Analysis of Immersive Virtual Reality through Senses

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Abstract

With the latest developments of Virtual Reality(VR) technology, the idea and desire of immersive sensory experience in Virtual Environments(VEs) have increased. Immersive VR system should produce different signals and stimuli in several ways to replicate the physical world and use various display devices to convey the user. For conveying the user, VR technology needs to display synthetic stimuli which are indistinguishable from natural stimuli for five human senses. These senses are sight, hearing, touch, smell and taste. The user needs to be presented with a believable sensory input to be immersed in a virtual reality environment. This research paper is aiming to investigate how people perceive the physical world and how does VR technology achieve the goal of immersiveness through tricking five human senses. Through examining current VR technologies by comparing human sensorial perception for each of the senses, this paper is aiming to arrive a conclusion regarding whether or not the VR technology is achieving the goal of immersiveness by tricking our senses.

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Abbreviations

2D - Two- Dimensional

3D - Three-Dimensional

CRT - Cathode-Ray Tube

DTSS - Displaced Temperature Sensing System

FCU - Force Control Unit

FOV - Field of View

FPS - Frames Per Second

GUI - Graphical User Interface

HCI - Human Computer Interaction

HDM - Head Mounted Display

HRTF - Head Related Transfer Functions

HVS- Human Visual System

ILD - Interaural Level Difference

IPD - The Interpupillary distance

IT – Information Technology

ITD - Interaural Time Difference

LCD - Liquid Crystal Display

NMES - Neuromuscular Electrical Stimulation

SPL - Sound Pressure level

TENS - Transcutaneous Electrical Nerve Simulation

VE - Virtual Environment

VPL - Visual Programming Lab

VR - Virtual Reality

Chapter One: Introduction

1.1 Introduction

With the rise and maturation of Virtual Reality(VR) technology, a novel human-computer interface has emerged that enables users to explore the immersive virtual environment. VR is an immersive sensory experience which is intended to simulate the physical world through the human senses. According to Grigore C.Burdea and Philippe Coiffet, the definition of Virtual reality is “a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels” (Grigore C.Burdea, 2003). These sensorial modalities are visual, auditory, tactile, smell, and taste. There is one key component that appears in the definition of VR, which is the immersion in real-time simulation through senses. The Immersion component of this high-end user communication technology involves five basic human sensorial channels. As an immersive Environment, VR needs to be similar to the real world in order to create a life-like experience grounded in reality. Real-time means that the computer can sense a user’s input and immediately change the Virtual Environment (VE) and render the simulation by a captivating user. Interactivity and its captive power lead to the sense of immersion that one can feel like part of the action on the computer. The technology of VR further drives immersion by the use of all human sensory system. For the immersive VR experience, users not only display graphical objects and control them on the screen, but also hear them, touch them, smell them and even taste them.

Ivan Sutherland proposed the concept of “the Ultimate Display” in 1965, which represent the birth of the modern VR. The ultimate goal was to make the virtual world “look real, act real and feel real” (Sutherland, 1965). The physical world is changing when one move. For instance, when one goes closer to a building, it gets bigger. When one turns his ear to a speaker, it gets louder. Once one touches a surface with his finger, he feels resistant when it makes interaction. There is an acceptable update to our senses for each physical activity in the real world. When the virtual reality works well, the virtual world changes as the physical world does. The motor and perceptual systems communicate with the virtual world in a way like in the real world in the virtual world. As virtual environments are intended to simulate the real world, VR technology must be able to trick the five senses of the user. The way the user perceives the VE is a core component of a VR experience. The immersive user experience is based on what the computer displays. The term "display" usually refers to the "visual" output. However, it does refer to any output modality that is visual, aural, haptic, olfactory, and taste (Kim, 2005) providing information to the brain.

1.2 Motivation

With the technological developments of VR, the idea and desire of immersive VR have increased. Immersive VR system should produce different signals and stimuli in several ways to replicate the physical world and use various display devices to convey the user through senses. This is not a trivial task, and the solution is not sufficiently found: on the one hand, VR technology should give the user feeling of immersion trough tricking senses, on the other, the solution must be workable. However, VR technology has not reached the level that as human perceive the real world yet. There are still many technological possibilities and challenges to explore achieving the goal of immersiveness by tricking our senses. Human senses – sight, hearing and touch - are commonly presented in a VR experience with synthetic stimuli. Smell and touch are still under development. VR technology is aiming to achieve the goal of immersiveness by tricking all human senses by computer-generated output rather than natural stimuli. For achieving the goal of immersiveness in VR, all of the human senses should be involved in VE like in the physical world.

1.3 Purpose of the Paper

To understand a user's experience with an immersive VR environment, we must first understand how human perceive the virtual environment. In order to understand this simulated reality experience, we must also first understand how our perception functions in the physical world. Therefore, this research paper is aiming to investigate how people perceive the physical world and how does VR technology achieve the goal of immersiveness through tricking five human senses. Through examining current VR technologies which are designed to trick our senses, this research paper is aiming to arrive a conclusion regarding whether or not the VR technology completely achieves the goal of immersiveness by tricking our senses through synthetic stimuli which are indistinguishable from natural stimuli.

1.4 Chapters breakdown

This research paper has the following structure. In chapter two, the paper will give a brief overview of VR passing through the history, evolution and future. In the chapters three, four, five, six and seven, the paper will discuss how we perceive the world with each of our senses and which VR technologies are used to achieve the goal of immersiveness. Each section will end with a brief assessment of the VR technology evaluation to increase the feeling of immersion. Our chapters will follow the order of sight, hearing, touch, smell and taste.

Chapter Two: Literature Review

2.1 What is Virtual Reality?

Grigore C.Burdea and Philippe Coiffet defined Virtual Reality as *I3* for "Immersion-Interaction-Imagination" (Burdera, 1993) as seen in Figure 1. As discussed in the very beginning of the paper, it is clear that interactivity and immersion are the essences of Virtual Reality. Imagination refers to the degree to which an algorithm can solve a particular problem (e.g. in medicine and engineering) related to perception to create an illusion of reality which is called imagination. The concept of imagination is beyond the scope of this research at present.

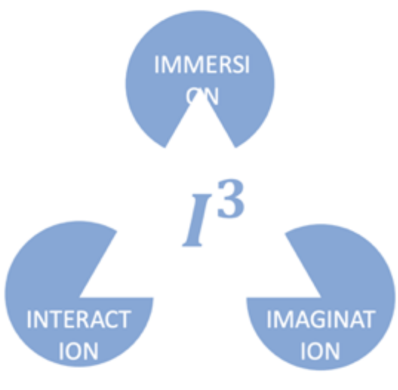

Figure 1: Virtual Reality Triangle proposed by Grigore Burdea (1993)

Wither and Singer described immersion as a psychological condition characterized by the feeling of being enveloped, including in, and interacting with an environment that provides continuous stimuli and experiences (J.Singer, 1998). According to Instrumental approach for immersion and interaction, Cognitive immersion and interaction research in the virtual reality environment is based on the subject's approach (Philippe Fuchs, 2011). User is at the heart of the VR system because the VE is intended for him. Thus, VE should have an anthropocentric approach for the user. In the absolute sense, Anthropocentric diagram schematism, as seen in Figure 2, is possible as if a user immersed in an artificial world. In that world, the motor and sensory interfaces work together to achieve the goal of immersiveness through tricking human senses.

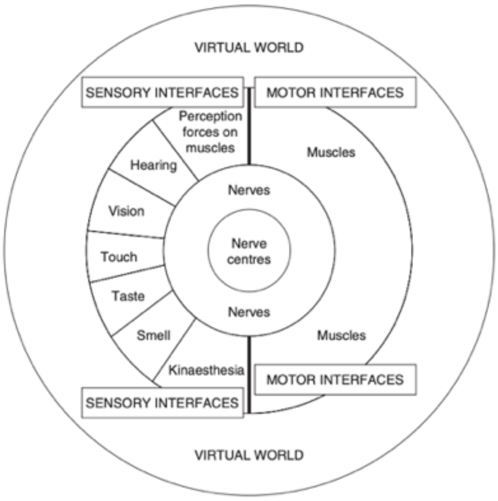

Figure 2: Anthropocentric diagram of user's vision of the virtual world

An ideal Immersive VR system typically comprises a series of sensory displays and a tracking system. The VR system maintains a dynamic database which is Virtual Environment, and the virtual objects are continuously displayed to the user. The displayed objects should at least be determined by the position and orientation of the individual user enabled with tracking technologies (e.g. head-tracking and eye-tracking), and should also include auditory, tactile, olfactory displays in order to trick our senses. Although the VR instrumentations vary, they consist of sensors that monitor and measure a variety of body movements, including head movements and eye movement.

2.2 Brief History of the Virtual Reality

Several aspects have been crucial for VR among us for thousands of years. Our ancestors had long ago been trained to look at the walls and imagine and world, which is also part of the VR history (M.LaValle, 2015). Some of the ancient cave paintings show us that our ancestors were thinking about three-dimensional(3D) environment even computational technologies were not enough at that time. Today's technology for virtual reality builds upon concepts from the 1800s, almost from the very beginning of practical photography. Human brain assesses distance by using stereopsis vision, also known as binocular vision. In 1838, Charles Wheatstone carried out the first experiment that demonstrated the 3D effect of the stereopsis vision by presenting a different image to each eye using a mirror. This device, called stereoscope (M.LaValle, 2015). Instead of just watching pictures on the stereoscope, researchers wanted to go one step further and move images and interact with them. This technology, which in the last decade, became popular, is called Virtual Reality. In 1965, Ivan Sutherland put forward the very first concept of this technology: "make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer' actions" (Sutherland, 1965). Sutherland's concept became the research agenda for scientists, researchers and technology industry for achieving the goal of immersiveness through tricking human senses. Sutherland's Promised Land has not been met yet, but much work has been done since then.
If one is to have a brief glimpse look at the last six decades of virtual reality research and its highlights:

- **Sensoroma – 1957 -** The Sensorama is the first known example of a multi-sensory simulator that is invented by Morton Heilig in 1957. The user was able to ride a motorbike through New York in the arcade cabinet. This arcade cabinet, as seen in Figure 3, had 3D video feedback which is obtained with a pair of side-by-side 35mm cameras. It was a coloured and stereo pre-recorded film was enhanced by stereo sound, scents, wind effects(using small fans located near the user’s head) and a seat which is vibrated (Jerald, 2015). Therefore, Sensoroma allowed the motorcycle ride through the New York to be simulated where the user felt the wind and sensed potholes of the road as the seat was vibrating. The user could even smell food when passing by through a shop. Thus, Heiling's Sensorama had almost all of the human senses, except taste, in a very primitive way. For this reason, Sensorama technology did not achieve the goal of immersiveness by tricking five human senses.

