMidObj
131	57512870916	57620978506	11	Wall
132	57669368533	57845038787	17	Wall
133	57869133395	58193093497	30	Wall
134	58248997959	58416843053	16	Floor
135	58697026694	58885337875	18	MiddleObj
136	58904821700	59196945050	27	MiddleObj
137	59345019247	59981041946	58	MiddleObj
138	60160960779	60929094776	70	MiddleObj
139	60985166194	61097089204	11	Wall
140	61221009431	61612990400	36	Floor
141	61956963952	62237115592	26	Wall
142	62269081736	62604921722	31	Wall
143	62616849838	63240862334	57	Wall
144	63252949058	64112891515	78	Wall

Sample: A participant eye movement manual analysis and result

Participant No. 1

frame no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
MiddleObj																		o	o	o	o	o		o	o	o	o	o	o	o	o	o	o	o	o	o	o	o																	
CornerObj																																																							
RightMidObj																																																							
LeftMidObj																																																							
LeftObj																																																							
BackObj																																																							
NONE OOI	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o						o																o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o

frame no.	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205
MiddleObj																																								o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	
CornerObj																																																							
RightMidObj			o	o	o	o	o	o	o	o	o	o	o	o	o	o	o																																						
LeftMidObj																																																							
LeftObj																																																							
BackObj																																																							
NONE OOI	o	o																o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o																o

frame no.	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355
MiddleObj													o	o	o	o	o	o	o	o	o	o	o	o	o	o	o				o	o	o	o	o	o	o	o	o	o	o	o					o	o	o	o	o	o	o	o	
CornerObj																																																							
RightMidObj																																																							
LeftMidObj																																																							
LeftObj																																																							
BackObj																																																							
NONE OOI	o	o	o	o	o	o	o	o	o	o	o	o																o	o	o													o	o	o	o									o

Fixation no.	Number of frames	OOI	Fixation no.	Number of frames	OOI
1	5	MiddleObj	26	8	RightMidObj
2	15	MiddleObj	27	5	RightMidObj
3	19	CornerObj	28	20	RightMidObj
4	12	CornerObj	29	13	RightMidObj
5	9	RightMidObj	30	15	LeftMidObj
6	7	RightMidObj	31	23	LeftMidObj
7	3	RightMidObj	32	25	LeftObj
8	15	RightMidObj	33	9	LeftObj
9	15	MiddleObj	34	14	CornerObj
10	12	MiddleObj	35	21	CornerObj
11	7	MiddleObj	36	12	CornerObj
12	27	LeftObj	37	24	CornerObj
13	14	LeftObj	38	19	CornerObj
14	15	MiddleObj	39	8	LeftObj
15	12	MiddleObj	40	9	MiddleObj
16	8	MiddleObj	41	25	MiddleObj
17	8	CornerObj	42	14	MiddleObj
18	11	RightMidObj	43	26	CornerObj
19	17	RightMidObj	44	7	CornerObj
20	8	MiddleObj	45	14	RightMidObj
21	12	MiddleObj	46	13	RightMidObj
22	14	MiddleObj	47	22	RightMidObj
23	17	LeftObj	48	13	MiddleObj
24	17	LeftObj	49	21	MiddleObj
25	13	LeftObj	50	28	MiddleObj

تتبع العين في نظام واقع افتراضي غامر لتسكين الألم

نجود علي آل حيان الغامدي

الملخص

الواقع الافتراضي هو أحد مجالات الحاسب الآلي ويمكن تعريفه بشكل مبسط بأنه واجهة مستخدم متطورة تتضمن محاكاة وتفاعلات في الوقت الفعلي من خلال عدة قنوات حسية ، وهذه القنوات الحسية من خلال: البصر والسمع واللمس والشم والتذوق.