Figure 3: Sensorama

- **The Ultimate Display Sutherland Display – 1965 -** Ivan Sutherland wrote about The Ultimate Display, in which interactive graphics, force-feedback devices, audio, smell and even taste senses were described.
- **The Sword of Damocles – 1968 -** Ivan Sutherland built a system with sufficient head tracking, which is considered the first Head Mounted Display (HMD). It supported a stereo view, which was adjusted to the user head location and orientation correctly.
- **Grope – 1971 -** The first prototype of a force feedback system implemented.
- **Videoplace – 1975 -** Myron Kruger developed artificial Reality system in 1975. The silhouettes of users taken from cameras were projected on a widescreen in Videoplace. Through image processing techniques positions of the user were determined within a 2D(two-dimensional)screen, and participants were able to interact with each other.
- **VIVED – 1981 -** Virtual Visual Environment Display, Nasa developed the prototype of Liquid Crystal Display(LCD) based HDM.
- **VCASS – 1982 -** Thomass Furness developed a virtual reality flight simulator that is called Visually Coupled Airborne Systems Simulator(VCASS). The user was equipped with an HMD which increased the outdoor view with the images describing target and optimum flight path detail.

- **VPL and Jaron Lanier** – The term "Virtual Reality" first coined in 1987 by Jaron Lanier, the founder of Visual Programming Lab(VPL). The virtual reality term is referring to immersive environments created by applications with visual and 3D effects. Previously, computer researchers such as Myron Krueger used terms such as "Artificial reality" in the 1970s (Machover, 1994). Moreover, VPL developed a large range of software and hardware for virtual reality. Data glove(1985) and Eyephone HMD(1988) which were the first commercial VR devices developed By VPL.
- **BOOM box –1989** - BOOM is a display with two CRT(Cathode Ray Tube) monitors that can be seen through the eye holes. The user can grab the display and keep an eye on displayed images. At the same time, mechanical arm measures the position and orientation of the display and moves through the virtual world.
- **Virtual Wind Tunnel – early 1990s**- The NASA Ames application was developed in the early 1990's, permitting flow field observation and research with the help of BOOM and Data Glove.
- **CAVE- 1992-** (CAVE Automatic Virtual Environment) is a scientific visualization and virtual reality system. Rather than using an HMD, it projects stereoscopic images on the room walls (users have to wear LCD glass shutters). This approach guarantees superior image quality and resolution and the broader field of view compared to HMD-based systems.
- **Sega VR glasses-1993-** Sega released the Sega VR, an addition to the console that was intended as a virtual reality headset. It was supposed to be released in 1994 with four launch games, but remained a prototype and became a flop for Sega. It was, however, the first major example of a gaming company that showed interest in VR.
- **Nintento virtual boy-1995**- Nintendo followed Sega's VR initiatives closely with a Nintendo Virtual Boy, a console capable of showing stereoscopic 3D graphics. For seeing a monochrome display, gamers would place their head against the eyepiece.
- **21st Century-** Latest technologies will be discussed based on human senses in the Chapters between three and seven.

2.3 Future of Virtual Reality

The term "Real-Virtuality"

Human with all five senses experience the physical world. Our perception of an environment is not only what we see; other sensorial inputs such as sound, smell, touch and taste also influence our perception. The interaction of cross-modal effects of senses can have a significant influence on how environments perceived to increase immersiveness through tricking the five basic human senses. If virtual environments are to be regularly used as a useful tool for the experiment in the virtual world with the confidence that the results are the same as they would be in the real world, then we must be able to compute these environments in a perceptive manner, as if we were "there" or "Real Virtuality" in the real world (Chalmers, 2010). Alan Chambers coined the term "Real Virtuality" or in other words, "there-reality" term (Chalmers, 2009).Unlike typical virtual environments, Real Virtuality is aiming to allow all five senses to be simulated in a natural manner simultaneously. The term refers to provide real experience in which all senses are stimulated in such a way the user has a fully immersive VR experience that he cannot tell whether it is real or not. Real virtuality is considered the ultimate limit to achieve the goal of immersivess through tricking the five basic human senses.

Simulation Hypothesis

In a ground-breaking paper in 2003, Oxford philosopher Nick Bostrom, "Are you living in the computer simulation?"(Bostrom, 2003), introduced a new interpretation of the previous sophistic and subjective ideas that claim the "real" world indistinguishable from the computer simulation. Bostrom starts his paper by recognising that the new, rapid and continuing development in Information Technology (IT) makes massive quantities of computational power available in the future. Based on the idea that large amounts of computational powers are to be available in the future, Bostrom's primary claim which he called Simulation Argument is that either humankind will achieve or will not have the technique to perform ancestor simulations. If any human being will ever do this, Bostrom concludes that we are much more likely than not to be within a simulation. As Bostrom concludes, "if the simulation hypothesis is true, you exist in a virtual reality simulated in a computer built by some advanced civilisation" (Bostrom, 2003). Furthermore, Bostrom concludes that a species reaches the point where its technology makes realistic ancestor simulations, then many such simulations are likely to be made. The development of a new simulation is like finishing a new instance of a video game server, although this must be a powerful server of our current technology standards believe there is a simple fact that produces several ancestor simulations. There will always be an exponentially large number of beings in these simulations every time a new simulation is formed. He believes that "as we gain more experience with virtual reality, we will get a better grasp of the computational requirements for making such worlds appear realistic to their visitors" (Bostrom, 2003). If we live in a computer simulation, when we leave the part of consciousness aside, one has to perceive VE as he perceives the physical world through his five senses. Is the current VR technology capable of achieving the goal of immersiveness through tricking the human senses?

Although Oxford philosopher Nick Bostrom coined the term the Simulation Argument in a landmark paper in 2003, the idea of living in a simulated reality has been around for a long time in science, fiction and media.

What we can learn from the Matrix Movie?

Some scholars have interpreted the "we are living a computer simulation" as a modern interpretation of the Evil Genius of Descartes (Descartes, 1641): how do we learn about the outside world? The latest version of this question is: how do we know that we do not live in a computer simulation? The question that has been posted in this way might seem unclear. We can understand the meaning of it by referring to the famous film inspired by the idea of Descartes: The Matrix(1999). In this film, the whole world is a computer simulation, and a computer hacker named Neo discovers that all life on earth can only be an elaborate simulation generated by enormous amounts of computing power. If we were Neo, how do we know that the world in which we see and communicate is real and not an advanced VR simulation which is tricking human senses?

In a famous scene, Neo has the option to take the red pill or a blue pill where the red pill would awaken Neo, while the blue pill helps him to stay in the simulated world, which is the Matrix. Neo wakes up after taking the red pill to know that what he thought was reality was just a computer simulation. He notices that in the real world, all people live in cocks, plugged in the Matrix that an extremely faithful video game is like a picture of the characters living in their lives. One can argue that The Matrix is an extreme case since in the current state of the world, we do not have the technology for recreating these scenarios. However, it seems that in current virtual reality technology, we can even do it on a smaller scale. One way to understand this theory is that people are already jumping into virtual reality in games like "Second Life" and "The Sims" where you can construct the entire life of a person with everything in real life. Therefore, some people say that if we can already do it, it can be achieved at a larger scale. Is the VR technology of today have achieved the goal of immersiveness through tricking five human senses? Although the Matrix was not an advancement in technology, it brought millions into the concept of virtual reality, another world that people could enter VE by "plugging in," considered one of the exciting films of the '90s. The Matrix helped change the way people look to the future of the VR technology.

2.4 Human Senses

Our senses are physiological tools to perceive information about the physical world. As defined and classified by Aristotle, human beings have at least five senses. These are sight, hearing, touch, smell and taste. Sensory processing is the capability to acquire, elaborate and incorporate information through our senses. There is a minimal point below which any stimulus does not produce any effect on sensory organs. Above this level, a stimulus' minimum perceptible variation is proportional to the absolute value of intensity (Weber's law). A specific sensory organ such as eyes, ears, skin, nose and tongue receives a stimulus which is above the minimum perceptible level. These sensory organs are the starting point for information transmission through the body through the nerve tracks. The afferent message from the sensory receiver is transferred to the nerve centres that are spinal cord, brain and cerebellum (Fuchs, 2017). Once information is integrated and processed in the brain, nerve centres pass the nerve messages to the related sensory organs (skeletal muscles, eye muscles, vocal cord muscles, etc.). If the VR technology is able to fool our brain, it can also achieve the goal of immersiveness through tricking our senses. The notion of fooling an organism can seem abstract, but through work in neurobiology, it can be made shockingly concrete. When an animal explores its surroundings, cell-shaped neural structures encrypt spatial information on its surroundings, as demonstrated in Figure 4(a). Every location cell is triggered precisely when the organism returns to a particular location covered by it. Moreover, grid cells represent positions close to the cartesian coordinates (M.LaValle, 2015) as seen in Figure 4(b). It has been demonstrated that these neural structures can develop in an organism even with a VR experience (M.LaValle, 2015). In other words, our brains can shape cells in places where they are not real. It is a reliable indicator that VR can achieve the goal of immersiveness when enough VR technology is provided for each of the senses.

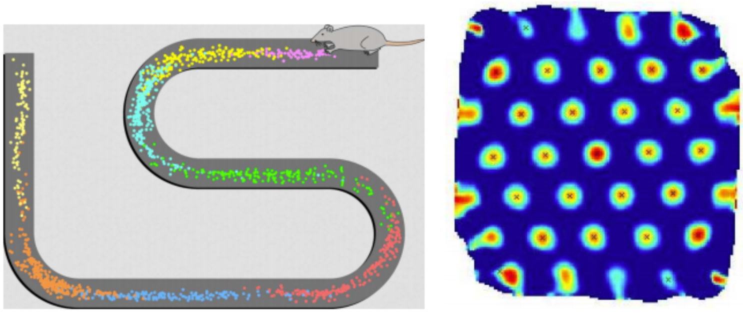

Figure 4: Fooling the brain (a) Animals assign neurons to cells which fire when they return to certain places. This figure shows the spatial fire pathways of eight cells in the rat brain as it goes back and forward along a winding path and (b) grid cells in the brain

The greatest thinkers have been fascinated by the nature of realism for many decades. The Cave Allegory, described by Plato in the Republic (Plato, 1807), is one of the oldest instances. In this book, Socrates describes the views of people who spent their entire lives as chained to a cave wall. These people face a blank wall and only see shadows projected as people pass through in front of the walls. He describes that the philosopher is like one of the cave people, who is released from the cave, instead of just be viewed through illusions, to see the true nature of reality.

Gilbert Hartman proposed in 1973 the concept of a brain in a vat (Figure 5), which it is derived from the notion of Evil Genius by the French philosopher René Descartes from his Meditations on First Philosophy (Descartes, 1647) that is first published in 1641. Moreover, Kant introduced the word "reality" to be distinguished from the physical world, which is also reality. Once VR technology can fool our brain, it can also achieve the goal of immersiveness through tricking five human senses.

Figure 5: A VR Perception Experiment: Gilbert Harman's head in a vat in 1973

In Virtual Reality, the function of the sensory interfaces is to allow the user to perceive the VE. Just as in the real world, the more senses the virtual world achieved, the higher user's feeling of immersion (Yokokohji, 2000). Morton Heilig, in 1952, studied the senses in terms of their capacity to activate human attention (Heilig, 1992). While we are investigating how VR technology achieves the goal of immersive experience in VE, it is essential to know the contribution of each sense while perceiving the world:

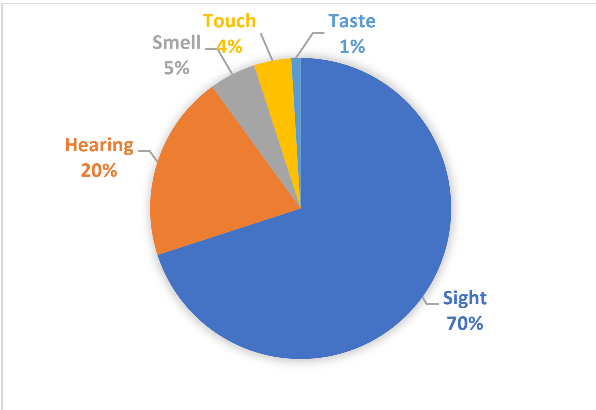

Figure 6: Human Sense Contribution

Figure 6 clearly shows that the sight provides most information and captures the majority of our attention. The stimulation of the visual system, therefore, plays a significant role in fooling our the senses. Hearing, which is also often taken into account, is the second most crucial sense. Touch does not in general play an important role comparing to sight and hearing, even when it is essential for specific manipulation tasks. Due to the marginal role and difficulties of implementation, smell and taste are currently under development in most VR systems. However, immersive VR system should produce different signals and stimuli in several ways to replicate the physical world and use various display devices to immerse the user.

2.5 Analysis

The progress of IT in recent years has followed the so-called "Moore's Rule" a phenomenon that is empirically focused on that the processing ability of IT doubles every eighteen months (Alexander Brezin, 2004). When we analyse the brief history of VR for the last six decades, its progress has accelerated as we approach the 21st Century. Sensorama was the first multisensory VR, but because of the technological limitations, it did not achieve the goal of immersiveness through tricking or senses. It may take less time to reach immersive VR experience(e.g. Real Virtuality) even fooling human brain (as in the Matrix and Simulation Hypothesis) may take less time than we thought with VR technology. To analyse the current state of the art VR, In the following chapters, we will discuss how we perceive the physical world with each of our senses and which VR technologies are used to achieve the goal of immersiveness. Each section will end with a brief assessment of the VR technology evaluation to increase the feeling of immersion. Our chapters will follow the order of contribution of each sense while perceiving the world.

Chapter Three: Sight

Human use sense of sight to assess the position of the objects with respect to them, so they can approach the objects, grasp them or avoid them for survival when needed. Some objects, for instance, food is particularly important to continue our lives; thus, we learn how to identify them in all sorts of positions. Without eyesight, the possibility of dangerous situations can be quite challenging to identify, so sight ensures that hazardous situations and materials need to be avoided. Moreover, sight plays an essential role in relationships and interaction. Eyes are the first point of contact between two people; thus, it is critical for social interaction. Eyes also play a significant role in appealing things, for instance, facial expression, body language and gestures.

Since sight is a sensory channel that provides most information and captures the majority of our attention, it is essential to achieve visual immersion that enables users to see the virtual world in a realistic way. For the Immersive VR experience, ideally, visual displays are able to produce feedback equal to or above the limitations of the human visual system (Heilig, 1992). Until the first understanding of human visual perception, it is difficult to answer the question of how visual displays achieve the goal of immersiveness trough the tricking our sense of sight. An efficient visual display should balance its image features with the ability of the user to view a simulated scene. Therefore, it is crucial to define the human visual perception system before attempting a comparison between current HMDs and human sight perception. In this chapter, the paper briefly depicts the current state of the HMD Displays for VR. This section will begin by describing the human visual perception that is currently most related to visual immersion in VR. We then discuss some current HDM displays by comparing human visual perception. Next, we summarize the status of the HMD according to the natural view of human and examine whether display technologies achieve the goal of immersiveness through tracking sense of sight.

3.1 Human Visual Perception

Visual perception is the ability to see and interpret an environment using light in the visible spectrum, which is reflected by objects in the surrounding environment. In human visual perception, the two eyes act as a sensor, and the neurons function as a connecting cable and the brain acts as a processor. Eyes as sensory receptors engage in the observation of the environment. They comprise more than 126 million photoreceptors with an irregular distribution around the retina (Jerald, 2015). Fovea, the centre of the retina, represents a high-resolution field of colour perception. Itis surrounded by the low-resolution photoreceptors of motion detection covering the majority of the Field of view. The Field of focus of the displayed images projected on the fovea. When light falls into photoreceptors of the fovea, they convert photons into electrochemical signals that travel through to the brain. Neurons are responsible for transmitting electrochemical signals to the thalamus. After signals reach the brain through the thalamus, which divides incoming signals, two sections, one contains the colour and information and the other one contrast and movement. Then these two messages move to the visual cortex, which is located back of the brain. The visual cortex is designed to reflect the back of retina sand allow a detailed image to be reconstructed.

Although Human Visual Perception is a broad research area, this paper will focus on the Field of view, Resolution, Depth perception, Color and Luminance, and

Frame Rate are most related with visual perception in VR to achieve the goal of visual immersiveness.

3.1.1 Field of view

A Wide Field of View(FOV) in virtual environments can enhance the sense of immersion and performance. The term FOV is one of the essential features of the Human Visual System(HVS). FOV is an angular measure that stands for an open, visible area through the eyes that human can see. For a healthy eye, two types of FOV function together to form human vision. Monocular FOV defines for one of our eyes the field of view, whereas binocular FOV is for both of the eyes. Moreover, the visible area through the eyes is generally indicated as an angle for the horizontal and vertical component of the FOV. Horizontal FOV is bigger than Vertical FOV since the vertical range is limited by checks and eyebrows. It is approximately 160 degrees horizontally and 130 degrees vertically when one eye is used and rises horizontally to 200 degrees when looking straight ahead with two eyes - thus we can see behind us by 10 degrees. When we rotate our eyes to one side or another, we are able to see an additional 50 degrees on each side (Jerald, 2015). Therefore, to cover the entire range of natural human FOV, HDM needs approximately 300 degrees FOV horizontally, as seen in Figure 7. Moreover, the human brain uses the horizontal change of picture location reported by both eyes to determine the depth or the distance to the virtual object displayed on the scene from the viewer (Council, 1995). This means that FOV is also crucial for depth perception.

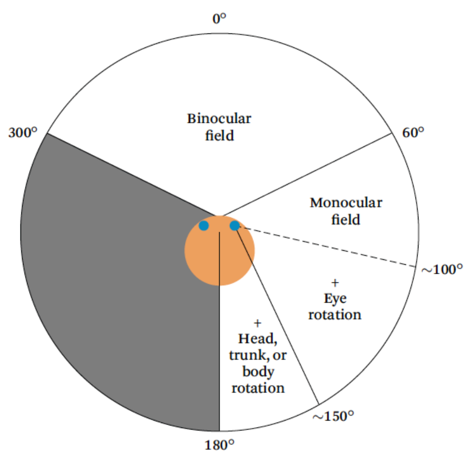

Figure 7: Horizontal FOV with straight ahead fixation, maximum lateral eye rotation and head rotation

Since the FOV refers to how much the user can see in the world of virtual reality; thus, the larger FOV is, the more realistic experience becomes with virtual reality headset. In current high-end HMDs has an average of 100-130 degrees FOV horizontally. On the other hand, StarVR already reaches 210 degrees horizontal, 130 degrees vertical FOV level (StarVR, 2020), but still, it is not enough comparing the natural FOV. As a result of this, the users thus sink into the immersion, as they observe black regions at the edge of their FOV. Larger displays are required in order to achieve natural FOV. However, extending display dimensions results in a reduction of pixel density and user can, therefore, distinguish single pixels. The use of displays with both higher absolute dimensions and greater pixel density is essential for the immersive VR sight experience.

3.1.2 Resolution

There are many features in order to determine the efficiency of the VR display screen comparing the human eye. The more important one is the resolution (Sutcliffe, 2012). The definition of resolution is a number of pixels shown on the screen. The resolution decides the smoothness of the displayed images on the screen. It is represented by pixels number per inch. It is measured by several horizontal and vertical pixels. For instance, full HD means 1920 pixels horizontally and 1080 pixels vertically. Since the human eye does not see by pixels, Considering a typical 20/20 eye resolution (one arc minute) and horizontal 160 degrees FOV per eye, a human resolution is calculated as 20K, which is 576 megapixels (Sutcliffe, 2012).