تتمثل الفكرة وراء الواقع الافتراضي في إعطاء مستخدمي الكمبيوتر تجربة الدخول إلى عالم ثلاثي الأبعاد يتم إنشاؤه باستخدام الحاسوب كما لو كان مكانًا يزورونه. إن من أهم مميزات الواقع الافتراضي هو الغمر أو الانغماس. ويعتبر أكاديميا وصف موضوعي قابل للقياس الكمي لما يمكن أن يوفره نظام واقع افتراضي معين للمستخدم. ويعتبر الباحثون أن الغمر مختلف عن الوهم النفسي الشخصي "الوجود" للدخول إلى العالم الافتراضي. فالوهم النفسي أو الوجود هو وعي نفسي يعتمد على سؤال الناس عن شعورهم بأنهم ذهبوا إلى العالم المنشأ بالحاسوب. في المقابل ، يمكن قياس الانغماس أو الغمر بشكل موضوعي على سبيل المثال ، استخدام حساب مجال الرؤية أو قياس جودة تباين شاشات الخوذة المستخدمة .

تتراوح أنظمة الواقع الافتراضي من درجة غمر منخفضة إلى درجة عالية، اعتمادًا على العديد من العناصر مثل مدى فعالية المستخدم في التفاعل مع الكائنات في العالم الافتراضي، وأجهزة الإدخال و الإخراج المستخدمة، مجال الرؤية ، جودة الرسومات ودقة شاشات عرض الواقع الافتراضي ، وعناصر وميزات أخرى.

وعلى الرغم من أن مفهوم استخدام أجهزة الحاسوب لإنشاء تجارب الواقع الافتراضي قد ظهر منذ بضعة عقود ، إلا أن التكلفة العالية للمكونات كانت العائق الأكبر في البحث والتطوير والانتشار لهذه التقنية. وفي الوقت الحالي، تتطور تقنيات الواقع الافتراضي بسرعة بعد إدخالها بعدة مجالات جديدة مثل العلاج ومنها أستخدام الواقع الافتراضي في أنظمة تسكين الألم. تشير الدراسات الأولية إلى أن الواقع الافتراضي لديه إمكانات هائلة لتقليل الألم الحاد أثناء العناية بالجروح.

في أنظمة الواقع الافتراضي لتسكين الألم يستخدم جهازان أساسيان وهما شاشة العرض الرأسي (HMD) والتي تتضمن تتبع حركة الرأس، وجهازتأشير تقليدي لتوجيه واجهة المستخدم مثل الفأرة . (mouse) يستجيب الحاسوب للإشارات الناتجة من أجهزة الإدخال وتغيير ما يراه المستخدم وفقا لذلك، في الوقت الفعلي. يساعد التفاعل مع الكائنات في العالم الافتراضي، ورؤية ردها، المستخدم على الشعور بوهم العيش بداخل العالم الافتراضي الناتج عن الكمبيوتر كما لو كانوا في هذا العالم.

يعد (SnowWorld) (عالم الثلج) أحد أشهرأنظمة الواقع الافتراضي لتسكين الألم، وهو أول نظام مصمم خصيصاً للسيطرة على الألم. تم تصميم برنامج عالم الثلج لجذب انتباه المريض بعيداً عن الألم من خلال لفت الانتباه إلى البيئة الافتراضية. تم تطويرهذه البيئة في مركز أبحاث الواقع الافتراضي بجامعة واشنطن ، بالتعاون مع Imprint Interactive Technology و Harborview Burn. يقدم عالم الثلج تجربة تفاعلية من خلال رسوم ثلاثية الأبعاد لمناظر طبيعية جليدية لمنح المرضى الشعور بالطفو على المناظر الطبيعية ويستطيع المريض في نفس الوقت قذف كرات الثلج على كائنات افتراضية مختلفة ، مثل رجال الثلج والكلاب وطيور البطريق باستخدام الفأرة .