The detail perception of the human eye depends on not only on the resolution and details of the displayed image but also on the distance that the image is viewed. The farther a picture is, the less detail we can perceive. Thus, to talk about angular resolution; it is the number of pixels for a particular angle of view. The target for 20/20 eyesight is to have a resolution of one arc-minute, so that healthy eye can distinguish details as low as one-sixtieth of a degree (Jerald, 2015). This is the normal standard for a healthy eye, and many people can have better visual acuity. Most of the current HDM resolution is affected by the screen door effect, as seen in Figure 8. It occurs when screen pixel density is low that the user can see the pixels and black orders around them. Considering 160-degree vertical FOV and

20/20 eyesight of one arc-minute, a resolution should at least or ideally greater than 8K, 9000x7800 pixels per eye will be sufficient to avoid a screen door effect (Bruno Arnaldi, 2018). The human eye cannot be able to differentiate between pixels in this resolution and thus perceive a perfectly clean and clear image. By using the eye-tracking technology, Pimax 8K achieved to reach the level 8K resolution, which is enough to avoid the screen door effect. On the other hand, considering natural human, which is 20K, 8K is still not enough to see the virtual world as a human does in the physical world.

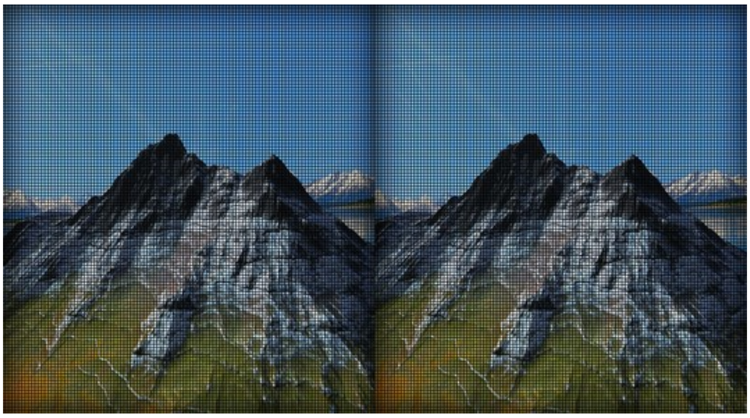

Figure 8: Example of screen door affect in HMDs

3.1.3 Depth Perception

Depth perception is the visual ability to perceive the physical world in 3D. In the real world, human see two independent pictures from the left and right eyes when looking through an object. These pictures are combined with the perception of a 3D scene. Human perceives the world as 3D because we have two slightly separated eyes. The interpupillary distance (IPD) that is the distance from the centre of one eye's pupil to the next (J.Adam Jones, 2016) allows each eye a slightly different view of the world. When the light is transmitted from objects and reflected in the retina of each eye, the images are combined in the virtual cortex via optic nerves and creating a 3D world vision.

The perception of depth comes from a variety of depth cues. These are generally classified as binocular cues and monocular cues. Binocular cues are based on the receipt of sensory information in 3D from both eyes, whereas monocular cues can be described in only 2D and viewed with one eye. In real-world, HVS uses all available depth cues automatically for determining distances between objects. To have both of these depth cues in the VR system, HMDs are taking advantage of binocular depth cues by using stereo displays.

The quality of the stereo vision depends on the correct alignment of the HMD lenses with the user's pupils. The average distance between the adult IPD in humans is 63mm (A.Dodgson, 2004). It may vary person to person, but for the majority of adults, IPD is between 50 and 75mm (A.Dodgson, 2004). Misalignment leads to lower stereo vision, diffuses the image quality, and may lead to headache or cybersickness. For the use of the HMDs in the wide range of populations, modern HMDs are produced based on average human IPD distance. Moreover, most of the HMDs have user-dependent IPD adjustment for millimetric adjustments that may vary from person to person.

3.1.4 Colour and Luminance Perception

The human eye has more than 126 million photoreceptors (Coiffet, 2003) which are scattered over the retina. The central region of the retina is called the fovea (several degrees around the viewing axis of eye) which is a represents a high-resolution field of colour perception. Colours do not exist outside us in the world but are created by our perceptive system. Objective reality consists of different wavelengths of electromagnetic radiation. A human can see between 8-12 million colours in the 400 to 700 nanometres of the visible spectrum (Zanyi, 2009). Although most modern computer displays are capable of showing almost 16 million colours, they are not capable of showing the full spectrum of lighting levels. For that reason, display technologies for HMDs do still not reach the level of human colour and luminance perception. Therefore, special colour mapping techniques need to be used in VR visual displays to achieve the best possible image quality.

3.1.5 Frame Rate

The rate at which the images appear is called as the frame rate and represented as the number of Frames per Second (FPS); the same value can be represented in Hertz, which is a frequency unit that usually describes occurrences per second (Sherman, 2002). The frame rate does not necessarily depend on the type of visual display used, but on the ability of hardware and software to render the

graphics and the virtual world's visual complexity. The frame rate significantly affect immersion in VR (Sherman, 2002)
Judder smearing is an important consideration in relation to the VR display frequency. Judder may be caused by different factors, but the head movement is the most related reason considering VR. In the physical world, turning the head at standard speed is around 120 degrees per eye per second or 240 degrees per second. In other words, when you have 60Hz display, your head moves two degrees per frames. Two degrees does not sound higher, but it is highly detrimental to visual quality, as seen in Figure 9. In theory, the higher the number of images per second, the greater the user immersion and satisfaction; so that HMDs have to calculate 120 images per eye per second which means 240 images per second (Bruno Arnaldi, 2018). Currently, most of the HDMs display only around 90 images per second. On the other hand, Valve index has reached the level of 144Hz (Valve, 2020) whereas Pimax 8K and Sony PlayStation reached the level of 120Hz. But comparing to natural head speed, even 144Hz is still not enough. For that reason, at least 240Hz frequency is required to allow the HDM user's brain to perceive fluid and continuous motion.

Figure 9: Example of two degrees judder smear in VR

3.2 HMD Technologies in VR

There are two types of HMD in the current market which are designed for smartphone and intrinsically designed for VR headsets. Display performance of smartphone-based headsets depends on the smartphone used such as resolution and colour. Cardboard type of headsets, for instance, Google Cardboard, offers minimal display quality and interactivity, ideally suited for watching a 360-degree video. On the other hand, headsets such as Samsung Gear VR are more powerful than the Cardboard type of headsets. They allow a user to adjust one or more parameters like IPD. On the other hand, they offer limited performance since their performance depends on smartphones which have a lower resolution screen comparing to headsets that are specially designed for VR. Smartphone-based HMDs cannot power immersive VR experience. The headsets that are intrinsically designed for VR devices have better functionality thanks to their hardware to be able to provide improved performance. There are currently two major players on the HDM market that are Oculus and HTC, and three new players (Varjo, StarVR and PiMax).

Many of the latest HMDs have a limited field of view (100-130 degrees) comparing with the human eye, which is approximately 300 degrees horizontally as discussed in the previous section. HTC Vive Pro (Vive, 2020) and Oculus Rift (Oculus, 2020) have 110-degree FOV, whereas Valve index (Steam, 2020) has 130-degree FOV. On the other hand, Star VR headsets, shown in Figure 10, offers the most extensive field of view of all the VR headset accessible on the market with 210 degrees horizontally and 130 degrees vertically (StarVR, 2020). It is the first "full-face VR headset" and Star VR reached the highest FOV level by combining standard and Fresnel lenses. Nevertheless, still, it is not enough by comparing natural FOV. Consequently, users sink into realism perception as they experience black areas at the edge of their FOV. To be able to create immersive sight perception, we need larger displays. On the other hand, extending display size results in a decrease in pixel density so that the user can experience the screen door effect. Using displays with higher dimensions and higher pixel density is essential for immersive VR experience.

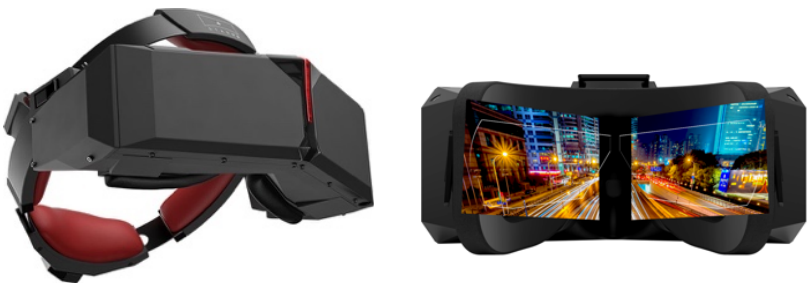

Figure 10: StarVR with 210 degree FOV

In order to avoid screen door effect, displays used in HMDs have steadily improved their resolution since the Oculus Rift DK was launched with a resolution of 840x800 pixels per eye. In the mass market, there are currently varying screen resolutions. Oculus Go and Oculus Rift have the resolution 1280x1440 per eye whereas, Oculus Quest has 1440x1600 (Oculus, 2020). Moreover, HTC Cosmos Elite has 1440x1700 pixels, and HTC Pro Eye is now at 1440x1600 pixels per eye (Vive, 2020). In the combination of Eye-tracking, Pimax 8K offers the highest resolution 8K, which is 2560x1440(perceived on the screen 3840x2140 with upscaling) (Pimax, 2020). As discussed in the previous section, most of the VR displays are suffering from the screen door effect, as seen in Figure 11, and at least 8K resolution needed to avoid it. Pimax 8K has reached the level that human eye cannot differentiate pixels and thus user perceives a perfectly clean and clear image (Figure 12)comparing to first-generation displays(Figure 11). However, 8K resolution is still not enough by comparing the natural human eye (20K).

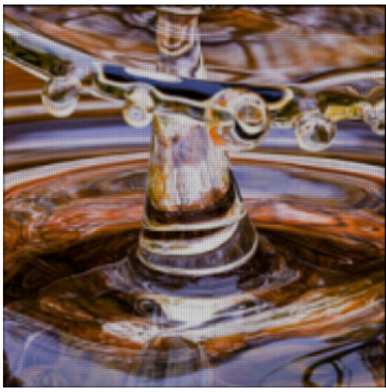

Figure 11: First generation VR

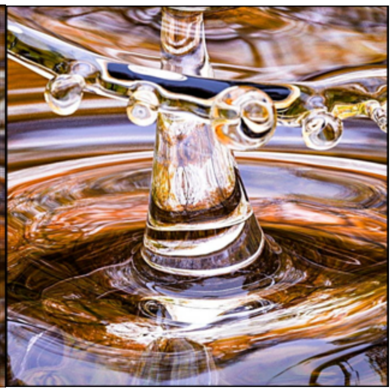

Figure 12:Pimax 8K Resolution

3.3 Analysis of HMDs for VR

Since sight is a sensory channel which provides the most information about our environment, it is important to achieve the goal of visual immersion that allows users to see the virtual world as a human does in the physical world. While looking for an answer to the question of how does visual displays for VR achieve the goal of immersiveness through the sense of sight, human visual perception discussed in section 3.1. In this section, human sight perception basics which are most related to increase immersive experience in VR defined as FOV, Resolution, Depth Perception, Color and Luminance and Frame Rate.

StarVR offers the highest possible FOV is 210 degrees horizontally, and 130 degrees vertically. However, a human can see 300 degrees horizontally, and 130 degrees vertically by considering eye movements. For the resolution, Pimax 8K has reached the level of 8K, which is the lower bound to avoid screen door effect but still not reached natural human resolution, not even close. During the virtual experience, the attention of the user's eye shifts spontaneously and unconsciously to the different points. If it is possible to determine where the user is looking instantly by using eye-tracking technologies, resolution can be increased partially based on where the user looks. Moreover, Depth perception does not only depend on the IPD but also depend on the FOV. Depth of perception immersiveness will not be achieved until the FOV reaches the level of the human eye, although the IPD is produced for the ordinary people and also can be adjusted for person to person. For the colour and Luminance perception, Although most advanced displays are able to show almost 16 million colours(whereas a human can see between 8-12 millions), they are not able to show the full spectrum of lighting. More research needed on the special colour mapping techniques. Furthermore, considering the Frequency, Although Valve Index reached the level of 144Hz, the level of 240Hz is needed for fluid and continuous motion to trick the user's brain. Since the sense of sight is the core of every VR applications including game, education, and healthcare industry, it is important to achieve the goal of tricking sense of sight. Although VR displays are designed to do so, they have not reached the level of a natural human eye yet.

Chapter Four: Hearing

The sound gives us precise details about our surroundings and can often help us assess the distance and direction of objects very accurately (M.Warren, 2010). Sense of hearing is very useful for humans and important for survival in many circumstances. We can detect a sound in the dark when we cannot see, so the auditory perception is omnidirectional, as opposed to limitations on the visual field of view, a human can detect sound from any place in 3D. In view of this omnidirectional aspect, hearing directs our visual senses, or "the function of the ears to point the eyes" as Cohen and Wenzel said (E.Wenzel, 1995).

Although vision is currently the dominant sense for human-computer communication, in Multimedia, hearing assumes at least equal importance to the user's feeling of immersion (Sutcliffe, 2012). A 3D (Spatial) audio-system enables a user to perceive the position of sound sources emanating of an arbitrary position in 3D space from speakers or pair of headphones. Spatial sound processing goes far beyond conventional stereo sound technologies by allowing virtual sound sources to possess attributes like left-right, up-down and back-forth. The basis for the 3D Audio is the ability to monitor the sensory signals that the user receives the virtual world. Spatial sound is important to be able to create an immersive virtual world through tricking sense of hearing. In this chapter, while looking for an answer to the question of how Audio technology in VR achieves the goal of immersiveness through tricking sense of hearing, it will begin by depicting the human audio perception. Next, it will discuss current audio technologies for VR based on human sound perception. Then, the section will end by analysing the audio technologies and examining whether they achieve the goal of immersiveness through tracking sense of hearing.

4.1 Human Sound Perception

The sound can be divide into two different aspects: physical and perceptive. Firstly, Physical sound is a pressure wave produced by an entity that vibrates rapidly backwards and forthwith in the material such as air. Sound frequencies are the number of cycles measured by Hertz(Hz) or vibrations that are repeated with changes in pressure. The sound amplitude is a pressure difference between the high and low sound wave peaks. Decibel(dB) is a logarithmic sound amplitude transition, which results in an increase of 3 dB by doubling the sound amplitude (Jerald, 2015). Secondly, in the perceptual aspect, the physical sound reaches the ear, the eardrum is activated, and the receptors are converted into electric signals through sound vibrations. The brain then turns these electrical signals into sound qualities like loudness, timbre and pitch. A human can perceive frequencies between about 20 - 22.000Hz with the largest sensitivity at approximately 2.000 - 4.000 Hz (Cunningham, 2014), which are the most important frequency interval to understand natural speech. In the natural environment, not only physical and perceptive aspects but also localization of sound is important while perceiving it. Spatial hearing permits a listener to identify locations and directions of sound sources which are coming from arbitrary places in 3D space. Sound localization is the capacity of the listener to perceive a sound source’s direction and distance.

4.1.1 Horizontal Localization

The simplest method of sound direction localization is to locate a sound laterally. When a sound signal is closer to the right ear, it hears the sound before than the left ear and perceives it as louder. The horizontal location mainly refers to the position of the sound source to the left or right in relation to the middle plane (Hickok, 2015). In order to localize sound horizontally, the human auditory system relies primarily on Interaural Time Difference (ITD) and Interaural Level Difference (ILD). ITD is the time difference between the arrival of sound to each ear. ITDs are the result of differences in the time of travel from the sound source to the ears closer to and farther from the sound source. Whereas, ILD is the Sound Pressure level (SPL) difference between the sound intensity levels on both ears.

4.1.2 Front and Back Localization

ITD and ILD, called binaural cues, are effective indicators of the angle of displacements of the sound source relative to the middle plane. But any sound source in a vertical or front and back location can also produce ITD and ILD. However, if the sound location varies across the horizontal plane, the listener can generate front/back confusion when asked the source of the sound. To overcome this confusion, humans depend on spectral sound modifications caused by the head and body. These spectral modifications include filters and sound reflections caused by head shape and size, neck, shoulders, torso and in particular, external ears that are called the pinna(Oculus, 2020). Since sounds from different directions interact differently with the geometry of our bodies, especially with pinnae, our brains use spectrum modification in order to decide the origin of the source. For instance, the sound coming from the front produce resonances from the inside of our pinna, while from the back sounds are shadowed by our pinnae. Likewise, the sounds coming from above can reflect our shoulders while the below sounds are shadowed by our torso and shoulders.

4.1.3 Head Related Transfer Functions

Filtering the spectrum of the sound source caused by a complex interaction between the sound waves and the ears, head, shoulders, torso and especially the pinna before entering the eardrum is known as the Head-Related Transfer Functions (HRFTs) (Bill Kaprolas, 2003). According to the head position, every sound wave passes through the pinna in a way unique to the sound source. The pinna of each ear filters these sound waves. In the view of these filtered signals, the brain estimates the exact sound source position relative to the listener. HRTF is the cornerstone of most modern 3D spatialization sound techniques (Oculus, 2020).

4.1.4 Distance Localization

Human auditory system can locate the sound source using a variety of cues such as Horizontal/Front/Back Localization and HRTFs. However, when the sound source is far, these indicators provide mostly spatial information with few indications for the distance from the sound source. A human can determine the distance of sound source by interaction with vision but however, even when we do not see our brains can estimate the distance of the sound source. Human Auditory system uses loudness, initial time delay, motion parallax, and high-frequency attenuation to determine distance (Oculus, 2020). Loudness is one of the distance cues which human use to estimate distance of sound sources based on the frame of reference to seize how much the sound has decreased in volume from its source. In the physical world, human familiar with many of the sound sources including human voices, animals, vehicles thus they can estimate the distances reasonably. However, when human have not framework for synthesis or unfamiliar sound sources, they rely on other cues or relative changes in volume to predict whether sound approaches or moves away. As being another distance cue, Initial Time Delay refers to the interval between the direct sound and its first reflection. When it is longer, human suppose sound source is located closer. On the other hand, Open environments cannot generate sensible reflections which makes it more difficult to estimate distance. Another distance cue is motion parallax which is apparent sound source movement through 3D space. By helping motion parallax cue, one can indicate the distance since nearby sounds exhibit a greater degree of parallax than distant sounds. When sound source travels rapidly relative to a stationary perspective, human tend to perceive this sound as coming from nearby (Oculus, 2020). Last but not least, High Frequency attenuates cues are faster than low frequencies; thus, over long distances, a human can interpret distance based on how attenuated frequencies are.

4.2 Audio Technologies in VR

4.2.1 Stereophonic Sound

Stereophonic sound, commonly called stereo sound, is a method of sound reproduction that splits the sound between two channels. In this method, sound is recorded on two separate sources, and then the captured sounds are combined, and certain components can be channelled to the left and others to the right. In stereo audio, the listener can localize audio sources horizontally (left and right) but not front and back or not related to head transfer function. Stereo sound cannot indicate the exact location of a source in 3D space. But when a user is in a virtual world, he moves and looks around just like we do in the real world. If the user hears a bird chirping in a tree on his left, he should hear to that sound in his left ear louder. However, when the user shifts his head to the bird directly, the sound in both ears should be equally balanced. For that reason, Stereo sound technology is not enough to achieve the goal of immersiveness by tricking the sense of hearing. Spatial(3D) sounds, however, at the sound source at any or all required locations in three-dimensional space. Spatial audio aims to recreate or synthesize a full acoustic environment. Moreover, it helps to build a new level of realism and creates a more immersive VE.

4.2.2 Spatial 3D Audio

A Spatial (3D) audio systems enable the listener to identify the position of a sound source, emitted from 3D space by a static number of stationary loud-speaker or by pair of headphones. 3D audio technology goes far beyond conventional stereo techniques and surrounding sound techniques by allowing the virtual sound source to have attributes like right, left, back-forth and up-down. Unlike stereo audio, in spatial audio, the sound is locked in space rather than the listener's head, as seen in Figure 13. This allows the listener to move around the VE, and the sound remains locked spatially to the surroundings.