عادة مايعاني كثير من المرضى المصابين بالحرائق من الأيدي المحترقة، وهؤلاء المرضى غير قادرين على استخدام الفأرة، لذا يستخدم هؤلاء المرضى عالم الثلج بدون تفاعل وذلك يؤدي لتقليل فعالية الواقع الافتراضي في تسكين الألم بشكل كبير. تهدف هذه الدراسة إلى تعزيز نظام عالم الثلج الحالي، لتخفيف الألم الحاد أثناء

العناية بالحروق وتعقيمها. تقترح هذه الدراسة إضافة تقنية جديدة لتتبع العين إلى برنامج الواقع الافتراضي لتسكين الألم عالم الثلج ، لجعل التفاعل مع الواقع الافتراضي متاحاً للأطفال الذين يعانون من إصابات بالحروق لأول مرة.

الفرضية الأساسية لهذه الأطروحة هي أن التفاعل عن طريق تتبع العين يمكن أن يعزز من فعالية الواقع الافتراضي في تسكين الألم. و لاختبار هذه الفرضية، أجرت هذه الرسالة دراسة مخبرية مع مشاركين متطوعين أصحاء، لتستكشف ما إذا كان تتبع العين التفاعلي يمكن أن يعزز الفعالية المسكنة في الواقع الافتراضي. وتعتبر بأنها أول دراسة تستخدم تتبع العين في أبحاث السيطرة على الألم في أبحاث ومراجع PubMed.

تبحث الأطروحة أيضًا في أنظمة تتبع العين الحديثة وتوفر خطوة أولية نحو فهم أنماط حركة العين أثناء الألم من خلال اقتراح خوارزمية الكشف عن ثبات حركة العين لمعرفة ما كان المستخدم ينظر إليه وذلك من خلال تسجيل احداثيات نظرة العين أثناء استخدام الواقع الافتراضي.

هذه الأطروحة مبنية على النحو التالي:

الفصل الأول يقدم استعراضا لمواضيع وأهداف البحث ، وسردا لمواضيع فصول الأطروحة.

تم تخصيص الفصل الثاني لمراجعة المعلومات والتقنيات الحالية لأنظمة تتبع العين. حيث يتزود القارئ بالمعلومات الأساسية اللازمة لفهم المصطلحات والتقنيات المستخدمة خلال هذا البحث . وبشكل أساسي ، يتم استعراض فسيولوجية العين ، وأنواع حركة العين ، ويغطي بشمول الأجهزة والبرامج المستخدمة في تكنولوجيا تتبع العين الحديثة.

يستعرض الفصل الثالث باختصار الإعدادات والتحديات الموجودة في المراجعة العلمية المتعلقة بالبحث.

بينما يقدم الفصل الرابع بحاثاً استقصائيا كخطوة أولية أتخذت نحو تقييم حالة الوعي بتتبع العين والمواقف تجاهه بين فئات المستخدمين المختلفة. تم تصميم استبيان خصيصاً لهذا البحث ووضعه على الإنترنت وتوزيعه عبر تطبيق الواتس ووسائط التواصل الاجتماعي، مستهدفاً قدر الأمكان الأكاديميين في مدينة جدة.

يحدد الفصل الخامس هدف تصميم نظام لتعزيز أنظمة تسكين الواقع الافتراضي السابقة وحل بعض قيود هذه الأنظمة من خلال إضافة تقنية تتبع العين لبرنامج عالم الثلج. بهذا الفصل تم وصف البرامج والأجهزة والمكونات المستخدمة في تصميم نظام مشروع البحث.

لدراسة الفرضية الرئيسية لهذه الأطروحة وهي أن إضافة تتبع العين تؤدي إلى وهم أقوى للوجود في الواقع الافتراضي، ويجعل تجربة الواقع الافتراضي يتطلب مزيدًا من الانتباه وبالتالي فأن الواقع الافتراضي مع تتبع العين سيقلل الألم بشكل أكثر فعالية من الواقع الافتراضي دون تتبع العين. يقدم الفصل السادس في هذه الاطروحة دراسة هي الأكبرفي أبحاث أختبار الألم بالواقع الافتراضي، باستخدام النظام المطور على مشاركين متطوعين أصحاء والذين تم تعيينهم عشوائيا إلى مجموعة من ثلاث مجموعات. كما تم استخدام كل من التصميم بين أفراد العينة والتصميم داخل أفراد العينة في تصميم التجربة.

الفصل السابع يستعرض الحقائق المتعلقة بحركات العين داخل واقع افتراضي غامر. علاوة على ذلك ، يقدم هذا الفصل عرضًا لخوارزمية مقترحة لاكتشاف حركة ثبات العين من خلال تسجيل حركات العين أثناء استخدام العين للتفاعل داخل الواقع الافتراضي. كما تم تقييم الخوارزمية من خلال مقارنتها بتقنية تحليل إطارات الصور وهي طريقة متفق على صلاحيتها وفعاليتها وتستخدم مع تسجيلات الفيديو أثناء أستخدام أجهزة تتبع العين الرأسية أو النظارات. تتبع حركات العين وتحليلها هنا هو خطوة نحو الانتفاع من هذا المشروع بدراسة أنماط حركة العين أثناء الألم ومدى ارتباطها بالألم الذي يشعر به المريض.

الفصل الثامن هو الفصل الأخير الذي يختتم بمناقشة سريعة لنتائج الأطروحة والقيود التي واجهت العمل. كما يشير إلى فرص الأعمال المستقبلية لهذا المشروع البحثي.

المستلخص

في هذه الايام تتطور تقنيات الواقع الافتراضي بسرعة حيث تتناول مجالات جديدة مثل العلاج. تشير الدراسات الأولية إلى أن الواقع الافتراضي لديه إمكانات هائلة لتقليل الألم الحاد أثناء العناية بالجروح. ومع ذلك فأن أنظمة الإلهاء عن الألم الحالية تتطلب من المرضى استخدام جهاز إدخال يدوي. ومن المؤسف أن كثير من مرضى الحروق الشديدة من الأطفال مصابين بحروق بأيديهم وغير قادرين على استخدام أجهزة الإدخال اليدوية. يهدف المشروع الرئيسي لهذا البحث إلى إيجاد حل لبعض القيود في أنظمة الإلهاء عن الألم الحالية من خلال زيادة وهم الوجود داخل البيئة الافتراضية وزيادة فعالية التسكين للأطفال الغير قادرين على تحريك أيديهم من خلال إضافة جهاز تتبع للعين يستخدم للتفاعل مع النظام لأول مرة.

تم بهذا البحث استكشاف تقنيات تتبع العين المختلفة، والتحقق من جدوى استخدام التقنيات الحالية بشكل تفاعلي بواسطة المستخدم أو بشكل مخفي عن المستخدم، وأيضا تقييم وعي الناس وموقفهم تجاه هذه التكنولوجيا. ومن ثم تم تطوير واجهة تحكم محسنة قادرة على تتبع العين واستخدام حركتها لزيادة التفاعل في نظام الواقع الافتراضي لتسكين الألم. كما يستكشف البحث المتطلبات الفنية للنظام المطور لهذا المشروع، حيث استخدمت تقنية حديثة لتعقب العين مضمنة في خوذة الواقع الافتراضي لتنفيذ نظام لتسكين الآلام يستخدم بالمعمل.

ومن أجل تقييم فعالية هذا النظام، أجريت دراسة عشوائية مختبرية للألم على متطوعين أصحاء لتحديد ما إذا كان استخدام حركات العين للتفاعل في نظام الواقع الافتراضي يزيد بشكل كبير من وهم الوجود ويزيد من فعالية تسكين الإلهاء بالواقع الافتراضي أثناء ألم حراري يتم إحداثه لفترة قصيرة.

كذلك ، قمنا بتصميم خوارزمية لتحديد حركة ثبات العين ونفذت باستخدام تقنية الواقع الافتراضي الغامرة المستخدمة في هذا المشروع كخطوة أولية نحو نهج مستقبلي آخر لاستخدام تتبع العين بشكل مخفي عن المستخدم من أجل جمع حركات العين لتقييم الحالة العقلية للمريض أثناء الألم.

تتبع العين في نظام واقع افتراضي غامر لتسكين الألم

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