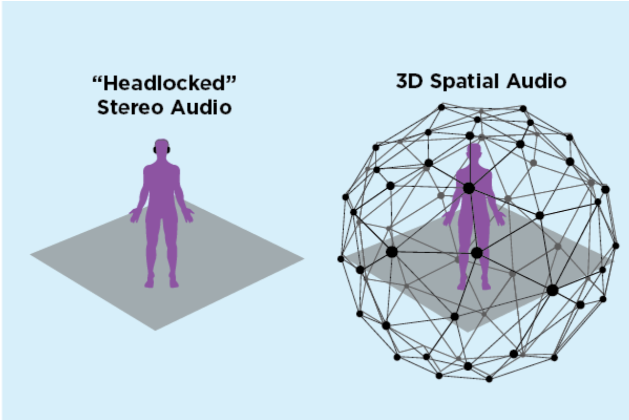

Figure 13: Stereo Audio and Spatial Audio

Spatial audio system spatializes a sound source by simulating some or all the horizontal and distance cues. Although only ITD and ILD cues are relatively easy to model and implement, they usually produce poor results and provide limited audio spatialization. In Spatial(3D) Audio, there are two key components to spatialize the sound: distance and sound localization as discussed in the human sound perception part. Distance localizations are achieved by using advanced audio software programmes. In real life, Sound localization is perceived based on our body and ear geometry(pinna). These variable effects are the cornerstone of HRTFs that 3D audio systems use to locate the sound. The most precise method of HRTF capture is taking a single person and putting two microphones in his ears (right and left) and then playing sound that is coming from all directions and recording them with microphones. After doing a sufficient number of discrete directions, these captured sounds are used to build a usable sample set (Oculus, 2020). On the other hand, every user needs customized HRTFs since their body, head and ear geometries are different from each other. But still, they are sufficiently similar to each other, in particular when it is supported with the head tracking through the VR headsets. With head tracking, this data is used to determine where the ears of the user in relation to the sound source and modify the sound accordingly. For instance, when a user turns his head 45 degrees, 3D audio system able to reflect that in an auditory environment. VR headsets such as Oculus Rift can monitor the head of the user, and by providing this information to a sound package, audio system modify the sound. Moreover, some of the 3D audio headphones such as Audeze Mobius 3D, Oassic X and Sennheiser can also track head.

4.3 Analysis of Audio Technologies for VR

Hearing skill is very useful to humans and necessary in many situations for survival. It gives us detailed information about our surroundings and helps us assess the direction and distance of the sound sources. For that reason, it is essential to achieve the goal of auditory immersion in Virtual Environments. In this chapter, we started with the Human Auditory perception when looking answer to the question of whether VR sound techniques tricks the sense of hearing. We found out that human can determine the distance and direction of the sound sources based on different cues. For the immersive VR experience, a human should perceive the virtual world as they do in the real world. For that reason, we analysed current Audio VR technologies by comparing human audio perception. In stereophonic audio, the listener can only locate the sound laterally, which is not enough for achieving the goal of immersiveness through tricking our hearing sense. However, with the Spatial Audio technology, the user can make distance and sound localisation as he does in the real world, which creates immersive VE. Distance localisations are achieved by using advanced audio software programmes, whereas direction cues are achieved by HRTFs. Head tracking technologies in VR headsets or headphones are used to track user’s head to provide this information to a sound package and as a result of this audio system modify the sound according to the virtual scene.

In the first-person shooting games, the player swings his camera from right to left and tries to find out the source of danger. It is important to find out where a threat is coming from by listening to the environment to increase the immersiveness of the player.

Chapter Five: Touch

Touch gives us our most simple tool for accessing the outside world (Ghinea, 2011). It is a critical sense for a human being to connect with the physical world and plays a central role in human communication with the environment. Important details, for instance, warmth, coldness, softness and friction or more nuanced emotional contacts between humans can only be experienced through the sense of touch. Touch has often called “the sense” that helps us to differentiate between

what is real and what is not (Ghinea, 2011). This ensures that the tactile information given by the skin is considered real by default, and we always come to touch on how genuine a sensory signal is.
The sense of touch leads to reduce the gap between the virtual and physical world (G.Sony Bhavani, 2017). It is important to trick the user's touch sense through haptic technology to achieve the goal of immersiveness in VR. In this chapter, we begin by describing the human haptic perception that is related to haptic technologies. We then discuss tactile feedback, force feedback gloves and bodysuits. The chapter ends with a brief assessment of haptic technology for VR.

5.1 Human Haptic Perception

Human sensation comes from the dermis layer of our bodies. The skin has a surface area of 18.000 square centimetres that is about 16-18% of the bodyweight of an adult; it is also the largest of our sense organs (Montagu, 1971). The dermis is lined with several sensory neurons' nerve endings (Alan Chalmers, 2009). When an entity touches or is touched, the sensors of the skin are activated by force. This force is then transmitted to the brain as a piece of information. A healthy human can feel about twenty different types of haptic sense of which hot, cold, pain are the most common ones. Some areas of the body contain more receptors than others, making them more sensitive to sensation. The tongue, for instance, has many nerve endings with pain and heat. For that reason, it hurts more when we bite our tongue and why we can burn our mouths quickly when we drink something hot. Other most sensitive places are palms, ears, fingertips and feet. Human haptic sensations can be classified into two major groups of Kinetic(force) feedback and Tactic(touch) feedback.

- Kinetic(force) feedback occurs when muscle, joints and tendons feel the forces. As a result of clinical studies (L.Askew, 1986) on human manual force exertion capability, it was found that males can exert a maximum force of 400 Newton while female hand strength is 60% to 80% of the males.
- Tactile(touch) feedback that includes feedback through the skin, such as a sense of touch, temperature, texture and skin surface pressure. There are four different types of tactile sensors that are Meissner corpuscles (the majority), Merkel disks, Pacinian and Ruffini corpuscles. When they are

excited, they create tiny electrical discharges that are perceived by the brain. Merkel and Ruffini are the most sensitive to lower frequency stimuli(0-10 Hz) whereas Meissner and Pacinian sensors respond to the higher frequency (50-300Hz)stimuli (Grigore C.Burdea, 2003).

5.2 Haptic Technologies

Haptic technologies allow the user to touch and feel the objects that simulated in VE. Haptic word is derived from Greek "haptai" meaning to "touch" that convey important sensory information which helps users to identify virtual objects and move them to perform a task in VE (Grigore C.Burdea, 2003). The study of haptics is a consequence of advances in VR. VR is a type of HCI (Human Computer Interaction) that creates an immersive virtual world that can be experienced by direct interaction with our senses. When added to the visual and 3D audio feedback, haptic feedback dramatically improves the reality of simulation (Grigore C.Burdea, 2003). To be able to increase immersiveness in the virtual world, haptic feedback must be given to the user. In HCI, Haptic feedback includes both force(kinetic) and touch(tactile) feedback as in the physical world.

5.2.1 Tactile Feedback Interfaces

Tactile feedback provides real-time information about contact geometry, surface softness and roughness, friction and temperatures (Grigore C.Burdea, 2003). It does not actively resist contact movement of the user and does not prevent the user from moving through virtual surfaces. In the commercial side, the most common tactile feedback devices are hand controllers serving as navigation, pointing and selection. They also have a hand tracking system to increase interaction in the virtual world. However, when interacting with the virtual world with hand controllers, their tactile feedback is only limited by vibrations. HTC Vive Controller and Oculus Touch are the examples of the commonly used hand controllers.

CyberTouch Glove

The CyberTouch, in Figure 14, glove provides vibrotactile feedback to the user. It has six vibrotactile actuators, one at the back of each finger and one on the palm of the hand. Each actuator has a plastic capsule containing a DE electrical motor. The motor shaft is vibrated by an off-centred mass that produces vibration. The vibration frequency can be changeable between 0 and 125Hz. Each actuator has a small force (1,2Newton) that can be felt through the singer's bones (Grigore C.Burdea, 2003).They can be individually programmed to vary the strength of touch sensation (CyberGlove, 2020). Whenever fingers or palms of the user interacts with the virtual object, the CyberTouch glove reads the user hand configuration and transmits the data to the host computer. Then the host computer sends the necessary comments for activating the vibrotactile actuators. In this way, the feedback loop is closed, and the user feels the vibrations on the skin. The glove enhances the user freedom of movement and sense of vibration significantly comparing to the hand controllers that require to kept on user's hands.

Figure 14: CyberTouch Glove

The Temperature Feedback Glove

The Temperature Feedback Gloves enable users to perceive thermal properties that can help to recognize the material of the product. These thermal properties are, for instance, temperature, thermal conductivity and diffusiveness. When grasped, materials with high conductivity feels cold and those of low conductivity, such as wood, feels warm. It is because of the heat transfer from the finger to the surface of the objects (Grigore C.Burdea, 2003). C&M Research developed a displaced temperature sensing system (DTSS) which consists of eight thermodes and control interface panel. Each thermode consists of a Peltier heat pump and a thermocouple temperature sensor attached to the skin-contact plates (Grigore C.Burdea, 2003). The fingertip temperature is determined by the thermocouple temperature sensors in real-time and then sent to the control system. The fingertip temperature is compared to the target temperature and sent to the DTSS control interface. The temperature difference between the target temperature and the user's fingertip temperatures is the input for the temperature controller system. The output is then forwarded to current amplifiers, which drive the Peltier heat pump and thermocouple temperature sensors. These thermocouple sensors are located in each fingertip and other locations such as on the palm. The host computer can modify the temperature according to the VR simulation requires.

HaptX

HaptX is another glove device which offers a convincing touch feeling to virtual objects by incorporating mid-air haptic technologies that touch the skin physically in ta similar way real objects do. Mid-air haptic technology makes a simulation of texture, shape and motion of virtual objects. There are 130 points of feedback displace user's skin up to 2mm (HaptX, 2020). User also can feel the size, weight of the virtual objects with the help of exoskeleton mechanism structure of the glove. It also produces force feedback to limit and resist the user's movements. However, it is almost impossible to replicate all data transmitted by touching a virtual object, including its surface and weight with HaptX glove.

5.2.2 Force feedback Interfaces

Force feedback conveys information on compliance with the virtual object surface, object weight and inertia in real-time. It actively resists and can stop the user's contact movement with large feedback forces (Grigore C.Burdea, 2003).

CyberGrasp system

CyberGrasp is an exoskeleton device. CyberGlove, as seen Figure 15, is the most well-known and precursor of all commercial exoskeletons (Perret & Poorten, 2018). It has a jointed structure that the user wears over his hand that transmits forces to his fingers. It is used to provide feedback from resistive force power. The system prevents the fingers from moving by applying the force resistance and not allowing the movements of the fingers when the user tries to move them. The system imitates the actual phenomenon when attempting to compress a rigid item in the physical world. The CyberGlove can also make users feel the weight to the virtual objects by using the same concept of force feedback.
The interface box of the CyberGlove transmits the finger position data to the Cyber grasp Force Control Unit (FCU). The same FCU collects wrist-position data from the 3D magnetic tracker. Both finger and wrist 3D positions are sent to the host computer during the simulation. The host computer then senses inputs that are resulting from finger touch forces into the FCU. The Cyber Grasp FCU then converts the contact force targets into analogue currents which are amplified and delivered to one of the five electric actuators in an actuator housing equipment. The actuator torques are conveyed to the user via a cable network and a mechanical exoskeleton that is placed on the top of the glove. The maximum force that can be generated on each finger is 16Newton (Grigore C.Burdea, 2003). One of the main disadvantages of CyberGrasp system is their large weight and height. For instance, CyberGlove weight is approximately 400 grams (Saddik, 2007). It could be trying for the user by considering the long simulations.

Figure 15: CyberGlove

5.2.3 Haptic bodysuits

In recent years, there have been several body haptic suits on the market; for instance, Tesla suit as seen in Figure 16, allow the user to touch and feel the sensation in Virtual Reality. The suit can actively stimulate heat, cold, vibration and tactile stimulation through a variety of electrical impulses by using conductive polymers and special add on materials as the primary structure of the suit. It has an ability to generate senses such as touch, pressure and pain by using two functional electrical stimulation: Neuromuscular electrical stimulation (NMES) and Transcutaneous electrical nerve stimulation (TENS) (Bernard, 2017). Touch sensation is mainly produced by the use of Transcutaneous Electrical Nerve Stimulation that is normally used in pain control treatments to block peripheral nerves (Kruijff, November 2006). Touch sense as tactile feedback can be simulated in bodysuits by varying frequency amplitude and pulse length. Moreover, Neuromuscular Electrical Stimulation is commonly used for muscle training and treatment for physiotherapy patients. It has the capacity to generate a sense of force or pressure on the user by producing muscle contractions, whereas TENS trigger a sense of touch depending on the virtual scenario.

Figure 16: Tesla Suit

5.3 Analysis of Haptic Technologies for VR

Sense of touch is the link between the physical world. It plays a crucial role in human contact with the environment. Since the VEs are designed to simulate physical worlds, it is important to achieve the goal of immersivess by tricking the sense of touch. Haptic technologies which we have discussed are capable of providing sensations not only for hands, wrist, and balms but also for the human body. However, the skin is the largest part of our body (18.000 square centimetres, 16-18% of the bodyweight) including ears and tongue. The Immersiveness is increasing when we involve more parts of the body in the simulation. Current VR haptic devices do not support HCI fully in real-time and new technological approaches needed to achieve the goal of immersion through tricking our haptic senses. HaptX glove is capable of providing both force feedback and haptic feedback to the user with the help of mid-air technology wand exoskeleton mechanism. Furthermore, haptic bodysuits have the ability to generate senses such as touch, pressure and pain by using electrical stimulation. However, there are a still number of limitations on all existing haptic devices. They have limited feedback capacity in comparison to the tactile sensory system in humans. The human hand consists of millions of specialist touch sensors all working in tandem, while the latest haptic interfaces typically have fewer than ten tactile feedback engines. Other limitations on existing haptic devices include a high price, large size and weight, bandwidth restrictions, latency between a human operator and force feedback, design for very specific purpose purposes and instability if the update rate is well below 1 kHz (Saddik, 2007) . Nevertheless, it will still take some time, until VR haptic technologies achieve the goal of immersiveness through tricking sense of touch.

Immersive Haptic technologies can be used in e-commerce. For instance, a human can test products by sensing the warm, cold, soft, hard, light or heavy properties of product's surfaces and textures. Since consumers usually tend to touch items (e.g. clothes) before purchasing. Haptic feedback is important for impaired people who are not able to VE through visual displays. Moreover, there is great benefit in meditation and training immersive VR haptic applications.

Chapter Six: Smell

Sense of smell, Olfaction, is essential to everyday life. It is a part of the chemosensory system that enables us to distinguish between a wide range of smells and tastes (Karunanayaka, 2018). Olfaction plays a vital role in making us understand the environment in real wold. It enables us to recognize food, drinks and also provides a sense of pleasure and warnings of danger. For instance, it advises us to leave a building with fire or if the food is rotten and poisonous. Furthermore, smell sense is more connected with feelings and emotions than thoughts and decisions (Karunanayaka, 2018). Sensory information from the olfactory can improve a sense of immersion in VE of the user by tricking the sense of smell.

Visual, audio and tactile senses are widely included in VR, but the technology to produce olfactory stimulation is currently limited and still under development. In this section, we briefly describe Olfactory perception and discuss wearable olfactory displays which are specifically designed for HMDs. The section ends with the analysis section, where we compare human olfactory perception and olfactory displays.

6.1 Olfactory Perception

The human sense of smell (and also taste) depends on complex, interconnected chemical sensors which analyse environmental molecules. The basis of smell perception is the interaction between chemical molecules, primarily in the gaseous state and the nose, which can be a detective by the olfactory epithelium and by the stimulus of the olfactory sensory neurons (Karunanayaka, 2018). This process ends in the higher cerebral centre, which makes us aware of an odour when activated. Human has a complex olfactory system that provides us with more sensitivity and dynamism to detect at least one trillion different odours (Karunanayaka, 2018).

6.2 Olfactory VR Technologies

The early digital smell interfaces in the field of HCI developed over the years are chemically based (Karunanayaka, 2018).They used chemicals to create the sensations of odour, for instance, Smell-O-vision and Sensorama. These systems are complex, costly to use frequently and require routine maintenance to operate smoothly. There are also other limitations such as switching from smell to smell, different control because gas and liquid molecules tend to float around the space, and it is hard to maintain a constant smell concentration molecule in the space. Therefore, generating smell sensation without the use of the chemical substance is also possible with digital smell technologies. Digital Smell technology is a combination of hardware and software. The function of hardware is to produce scents, and the software is responsible for determining the scent equation and generate different signals for a distinct smell. Wearable Olfactory Displays are used to increase the feeling of immersion in VR.

6.2.1 Wearable Olfactory Displays

FeelReal Mask, as seen in the Figure 17, is a scent enabling device in VR by emitting synchronized smells to the VE. It can be directly attached to the HDM and provide nine different scents for the user. Moreover, cold and warm air that blows in the face of users and an ultrasonic ionization part is used to produce water mist. The FeeReal mask also provides haptic feedback using vibration engines and a microphone for external communication. It is compatible may of the HDMs including Samsung Gear VR, Oculus Rift, Oculus Go, HTC Vive and Playstation VR.

Figure 17:FeelReal Mask

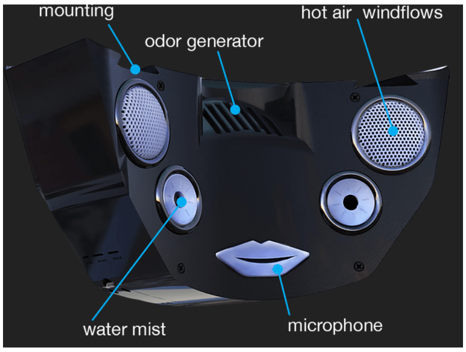

Figure 18: FeelReal Mask inside

As seen in Figure 18, by two-sided winds, hot and cold air are funnelled along user's upper cheekbones to simulate the wind, while checks are sprayed gently by water mist at different dual-sided winds. The odour generator that is located under the user's nose when wearing the headset provides available scents in the device. The basic aroma set includes flowers, jungle, ocean, fire, burning rubber, gunpowder and aphrodisiacs (FeelReal, 2020). FeelReal also produces custom-made smells as per the customer requests. However, the device is limited to nine removable individual aroma cartridges.

Likewise, FeelReal Mask, Vaqso (Figure 19) is a scent enabling device that able to produce up to fifteen different scents and five scents simultaneously to mimic what the user sees in the virtual display. The current scent line up has three basic categories that are: Environmental, Food/Drink and Others. The environmental line-up includes ocean, fire, forest, wood and soil. In Food line-up includes coffee, caramel, chocolate, curry, fried chicken whereas others include zombie, woman, mint, Gas and flower. Since Vaqso is designed in a band type, it is capable of attaching most of the HDMs including HTC Vive, Pimax, Oculus Rift and PlayStation VR (Vaqso, 2020).

Figure 19: Vaqso

6.3 Analysis of Olfactory Displays for VR

Olfaction has a strong influence over humans. The sense of smell is closely connected with the memory of an emotion. For that reason, it is important to achieve the goal of immersivess by tricking the sense of smell. However, Olfactory simulation technologies have not reached that level yet and still under development. Due to some limitations on the chemically based simulation as discussed, digital smell studies have gained speed in recent years. Real Feel and Vaqso devices are examples of digital smell devices which are specifically designed for VR headsets. They are able to create limited smell sensations as well as water mist, wind, heat and vibrations. However, a human can differentiate one trillion different odours, whereas Feelreal can only simulate nine different, and Vaqso is fifteen simultaneously. By comparing the natural olfactory system, it is quite low and not even close. For that reason, Olfactory displays are still under development to achieve the immersiveness by tricking sense of smell. When technology reaches or at least approaches to human smell perception, it can be used a wide range of VR applications including meditation, learning, movies and game VR applications to increase user’s feeling of immersion. Game developers can use custom made smells and effects based on the content of the games. Smells and effects can also be added in VR movies without any programming skills.

Chapter Seven: Taste

Taste plays a major role in human life. As a human being, we need food to survive. When we are eating, the taste of the foods directly influenced what we eat and how much we consume from them. Sense of taste, Gustation, is directly related to foods, and for that reason, it is one of the most important sense for life. Without sight, hearing or smell, people in our societies can still live a normal life. However, people who lack taste generally may not eat and may ultimately die if no medical treatment exists (Karunanayaka, 2018). Moreover, the taste of sensation can enhance the mood of the people. Research has shown that when human eat their favourite food, it triggers the production of β-Endorphin, which enhances the mood (Drewnowski, 1997). It explains why we feel happier when we eat chocolate. It is therefore stated that if food is the body, the taste is for the soul (Drewnowski, 1997).Moreover, taste also serves as a human defence mechanism. For instance, we judge the quality of the food on the basis of certain taste sensations and avoid decompose food.

Despite the importance of the sense of taste in our daily lives, Research and developments for taste simulation in VR much lower compared to other senses. However, to be able to achieve the goal of immersiveness through tricking human senses, all of the human senses should be displayed in the VR. In this chapter, we briefly describe human Gustation Perception and then discuss a gustation technology based on chemical and non-chemical approaches. The chapter will conclude with the analysis section, where we will summarize the gustation technologies.

7.1 Gustation Perception

Human detects chemical characteristics of foods with the cells of the taste receptor. They are placed in taste buds that are located across the tongue. The human tongue has approximately 10,000 taste buds, each with a group of 50 to 150 taste receptors (Smith, 2008), which allow us to distinguish different taste. Although a human can taste a vast array of chemical entities, there are five distinct sensations of taste: sweet, bitter, sour, salty and umami. Each of these taste sensations is being detected in distinct taste receptor cells (Kortum, 2008) These receptors located in the human month, especially on the tongue, and identify different taste sensations. Simulating the taste sensation also requires one or more chemical substances in the mouth. The stimuli must also be dissolved or soluble, dissolved in saliva (Karunanayaka, 2018). Therefore, Taste simulation system should be used to manipulate chemical substances accurately to integrate the sense of taste as a type of information. It is difficult to control stimuli because it requires sophisticated mechanical controls and mixing methods (Karunanayaka, 2018).Moreover, the mixture of the taste sensation is difficult to predict due to complex interactions between the other senses. The concept of taste is a perceptual experience that combines indications of taste, smell, temperature, touch, sight and sound. Therefore, the mechanisms that create a flavour experience are difficult to understand.

7.2 Gustation technologies

The current methods of taste simulation can mainly be divided into two categories: Chemical and non-chemical (Ranasinghe, 2013).

7.2.1 Chemical Based Approaches

Although it is fairly complex to use chemicals in an interactive system to simulate taste sensations, chemical taste simulations have been used to develop new HCI (Ranasinghe, 2013). For instance, "Food Simulator" uses chemical and mechanical links to simulate sensations of chewing by supplying the user with flavouring chemicals and biting pressure chewing sound and vibration (Karunanayaka, 2018). The mechanical portion of the system consists principally of a vibration motor, a vibration sensor and connections. The segment within the mouth is lined with rubber. The rubber cover is designed to withstand a bite, and the motor provides sufficient mouth resistance along with chemical products and chewing sounds. According to demonstration results (H. Iwata, 2004), 96% of the participant recognized the chemical taste of virtual food whereas on 4% could not recognize virtual test at all. However, in the experiment, only two food types are simulated which are cracker and cheese (H. Iwata, 2004).
TasteScreen (D.Maynes-aminzade, 2005) device is another example of the use of chemicals to trigger a sense of taste. The device that connects to the top of the user's computer screen has twenty separate flavouring chemical cartons to be

combined and sprayed to the monitor. The user can flavour the dispensed flavour with a liquefied tube. However, two elements of this approach are unclear. Firstly, the use of a computer screen as the system of supply for chemical products which can harm the device. Second, the suggested user behaviour may not be feasible because most users consider their screens uncomfortable to lick.
Another Example of the chemical-based taste simulation is the Virtual Cocoon machine. The machine sprays chemicals into the mouth of a wearer to produce various sensations of savour (M.Einsenstein, 2010). It stimulates not only taste but also other senses, touch, smell, vision and hearing. For that reason, it is an example of multisensory VR displays. A tube attached to a chemical bottle sprays in the nose and mouth of the customer to create various flavours. However, there are some issues with the design, primarily the functional use of the device and its scale. The machine is much bigger, as it uses various chemical ranges to activate senses of smell and taste; thus, it is not compact. Furthermore, refilling, cleaning and durability are a number of other aspects that can be improved.

7.2.2 Non-chemical based Approaches

The technology for man-made taste by using non-chemical methods is still in its infancy (Ranasinghe, 2013). Alessandro Volta was one of the first scientists to investigate sensory effects of electrical stimulation on the senses of humans, specifically touch, taste and vision, known for inventing electric cells and discovering voltage. He put two coins on both sides of his tongue (up and down) and connected them by wire, made of various metals. He said he felt a salty feeling during the experiment (A.Volta, 1800). Based on this very initial research on Electrical and thermal simulation of taste sensations, Nimesha Ranasinghe and his team developed digital lollipop in 2013 (Nimesha Ranasinghe, 2016). It is an electronic device that synthesis virtual tastes with electrical currents by activating the human tongue. Digital lollipop, as seen in Figure 20, consists of two main components which are the control system and tongue interface. The system is able to manipulate electrical currents such as magnitude, frequency) to produce various stimuli. Experiment results (Nimesha Ranasinghe, 2016) demonstrated that Digital lollipop could able to simulate several basic taste sensations such as sweetness, bitterness, saltiness and sourness. As being an electronic taste simulator that could be replaced by conventional chemical-based approaches in the future and build new experiences. For instance, in future, Scientists can manipulate the taste of Digital lollipop with and smartphone application. Moreover, Digital lollipop can also be used in VR games and in health applications.

Figure 20: Digital lollipop

After Digital Lollipop, Nimesha Ranasinghe and his team developed Voctail(Virtual Cocktail), as seen in Figure 21, is an interactive drinking device which simulates multisensory flavour sensations digitally (Nimesha Ranasinghe, 2017) It uses three specific sensory tools that are taste, smell and visual(colour of the drink). Voctail is coupled to a mobile application that allows users to create personalized virtual taste sensations by setting up each stimulus via Bluetooth. The device consists of a cocktail glass which is integrated into a 3D printed frame, containing three fragrance cartridges and three micro-air pumps (Nimesha Ranasinghe, 2017). When user drinks from the Vocktail glass, visual (RGB light projecting onto the drink), taste (electric stimulation at the tip of the tongue) and smell stimuli(micro air pumps emitted) are combined to generate a virtual flavour sensation that changes the taste of the drink. Users have virtual tastes in viewing the colour of the beverage, inhaling the stimulated scents, and stimulating their tongues with electric taste sensations. Visual perception is also key here because when we look at the beverage, we set our pre-taste perception based on its colour, fizziness, and other physical characteristics (Nimesha Ranasinghe, 2017). For the smell perception, three scented cartridges are stored in the 3D glass connected to micro air pumps. These pumps release scent molecules, and this affects the understanding of a drink’s taste. Lastly, for the taste sensation, there are two electrode stripes on the surface of the Voctail glass as a mouthpiece. This mouthpiece ensures that the tongue of the user attaches to the electrodes to imitate electric taste sensations correctly. This is critical since these electrode stripes give electric pulses to the tongue of the user to stimulate taste buds. To be able to deliver three different taste to the user, different settings needed for each of the tastes. A volt of 40 microamps(μA) imitates a salty taste, while 80 μA needed for the bitter taste and 180 μA for the sour taste (Nimesha Ranasinghe, 2017). This taste experience can be remotely controlled via Bluetooth using a mobile app, enabling the users to have complete control over their custom taste creations. Although currently, Virtual Cocktail is available in the form of a mobile app (Figure 22), it can be applied to virtual reality to trick our sense of taste to achieve the goal of immersive VR.

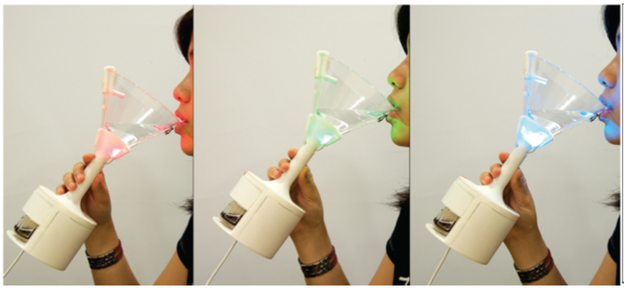

Figure 21:User interact with the Voctail

Figure 22: Voctail Mobile App Screen

7.3 Analysis of Gustation technologies for VR

Gustation, as one of the five most important senses, plays a significant role in human life. It is not only needed for survival but also directly connected to our mood. However, at present taste sensations are difficult to use as a VR output by comparing other human senses, for instance, sight, audio and touch. Two main methods are in use to simulate the taste, which is chemical-based and non-chemical based approaches. Food simulator, Taste screen and Virtual cocoon are examples of the chemical-based approaches. However, there are some limitations such as limited virtual taste availability, refilling, cleaning, the durability of the devices since the chemical content can be harmful to the device. Due to the limitations on the chemical based taste simulations, current researches are heavily continue based on digital taste devices. However, since digital taste simulation technology is quite new, there is no specific method for it. Only three different, which are salty, bitter and sour achieved the simulate in Voctail whereas human tongue can approximately differentiate 10,000 tastes. The mixture of the taste sensation is difficult to predict due to complex interactions between the other senses; therefore, the sense of taste is currently considered the ultimate limit for creating immersive VR (Nimesha Ranasinghe, 2016).A new methodology is

therefore needed to achieve the goal of immersiveness through tricking sense of taste in VR.
Immersive gustation VR technology can be used widely in games and the medical industry. Game designers can integrate smell and taste sensations as important dimensions of body perception to increase the immersiveness in the virtual games. Furthermore, it has great potential in the medical industry; for instance, diabetic patients could taste some of the foods like sugar and chocolate again.

Conclusion

This research paper started by asking the questions of how human perceive the physical world and how does VR technology achieve the goal of immersiveness through tricking five human senses. After VR technologies discussed by comparing human perception for each of the senses, we found out Spatial audio technology can achieve the goal of immersiveness by tricking the sense of hearing. Although virtual display technologies come a long way since the Sensorama, the human eye perception has not been reached yet due to the complexity of it. For the sense of touch, since the skin is the largest part our body and haptic technologies have limited tactile and force feedback technologies, the goal of immersiveness has not achieved yet. Moreover, the human sense of smell and taste depends on complex and interconnected sensors, Olfactory and Gustation technologies still under development to achieve the goal of immersiveness.

With the current technologies, the most immersive multisensory VR system can be the combination of Pimax 8K(highest resolution), Star VR(highest FOV), Spatial Audio(sense of hearing), HaptX glove(tactic and force feedback), Tesla suit(heat, cold, vibration and tactile stimulation for the body), Vaqso(sense of smell) and Digital lollipop(sense of taste). For the full immersion, each of the display technologies should achieve the goal of immersion and then should be combined in a system which allows multisensory VR experience as in the term "Real Virtuality" coined by Alan Chambers. It is considering the ultimate limit to achieve the goal of immersiveness through tricking human senses. Further researches needed to achieve the goal of immersiveness by tricking sense of sight, touch, smell and taste. After achieving the goal of immersiveness for each sense, they should be combined in on VR system.

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